

Technical Review

Vol.21 No.2



Comment on the Cover

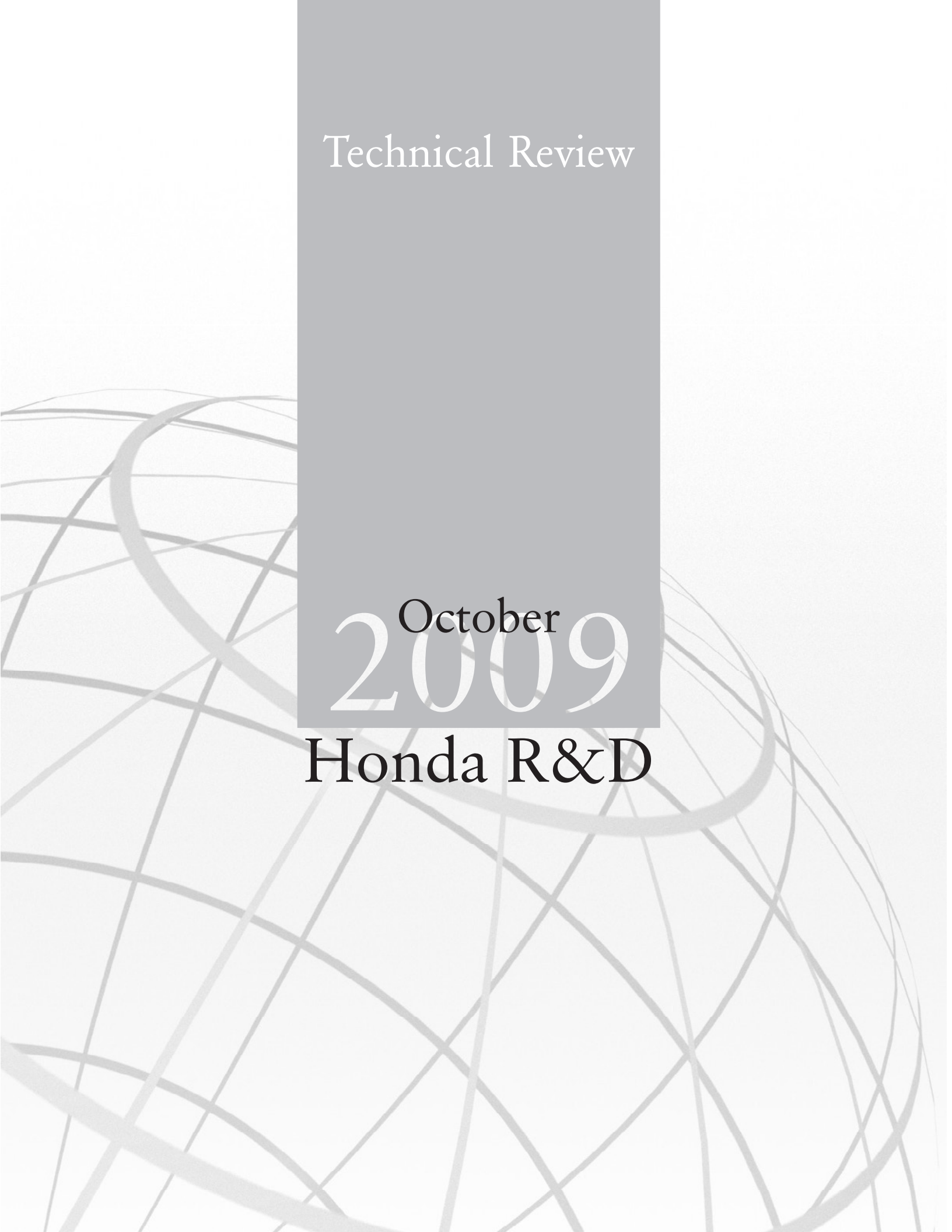
About the Cover / From the Illustrator

The breadth of Honda products is incomparable, and this impressive diversity has always excited people and will continue to do so. Everyone has their own stories about each of these products in our life. Together, they make up the interwoven tapestry of Honda achievements.

In my case, a LIFE STEP-VAN was there at the start of my parents' relationship. That was the very first chapter for my mother and father. As I drew each vehicle and product on the cover, I imagined the story that would unfold for each owner.



Power Products R&D Center
Asagi MIWA

The background features a light grey wireframe sphere on the left side, composed of intersecting curved lines. A solid grey vertical bar runs down the center of the page, serving as a backdrop for the text.

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Style and Design of New Model INSIGHT

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ABSTRACT

The new model INSIGHT was developed based on the key concept - “A Compact Car Standard for the Next Generation.” During the development, the aims for the new INSIGHT were to achieve good fuel economy and low exhaust emissions in a compact class car, and to be used by even more customers.

The exterior design theme is that of an “Aero Athlete,” and aims for not only an advanced style, but also a running form backed up by proven aerodynamic performance.

The interior design theme is that of an “Emotional Hybrid Interior” that fuses the fun of driving a car with the advanced, futuristic feeling of a hybrid car.

1. Introduction

Honda has continued to release models that take into account the environment since the release of the CIVIC in 1972 equipped with the CVCC engine.

The first generation INSIGHT was released in 1999 as a hybrid car, and it achieved the goal of “providing the maximum fuel economy performance to customers.” However, due to its release in the two-seater coupe category, it was unable to provide the benefits of a hybrid car to many customers.

The new INSIGHT was developed with the grand concept of “A Compact Car Standard for the Next Generation” so that the hybrid car benefits of good fuel

economy and low exhaust emissions could be provided to even more customers. Emphasis continued to be placed on good fuel economy and low exhaust emissions performance in order to achieve an environmentally friendlier vehicle. Another element realized by the design package was the innate pleasure of car driving incorporated with INSIGHT’s usable cabin and luggage space demanded from a standard car. These elements were realized in an affordable package thus helping to enable hybrid cars to be offered to a greater number of customers.

Figure 1 shows the new model INSIGHT released in 2009.



Fig. 1 2009 model year INSIGHT

* Automobile R&D Center

2. Package Layout

To give concrete form to the package concept of “A Global Standard for High Efficiency,” a five-door hatchback style was selected. INSIGHT’s package offers the convenience of allowing comfortable seating for up to five adults, and provides sufficient cargo space while the size remains compact with a low overall height of 1425 mm (Fig. 2). The overall height and width are standard throughout the world, and only the total length

differs depending on the front license plate specifications - 4375 mm for North American specifications, 4390 mm for Japanese specifications, and 4395 mm for European specifications.

The basic platform uses that of the FIT, with the fuel tank location changed to under the rear seat so as to lower the front-seat hip point by 50 mm compared to the FIT.

The wheelbase was lengthened by 50 mm compared to the FIT to 2550 mm. This resulted in a space that provides both front and back seating comfort for adults

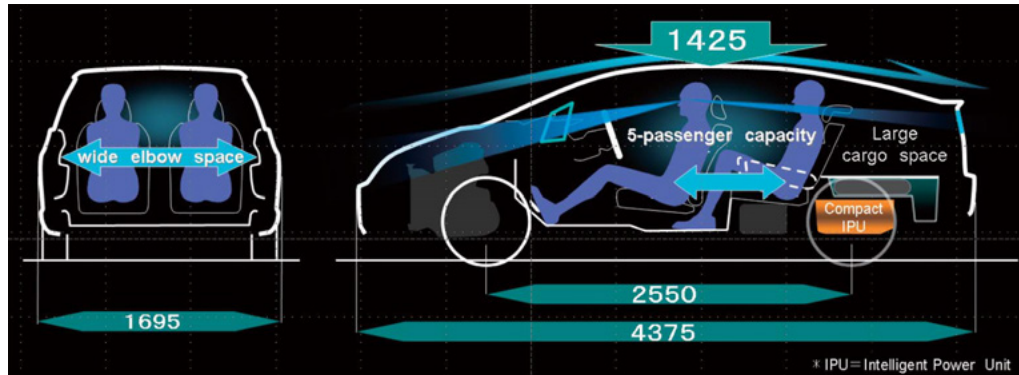


Fig. 2 Package layout (North American specifications)



Fig. 3 Luggage compartment for European and Japanese specifications



Fig. 4 Front visibility

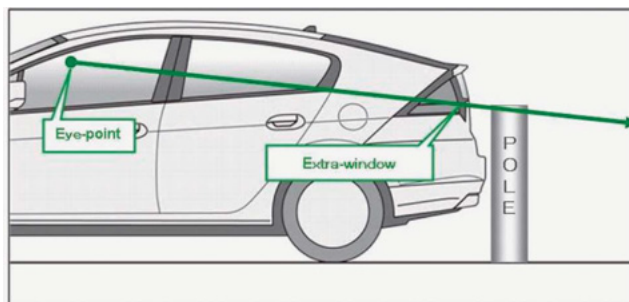


Fig. 5 Extra window

equivalent to that of the 2003 model year European and Japanese ACCORD (North American ACURA TSX), even in a compact size.

The low floor luggage compartment exceeds the standard for this class, and the use of a downsized Intelligent Power Unit (IPU) with an under-floor layout achieved a luggage compartment capacity of 355 L. European and Japanese models can also select specifications without spare tires which further lowers the floor by 105 mm and increases the luggage compartment capacity to 400 L (Fig. 3).

The front pillar was moved forward to increase the area of the side windows in the forward direction, and the side mirror mounts have been reduced in size enabling the realization of good forward visibility (Fig. 4).

The extra window area was increased by using a thin rear spoiler to enhance rear visibility thus making it possible to see a pole (i.e., representing a young child) (Fig. 5).

3. Exterior Design

“Aero Athlete” was selected as the key concept for the exterior styling evoking an aerodynamic and powerful running form. In the chassis, a low total height has been maintained in order to enhance aerodynamic performance. Furthermore, the low height combined with the integrated line from the tip of the hood to the cabin achieves a more compact looking engine compartment and produces an advanced overall form.

The bold and sharp wedge lines used for the sides of the vehicle express a sense of speed and optimize the airflow around both the cabin and the body. The surfaces that envelop these forms were sculpted in the image of the supple tension of an athlete’s muscles (Fig. 6).

Testing and design proceeded concurrently in the development process, with the results of aerodynamic tests using models being fed back into the design before the final design image was fixed. A CD value of 0.28 was

achieved in actual running tests, resulting in a stylish design with proven aerodynamic performance.

The thin and wide headlights make the front appear even lower and wider. The rear combination lamps and the high-mount stop lamp were made continuous for a distinctive rear appearance (Fig. 7).

The rear combination lamps adopt an advanced design utilizing LEDs with low power consumption to enhance fuel economy (Fig. 8).



Fig. 7 Final rendering

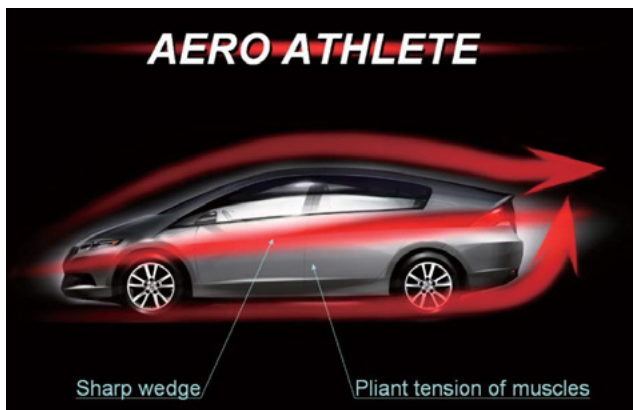


Fig. 6 Exterior design concept



Fig. 8 Rear combination lamp

4. Interior Design

“Emotional Hybrid Interior” was selected as the key concept for the interior styling. The aim was to establish an interior space that combines the advanced driver’s cockpit and exhilaration with an everyday utility.

The cockpit, which is triangular with a vertical layout, uses a multiplex meter; an advanced interface that was developed originally by Honda. In addition, the instrument panel framework is rounded towards the front of the car, which both emphasizes the cockpit area and reduces the instrument panel volume. The upper and lower parts of the instrument panel are formed by concave surfaces realizing a clean field of vision and a feeling of space around the knee area (Fig. 9).

The multiplex display shows a digital speedometer and an ambient meter on the upper level. Drivers are able to recognize driving conditions by changes in the background color, which naturally leads to more fuel-efficient driving. The ambient meter uses an earth motif that expresses the aim to “Increase the Green on this Blue Earth!” The lower level locates a tachometer, ASST/CHARG meter, and fuel gauge around a multi-information display. Analog displays present an exciting sense of accuracy with the mechanical feel of a machine. The multi-information display shows the conventional vehicle information, and features an eco-

assist bar that provides coaching for accelerator and brake operations for more fuel-efficient driving. These displays, together with the heater controls and an ECON switch located strategically around the steering wheel, create a cockpit that seamlessly integrates an advanced feeling with “FUN to DRIVE” functionality (Fig. 10).

Cup holders, storage for small items (Fig. 11), and a console box and armrest (Fig. 12) are provided in the limited width between the right and left front seats to increase driver convenience. In addition, practicality has been enhanced in consideration of users downsizing from larger cars, such as by providing a security pocket below the car stereo that can be used to hide a garage door opener or other items (Fig. 13).

The interior lining is comprised of concave surfaces



Fig. 9 Interior design concept



Fig. 10 Drivers cockpit

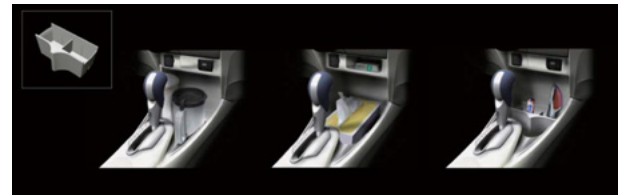


Fig. 11 Cup holder and storage

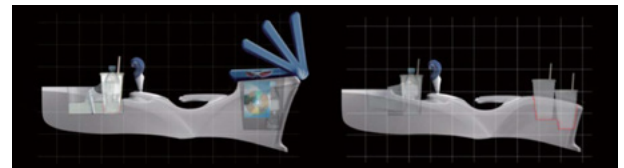


Fig. 12 Console box and armrest



Fig. 13 Lid type center pocket



Fig. 14 Interior rendering

scooped out to the top and bottom centering on the shoulder line, which assists in securing the largest cabin width within this class. This enables two sets of two cup holders to be used when there are four passengers, and creates a simple yet comfortable space that exceeds the standard for this class.

The front seat design firmly supports the lower back and has sporty styling that helps keep the driver's upper body facing forward. The rear seats are fold-down types with a 6:4 seat back partition that increases convenience by enabling use as both a 5-person car and a full-flat luggage compartment. The luggage compartment floor can be moved up and down in two levels enabling under-floor storage of a tonneau cover and the like. In addition, detailed measures were taken such as the addition of wickets to help prevent small items from rolling around or items from tipping over (Fig. 14).

5. Color Design

Based on the definition of hybrid as being a "combination of two different characters," a feeling of freshness was realized in the color design through the contrast or fusion of two elements.

5.1. Exterior

Spectrum White Pearl and Brilliant Sky Blue Metallic were selected as the image colors to directly convey the impressions of "Clean, Ecology and High-Tech", which is the exterior color theme.

Spectrum White Pearl is a new color with an advanced color sense that is based on a completely new and clean white tone befitting a new generation. New materials are blended in that manifest varied colors like a rainbow, depending on the light source and the angle of view, just like an actual pearl. The resulting gold highlights and bluish-white shading create a dichromatic effect that further enhances the muscular body form and full lines.

The grill color uses large and high luminance metallic components to provide an advanced look with a strong sense of presence. Two color schemes, light tone and medium tone, were set to help ensure optimum compatibility between all exterior colors (Fig. 15).

5.2. Interior

The interior color theme, "organic and inorganic," has been expressed in the design of the interior colors, materials, and surfaces.

The interior uses two differing hues, with the entire interior being enveloped in a warm gray that provides a sense of security, and the functional parts colored in blue, which gives them an advanced feel. Metallic accents have been used to help enable the achievement of a balance between these two colors in the cabin as a whole.

For the surfaces, the use of a natural leather pattern throughout the interior provides a sense of harmony, and this pattern is contrasted by a mechanical geometric pattern used for the functional parts.

For the seat fabric, a mesh-like, pin-dotted fabric with a lightweight feel has been used for the seat centers, while the side bolsters use a dense and thick suede-like fabric with a wave pattern. This combination of different materials emphasizes the form of the seats with their subtle modulations.

For the seat fabric colors, the use of blue and warm gray as alternative seat colors enables the efficient realization of two distinct interior types as opposed to the use of a single interior color type (Fig. 16).

Image not displayed for copyright reasons.

Fig. 15 Exterior image colors and grille colors

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Fig. 16 Interior and material colors

6. Conclusion

The design of the new INSIGHT proceeded from the key concept, “A Compact Car Standard for the Next Generation.” In addition to realizing an easy-to-use vehicle that can comfortably seat five adults in any part of the world, the design fuses a sense of advancement as a hybrid vehicle with the appeal of the innate pleasure of driving a car.

The authors believe that the appealing vehicle created displays a form that points towards the automotive future.

No matter what the specific developments of the period in question, the authors hope that more and more customers experience the pleasure of using a vehicle and protecting the earth’s environment at the same time.

The authors sincerely hope that the development of the new INSIGHT has thrown open a door towards the next generation of cars.

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Development of CITY aimed at Advanced Proud Sedan

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ABSTRACT

The CITY was developed with the aim of setting a new standard for small sedans that are in high demand, particularly in emerging countries.

The concept during the development process was to create an automobile that purchasing customers could take pride in owning and also be proud of themselves.

One aspect of building a small sedan is that it is based on an earlier hatchback model, and the CITY was similarly based on the 2008 model year FIT (JAZZ).

All aspects of the CITY small sedan were developed toward achieving the concept of an Advanced Proud Sedan, and the results have been favorably received in every country where it is sold. An automobile that delights customers around the world has been created.

1. Introduction

The CITY was first sold in 1996 as an Asia-only model. The nations marketing it have since increased, and today it is manufactured at six locations in Asia, including Thailand, China and India, as well as in Brazil, making it a truly global car.

In addition to adding locally required specifications and equipment to the development tasks, the development team spent many hours listening to the opinions of customers of small sedans.

Additionally, for the interior and exterior styling and packaging development process, meetings with customers in the key nation of Thailand were held in order to check the model.

Simultaneously, the team also met customers from other countries at the same time and worked to reflect their valued opinions in the model.

Also, to confirm cruising performance, driving tests were conducted in urban high-traffic areas, on expressways and ordinary suburban roads in Thailand and India to focus the direction for CITY tuning.

This was the background to the development concept for the CITY.

The “base model” in this paper is the 2008 model year FIT (JAZZ).

2. Development Concept

During development of the CITY, the team interviewed numerous individuals in the model’s markets to determine their sense of values. The results indicated that people are always thinking of moving up and that they value being seen as successful, being recognized by others, and taking pride in themselves. What people want from the automobiles they own is a sense of being advanced, to receive recognition from their families as well as others, and to take pride in using their automobile for a variety of purposes.

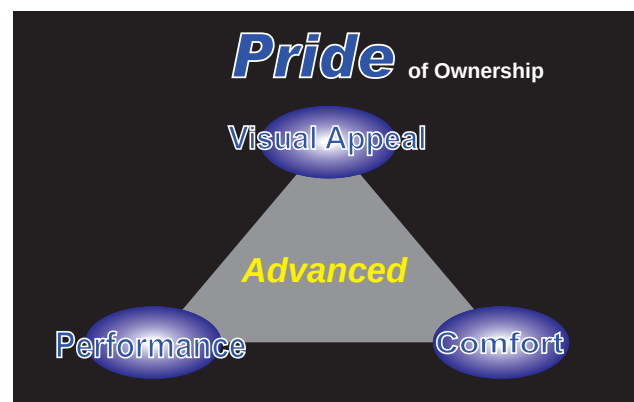


Fig. 1 Grand concept : Advanced Proud Sedan

* Automobile R&D Center

Table 1 3 dimensions and wheelbase

	Previous CITY	Newly developed CITY	FIT (JAZZ) 2008 year model
Overall length (mm)	4390	4395	3900
Overall width (mm)	1690	1695	1695
Overall height (mm)	1485	1470	1525
Wheelbase (mm)	2450	2550	2500

The grand concept determined for the CITY was to develop an “Advanced Proud Sedan” (Fig. 1), an automobile with the visual appeal that makes the owner proud just to look at it, the performance and comfort that make the owner proud to use it, and a sense of being advanced.

3. Strong Styling

3.1. ARROW SHOT FORM

As the studies progressed in each of the regions, the result that emerged was that the common expectation from a small sedan is visual appeal with strength. However, if cabin comfort is solely enhanced in order to reflect this value in the styling design of the model, this becomes clearly apparent in the external view and detracts from the visual appeal. The team therefore conceived of the “ARROW SHOT FORM,” a styling theme to provide the required visual appeal as well as comfort.

The form expresses comfort wrapped in powerful visual appeal, an effect made possible by exterior styling that captures the dynamic motion of an archer drawing a bow, and a cabin area that also expresses the pent-up energy of the drawn bow (Fig. 2).

3.2. Packaging and Exterior Styling

Most small sedans are shaped like the hatchbacks on which they are based, with the addition of a trunk. Some models are indistinguishable from the hatchback model when seen from the front. The project decided to take a different approach when it developed the CITY, aiming to create clear differences in the external view. In post-

sale market surveys, customers responded favorably to the strong original styling.

3.2.1. Three dimensions and wheelbase

While maintaining the good maneuverability of the previous CITY, the increase in length and width was limited to 5 mm. The team reviewed how to lower the automobile height as much as possible, while using the same floor panel and the front seat frame as the base model. As a result, a height 15 mm lower than the previous CITY was achieved. This necessitated changing the driving position relative to the base model, so a new design for the bracket supporting the seat rail lowered the position by 7 mm. An adjustment of cushion urethane thickness and a new design of the cushion spring lowered the position by another 8 mm.

To enhance the auto’s proportions as a sedan, the wheelbase was analyzed by imaging simulation and extended by 50 mm over the base model and 100 mm over the previous CITY.

Table 1 compares the three dimensions and wheelbase, while Fig. 3 shows the CITY’s packaging design.



Fig. 2 Exterior design theme: Arrowshot Form

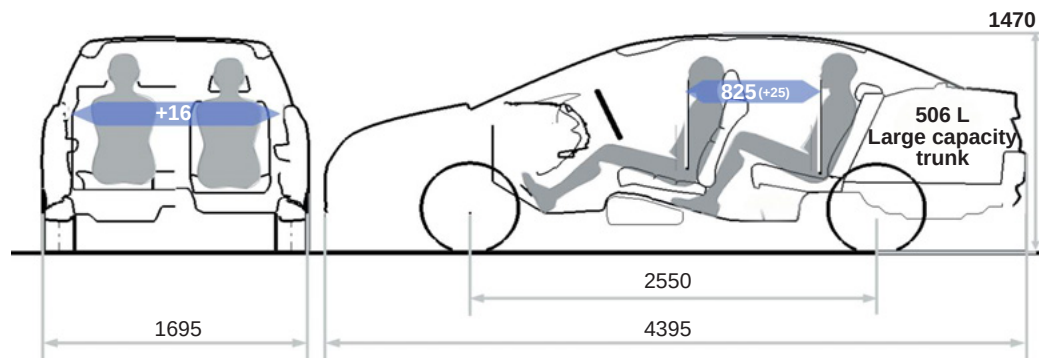


Fig. 3 Package design

3.2.2. Side styling

Market studies indicated that important elements included strength plus a silhouette that flows smoothly from the tip of the hood and over the roof to the rear of the vehicle, and these values were incorporated into the side styling (Fig. 4).

The body side seeks to harmonize visual appeal and comfort. Compared to the previous CITY, the external width is 5 mm greater, while cabin width is 16 mm greater, and the body side panel was finished to give it a

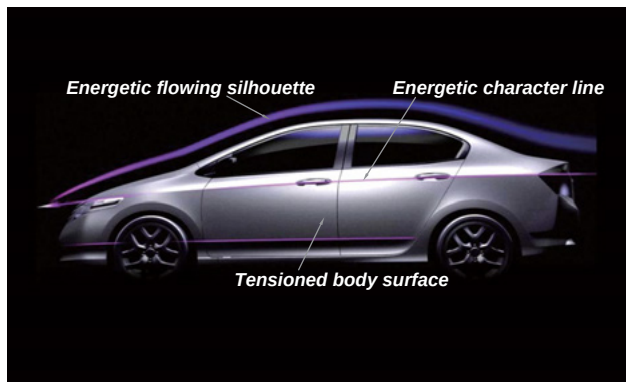


Fig. 4 Side styling : Solid and imposing design



Fig. 5 Front styling : Powerful, forward-thrusting, front-end design



Fig. 6 Rear styling : Sharp rear-end design

tensioned surface.

The body's side character line, sharp from front to back, recalls the impression of the arrow in the ARROW SHOT FORM theme as an integral part of the active styling.

3.2.3. Front styling

The goal of the styling of the front mask was to pack it with power (Fig. 5).

The trigger of this concept was the words by the president of a Honda dealership in Thailand: "If you look a person in the eyes, you know his ambition. It's the same with automobiles." Many small sedans are equipped with single-bulb headlights bearing an elliptical motif. The CITY, in contrast, uses horizontally-wide and longitudinally-slim single-bulb headlights with styling like eyes to render a powerful impression. The model takes advantage of cross-direction lighting to achieve the same level of performance as the previous CITY.

The grill design, which is continuous with the headlights, completes the characteristic front mask, while the front styling incorporates the functional elements of collision performance, pedestrian protection and forward visibility.

3.2.4. Rear styling

The goal for the rear styling is to establish an appearance that would leave a strong impression (Fig. 6).

The forceful line leading from the tip of the hood, the solid look leading from the side, and a form that creates trunk volume, combine into dynamic high-deck styling.

The body's side character line connects to the rear end's characteristic taillights, creating an image of arrow feathers.

The taillights are of a one-piece construction mounted on the side panel. Taillight size was balanced against the size of the trunk opening line, making the trunk easy to use despite the limited body width. The one-piece construction is designed to house the rear fog lights that are required in Europe.

4. Creating Attractive Performance

4.1. Powerful yet Relaxing

Test-drive sessions were held in Thailand and India as representative of the CITY's sales markets. These test drives included competing models, and based on the results, the key requirements in these regions were narrowed down to the following.

1. Power plant standing start and acceleration response suitable for heavy traffic and high-speed cruising (Fig. 7)
2. Comfortable riding on rough roads, whether in the city or on its outskirts

Therefore, the performance theme chosen was "powerful yet relaxing," and the team tuned the common platform to achieve this theme.

4.2. Power Plant and Engine Room

The power plant used the same specifications as the base model, i.e., a 1.34 L or 1.5 L i-VTEC engine, each available with manual or automatic transmission. The CITY is additionally available with a power plant that combines an automatic transmission with a 1.8 L i-VTEC engine.

The engine room was designed to accommodate the large-size 1.8 L space layout. A summary comparison of the size of the 1.5 L and 1.8 L engines is shown in Fig. 8.

The same major parts as the base model were successfully utilized on the dashboard side. It was

necessary to expand the space on the front side, however, in part to accommodate a larger battery, so the overhang was extended 105 mm compared to the base model. A view of the 1.8 L engine room from above is shown in Fig. 9. The view from above shows that the battery goes in at an angle to limit how much the total length and width of the small sedan had to be increased.

4.3. Chassis

The chassis is a major determining factor for performance. As with the power plant, the CITY uses the

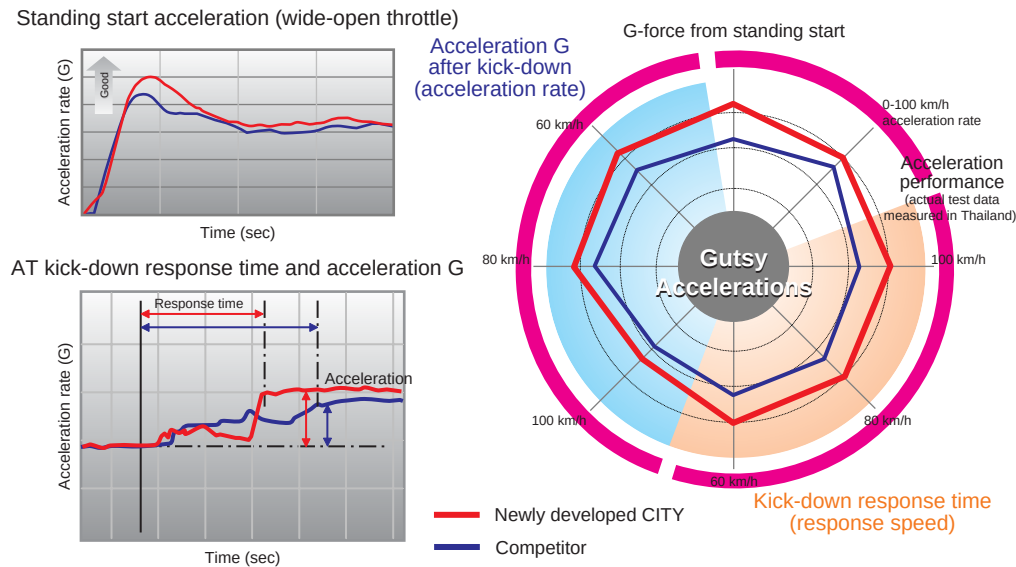


Fig. 7 Acceleration rate : Powerful Accelerations

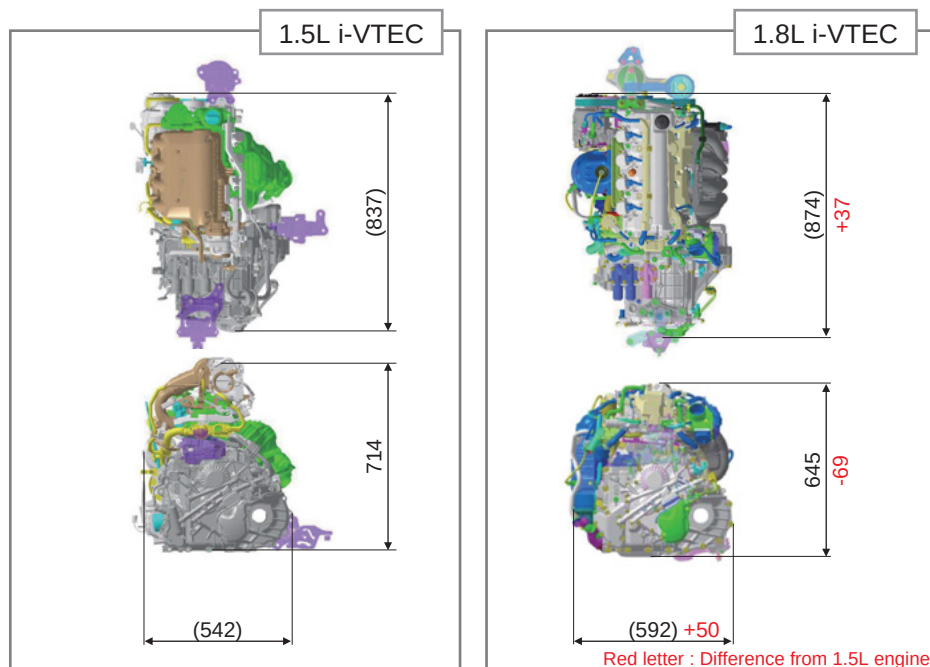


Fig. 8 Engine size comparison

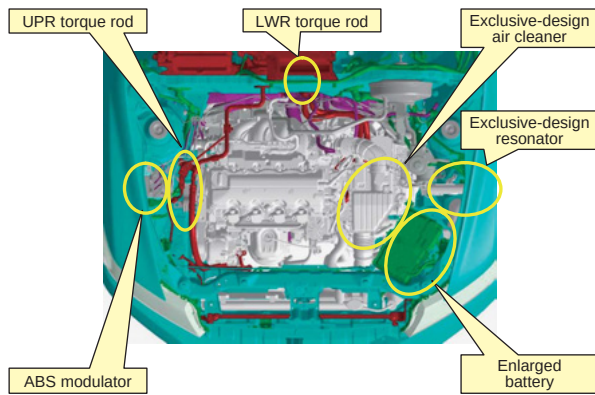


Fig. 9 1.8L engine room

same chassis as the base model, with three major exceptions stemming from the fact that the bodies are shaped differently.

1. The wheelbase is 50 mm longer
2. The 1.8 L engine and front overhang
3. The trunk room and rear overhang

In addition to the above, there is a different weight balance between front and rear, and exclusive designs and tunings were applied to the chassis in order to achieve the aim of a “powerful yet relaxing” design. The structure of the chassis and differences with the base model are shown below (Fig. 10).

4.4. Suspension and Power Steering

The CITY uses the same suspension as in the base model, including the body structure to which the suspension is attached. However, unique tuning was applied for the spring rate and damping constant. Additionally, the stabilizer diameter was decreased from 21 mm to 19 mm. Unique electric power steering data settings were applied to account for the suspension’s characteristics. This tuning functions as the base for powerful acceleration, while enhancing relaxing performance with a flexibly comfortable ride, high stability, and crisp steering feel.

4.5. Exhaust System

The exhaust system is affected by all three of the previously noted major differences in the chassis. Differences in the exhaust system specifications are shown in Fig. 11.

4.6. Body Rigidity

Simulations were employed to study body rigidity, which supports cruising performance. By increasing the bonding rigidity in each part, a light but highly rigid construction was achieved.

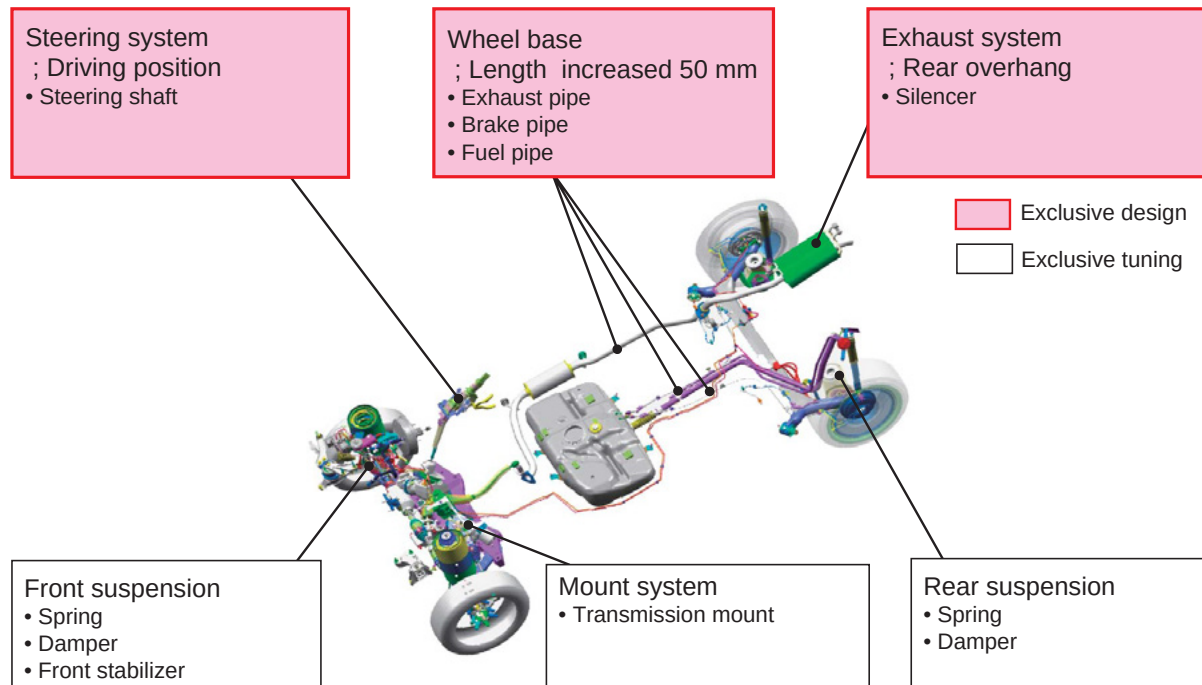


Fig. 10 Chassis platform for 1.5L

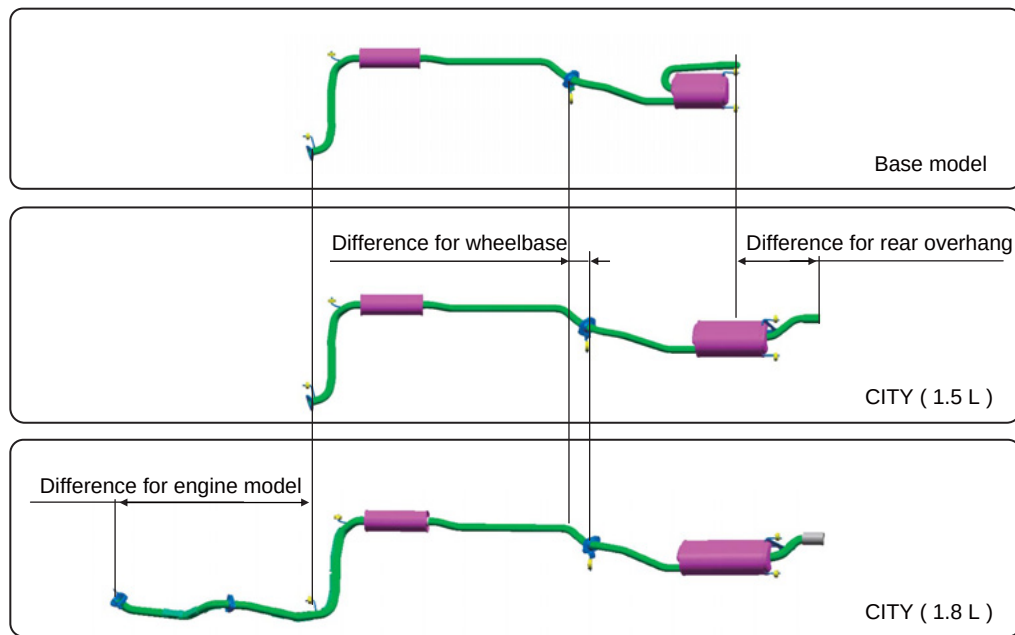


Fig. 11 Exhaust system comparison

The barrier between the cabin and trunk room (i.e., the rear bulkhead), a part of the automobile that differs greatly in construction from the hatchback, is integral to body rigidity in a sedan (Fig. 12). Here, the CITY uses the same rear wheelhouse, where the suspension is attached, as the base model. In addition, the trunk room was given a wide opening and a highly rigid framework was achieved.

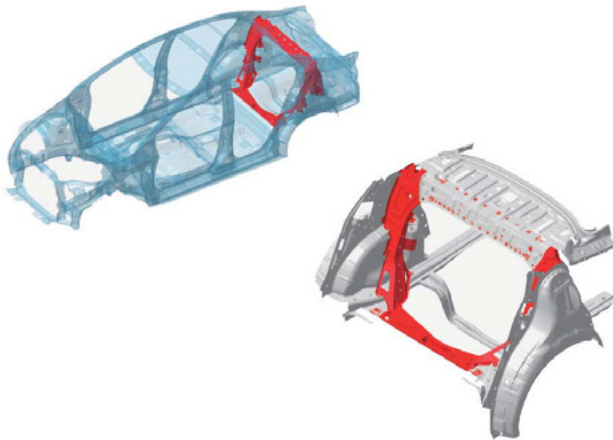


Fig. 12 Body rear bulkhead

5. Exclusively Designed Comfortable Space

5.1. Generosity and Strength

It is the team's desire to provide a comfortable interior space isolated from the road environment (for example, heavy traffic) and the weather (such as sudden squalls). The CITY was styled to envelop passengers in generosity and strength so they can take pride in being inside this interior space.

5.2. Front Seat Interior

The front seat impresses the observer with the strength that is expressed by the interior (Fig. 13). One can see this strength in the forceful character line and color flow from the silver-colored panel in the center of the instrument panel to the front pillar, door interior, and console.



Fig. 13 Interior styling 1

The lively steering wheel, which is also used in the base model, hardly seems out of place in the sedan's interior, and was highly praised in market studies.

The meter design features edge lights and metallic-finished 3-D faces, as well as a fuel consumption indicator designed to make the meters appear advanced (Fig. 14). The meters have the same panel as in the base model, with the difference expressed in their appearance.

5.3. Rear Seat Interior

Sitting in the rear seat, however, the strong form that is apparent in the front is sensed as a generous flow. The roof surface, extending from above the passenger's head to the front, appears to pass through the glass (including the side glass) and spread out as it blends into the outside scenery (Fig. 15).

Thanks to a front-to-back-seat tandem distance that is 25 mm greater than in the previous CITY, the rear seat space is greater than the standard for small sedans (Fig. 16). As a result, the ease of sitting in the rear seat makes not only owners themselves, but also family, friends or guests keenly feel how comfortable the space is. Consequently, "Pride of comfort" for owners was achieved.

Compared to the base model, which comes with a ULTR Seat, the CITY's rear seat focuses on the comfort expected of a sedan. It has a fixed seat face with plenty of cushion, with the space below functioning as a storage space. When this was arranged, incorporating study results, the team assumed that umbrellas and shoes were the type of items that would be placed in the storage space, and considered how it would feel on the



Fig. 15 Interior styling 2

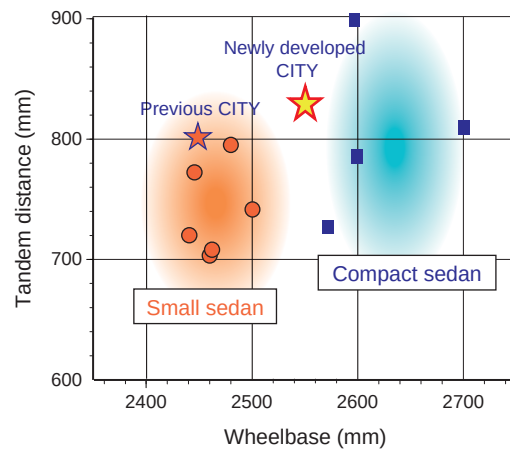


Fig. 16 Tandem distance

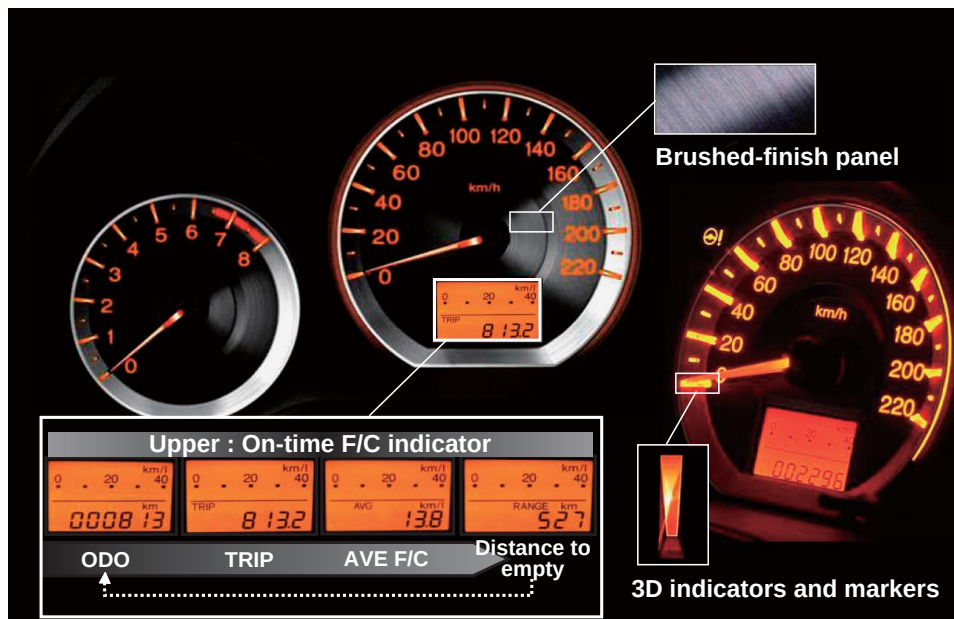


Fig. 14 Meters : Advanced meter design

passengers' heels while seated, in addition to appearance and theft prevention (stored items are not easily visible when the door is open).

The rear seat back is of the fixed type, but in addition there is a high-end variation that has the same lock and striker as the base model and uses a reclining mechanism (Fig. 17).

5.4. Trunk

While the hatchback model prioritizes cargo room utility, trunk spaciousness is what is required in a sedan (Fig. 18). The team studied the ease of trunk use in competing models and the types of objects put in the trunk in various regions, then designed a high-capacity trunk of 506 L, an opening that does not impede the user from placing items in the trunk or removing them, and a trunk opening threshold that is low enough for ease of loading and unloading.

5.5. NV Performance

The CITY's response to noise and vibration, as part of offering customers a comfortable space, is to emulate the configuration of the base model but use an exclusive design in the parts of the package that differ from the base model.

To equip the automobile with a 1.8 L engine, all mount systems have an exclusive design.

Sound blocking and sound absorption were accomplished through unique designs in the trunk and rear bulkhead area, which differ in configuration from the hatchback model. In the rear pillars in particular, to enhance the comfort of rear-seat passengers, the design blocks noise by placing a seal over the large aperture where the seat belt retractor is attached.

Furthermore, in pursuit of the comfortable space expected in a sedan, a dynamic damper for the side frame tip was adopted to reduce interior booming noise.



Fig. 17 Rear seat and under-seat tray

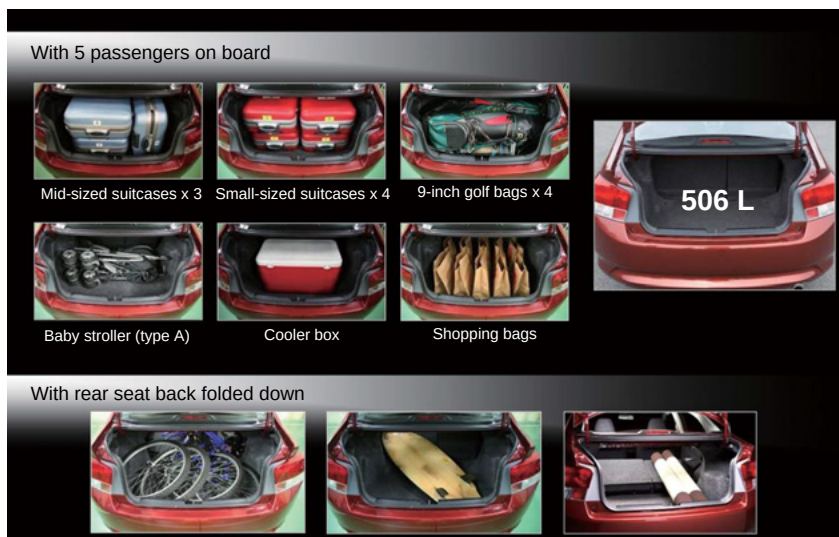


Fig. 18 Trunk room

6. Presentation of Advanced Features

The advanced equipment of the CITY is one step ahead of, yet easier to understand, than the equipment of competing automobiles.

Although taken for granted in the Japanese market, in the CITY's markets the fuel consumption indicator is regarded as advanced equipment that makes one think of a "driving computer." Following introduction of the automobile, the indicator received favorable evaluations, coming at a time when users have a reason to limit fuel consumption.

The upper-end variation has side turn signals located in the door mirrors, which enhances the image of the series as a whole.

The Steermatic function, also on the high-end variation, elevates the sporty impression.

Finally, the CITY is equipped with an audio system specifically developed for use with digital media players (below, DMP) as another feature in which people purchasing the CITY can take pride. This audio system was developed exclusively for the CITY to meet the needs of users in the model's sales regions.

7. Advanced Audio

Initial studies revealed that audio is a subject of in-car entertainment interest in the CITY's sales region, and so the team decided to develop an audio system for this model alone. This exclusive development included identifying the following three points as changes in the needs of the CITY target customer and incorporating them into the audio concept.

1. Conventional small sedans typically come with a 1DIN-size audio system. However, there is an increasing trend for even small sedans to come equipped with audio systems integrated into the panel and featuring the refined styling already widespread in the upper segment of the market.
2. Highly portable DMPs are rapidly growing in the market.

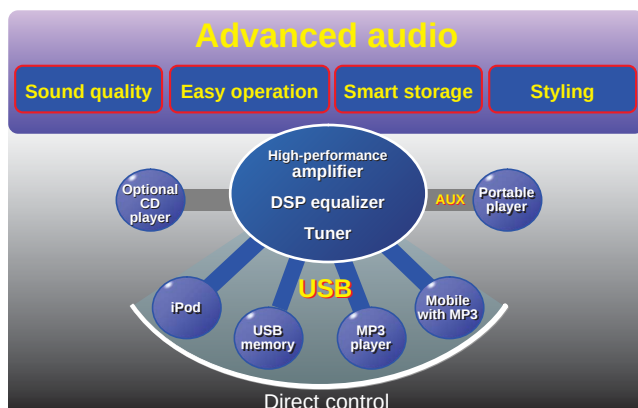


Fig. 19 Audio concept

3. CITY target customers keep a large number of music pieces on their personal computers in the form of compressed audio and listen to them in that form.

As these three points imply, an audio system suitable for the CITY in these markets is one that is integrated into the panel and is designed primarily to connect to a DMP. The following were the specific development points.

1. The system should be able to connect to many types of DMPs
2. It should be easy to operate as well as select songs
3. It should be able to play back compressed audio at high sound quality
4. It should have added functionality and a forward-looking façade design to increase the joy of ownership

A CD player, moreover, is an option and was designed to be installed at the request of any customer desiring it. Figure 19 demonstrates this concept.

This audio system, developed under the name of "advanced audio," has earned high praise in the market, with many users commenting, "I'd been hoping for something like this."

7.1. Playback of Compressed Audio

In line with the concept that the main function would be to play back compressed audio from a DMP, the different hardware components were tuned, including exclusively tuned condensers (Fig. 20), with the goal of high-quality playback performance as a basic function.

The system includes a DSP graphic equalizer, which lets users easily alter sound quality as the mood strikes them; choices include "Natural," "Relax" and "Energy." The equalizer also has an "MP3 mode" to emphasize the audio's musical contours and reverberation, which are often lost in compression. This addition enhances the functionality of the unit as a primarily DMP audio system.

System designers enhanced the performance of the head unit and tuned the six-speaker acoustic qualities by first considering both the preferences of customers and the characteristics of music in the sales region.

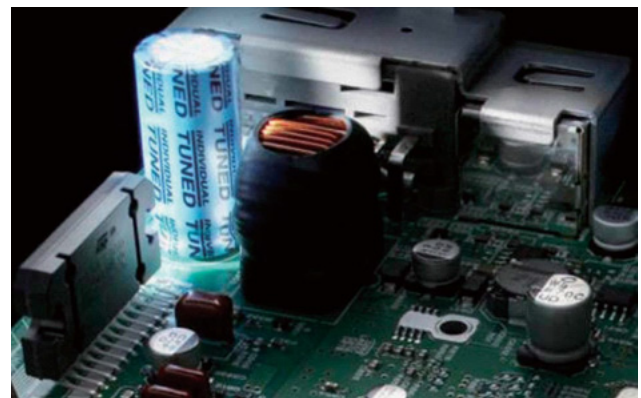


Fig. 20 Exclusively tuned condenser

7.2. Reflecting the Way DMPs are Used

The greatest advantages of DMPs are that they hold so many songs and allow stress-free operation and song selection. A car audio system based on DMP playback must have an operating system that makes it easy to select songs. Therefore, a large rotary selector with high-speed search function was added to the system. In addition, considering the fact that DMP users frequently skip to the next song during random playback, the system has larger left and right skip buttons corresponding to this function.

The steering wheel features an audio switch that, together with the unique way of using DMPs, enhances operability while driving.

7.3. Media Storage Function

To design this audio system based on a DMP connection, the project took advantage of developing the system as an integral part of the vehicle. The hardware of the audio unit, which is normally built to DIN specifications, was made smaller and given an exclusive design, and a pocket was built into the vehicle to accommodate the DMP.

The pocket lid with LCD is designed to deter theft (items within are not directly visible from outside the vehicle) while enhancing appearance (connectors and cables are hidden). The lid uses metallic cam hinges such

as are used on folding mobile phones, giving the lid a high-grade feel when opening and closing while enhancing durability and expanding pocket size (Fig. 21).

7.4. Advanced Styling

By accurately grasping market needs and developing an integrated new-design audio system that is not limited by existing specifications, styling freedom has been effectively expanded. The shiny black audio system positioned in the center of the instrument panel has achieved advanced styling equal to its functionality (Fig. 22).

8. Conclusion

For small sedans based on hatchback models, using common components and efficiency are critical issues. During development of the CITY, the power plant, the platform including the chassis, the construction of the body supporting the platform, and the interior and exterior all feature a large number of shared functional components (e.g., the steering wheel and small items), as well as components in areas that are hidden from view on the surface (e.g., the front seat frame and meter panel).

Even more important, however, is to assume the point-of-view of customers who are looking for a real sedan. The CITY was developed by engineers who based their concept on specific market needs. The strong sales of this automobile attest to the fact that they created a product that both responds to those needs and delights its users.



Fig. 21 Smart storage



Fig. 22 Advanced styling

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ABSTRACT

A flexible-fuel motorcycle (FFM), able to be operated using gasoline, ethanol, or any mixture of the two, has been developed in order to respond to the needs of the Brazilian market. Four-wheeled flexible-fuel vehicles (FFVs) are generally provided with gasoline sub-tanks and fuel injection systems to supply gasoline to enable engine start at low temperatures, but fitting this type of additional equipment in a small motorcycle represents a challenge. This was an issue in the development of the new motorcycle. The use of a control logic that judges the ethanol concentration range of the fuel and an indicator that recommends supply of gasoline when the concentration range is not optimal for low-temperature engine starts in the Mix Fuel Injection System, developed for the new motorcycle, has enabled the realization of a simple system configuration that does away with the gasoline sub-tank. In addition, fuel system components were developed considering the characteristics of ethanol.

1. Introduction

Ethanol is produced in Brazil using the country's abundant sugar cane resource as raw materials, and the introduction of ethanol fuel has been promoted as national policy for more than 40 years. Gasoline sold as automobile fuel is mandated to contain a mixture of 20 to 25% ethanol, and 100% ethanol (hydrated ethanol containing approximately 7% water) is also sold. Brazil is said to be the most advanced country to date in the introduction of bio-ethanol, and has established a social infrastructure that enables either type of fuel to be obtained at gas station throughout the country.

Sales of four-wheeled flexible-fuel vehicles (FFVs) in Brazil began from around 2003, and Honda has also released CIVIC FFV⁽¹⁾ and FIT FFV. The flexible-fuel function enables operation using gasoline, ethanol, or any mixture of the two, which is attractive in terms of cost performance, as users can freely choose the fuel according to the fuel price. Currently, 80% or more of all new passenger cars sold in Brazil are FFV, so FFV is becoming the standard. This cost performance function of flexible-fuel is similarly demanded of motorcycles, and the release of

flexible-fuel motorcycles has been desired for some time.

Honda released the CG150 Titan (gasoline specifications), which complies with the new exhaust emission regulations, PROMOT3, that take effect from 2009. The CG150 Titan MIX flexible-fuel motorcycle was developed using this CG150 Titan as the base model. This paper introduces the technologies used in this development.

2. Development Goals

When developing a flexible-fuel motorcycle, the CG150 Titan, which is the best selling model in Brazil, was selected as the base model to make the merits available to as many users as possible. The following three items were set as development goals to realize a vehicle that matches motorcycle user needs.

- (1) Ability to operate using gasoline, ethanol, or any mixture of the two
- (2) Ability to share main components with the base motorcycle
- (3) Provided at an affordable price in accordance with motorcycle user needs

* Motorcycle R&D Center

3. Developed Vehicle

3.1. Vehicle Exterior View

Figure 1 shows an exterior view of the CG150 Titan MIX, and Table 1 lists the body specifications. The appearance is almost the same as the CG150 Titan base model. The only changes in appearance are the instrument panel, and the exchange type secondary fuel filter located inside the side cover.

3.2. Engine

Table 2 compares the engine specifications, ignition and fuel supply systems of the gasoline and flexible-fuel models, along with the 2007 model year CG150 Titan⁽²⁾ used as the base model.

Figure 2 shows an exterior view of the engine and the location of the oxygen sensor. The 2009 model year CG150 Titan assumed development of a flexible-fuel motorcycle, and was developed using shared engine specifications for both a gasoline fuel vehicle and flexible-fuel vehicle. The valve and valve seat materials were changed as a countermeasure against ethanol-induced wear.

Table 1 Body specifications

Items	Specifications
Frame type	Diamond type
Dry mass	116.4 kg
Overall length	1988 mm
Overall width	730 mm
Overall height	1098 mm



Fig. 1 CG150 Titan MIX

Table 2 Engine, ignition and fuel supply specifications

		2007 model	2009 model	
		Gasoline	Gasoline	MIX Fuel
Fuel		E20 - E25	E20 - E25	E20 - E100
Cooling system		Air	Air	Air
Bore x stroke	(mm)	57.3 x 58.84	57.3 x 58.84	57.3 x 58.84
Displacement	(cm ³)	149.2	149.2	149.2
Compression ratio		9.5	9.5	9.5
Valve train		SOHC	SOHC	SOHC
number of valves		2	2	2
Valve material	IN	SAE HNV3	SAE HNV3 (increased hardness)	SAE HNV3 (increased hardness)
	EX	LV21 - 43	SAE EV8 +Metallizing	SAE EV8 +Metallizing
Valve seat material	IN	Sinter alloy	Wear-resistance sinter alloy	Wear-resistance sinter alloy
	EX	Wear-resistance sinter alloy	High wear resistance sinter alloy	High wear resistance sinter alloy
Fuel system		Carburetor	Programmed fuel injection	Programmed fuel injection
Throttle type/Diameter	(mm)	Piston / 22.8	Butterfly / 26	Butterfly / 26
Throttle position sensor		—	On throttle body	On throttle body
Absolute pressure sensor		—	On throttle body	On throttle body
Oil temperature sensor		—	On cylinder	On cylinder
Oxygen sensor		—	Without heater	With heater
Ignition control		Engine speed table	Engine speed- throttle opening map	Engine speed- throttle opening map

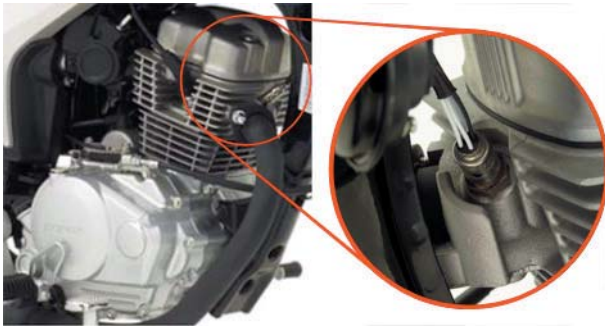


Fig. 2 Exterior view of engine and oxygen sensor

The fuel supply system was changed from a carburetor to the PGM-FI in the 2009 year model to comply with stricter exhaust emission regulations (PROMOT2, equivalent to Euro-2 → PROMOT3, equivalent to Euro-3). An oxygen sensor is located on the exhaust port of the engine head, and fuel injection amount feedback control is performed using the output signal from this sensor to enable the exhaust catalyst to exhibit sufficient purification performance. With the change to the PGM-FI, ignition timing control was also changed from that of spark advance setting, depending on engine speed, which does not vary according to the operating duty, to map control using the engine speed and throttle opening.

3.3. Output Characteristics

Figure 3 shows the engine output power performance at full throttle for gasoline (ethanol 22%) and ethanol (water content 7%). This shows that while the output

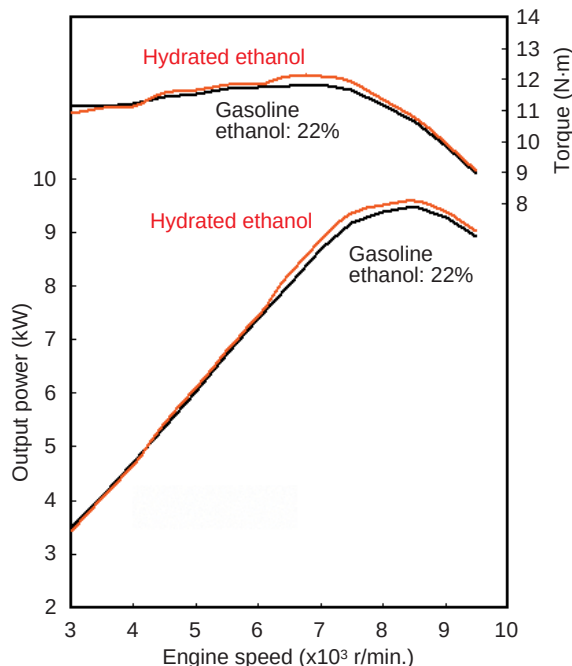


Fig. 3 Engine performance

Table 3 Fuel properties

	Gasoline	Ethanol
Specific gravity	0.73-0.75	0.79
Heating value (MJ/Air kg)	2.95	2.99
Octan number RON/MON	93/81	110/92
Stoichiometric air fuel ratio	14.6	9.0
Flash point (°C)	< -30	13
Boiling point (°C)	25-200	78
Ratio of moles before and after combustion	1.07	1.14

power is slightly higher for ethanol, it is approximately the same, and there is almost no difference in running performance according to fuel.

4. Brazilian Fuel Properties and Issues

Table 3 shows the fuel properties of gasoline and ethanol.

Commercially available motorcycle fuel in Brazil can be broadly divided into the two types of gasoline and alcohol. Gasoline fuel is not pure gasoline, and government regulations mandate that gasoline contain a mixture of 20 to 25% ethanol. Alcohol fuel is hydrated ethanol with water content of approximately 7%. Pure gasoline is not generally sold. When using ethanol as fuel, there are three main issues.

The first issue is the construction of fuel injection control for the different fuels of gasoline and ethanol. The fuel supply system of a gasoline engine measures the intake air mass and determines the fuel injection amount according to that air mass. The fuel mass ratio (stoichiometric air-fuel ratio) that results in complete combustion relative to the same intake air mass differs for gasoline and ethanol. This ratio is 14.6 for pure gasoline, and 9.0 for ethanol. When using only gasoline as fuel, the fuel mass ratio can be preset to achieve a constant air-fuel ratio, but when mixing in ethanol, the ideal air-fuel ratio changes greatly. To maintain a good engine operating state, the ethanol concentration in the fuel used should be understood, and appropriate fuel injection amount control performed accordingly.

The second issue is securing engine start performance at low temperatures. Gasoline has an ignition point of -30°C or less, but ethanol's ignition point is higher at 13°C, which makes starting under low temperature conditions a challenge when using only ethanol fuel. As a countermeasure in four-wheeled FFV, a separate sub fuel tank for gasoline is installed inside or close to the engine room for cold engine start, and a special fuel injection system is also provided. Figure 4 shows the fuel tank and fuel supply system layout in the CIVIC FFV, and Fig. 5 shows the layout of the sub fuel system for engine start⁽¹⁾. When attempting to add a similar system to a small motorcycle, it is a challenge to secure mounting space,

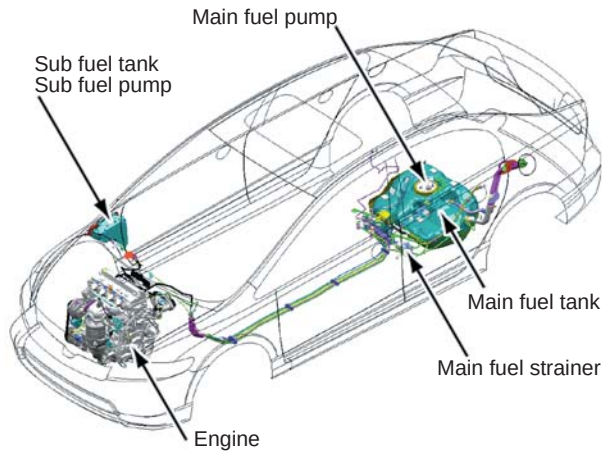


Fig. 4 Exterior view of CIVIC FFV fuel supply system

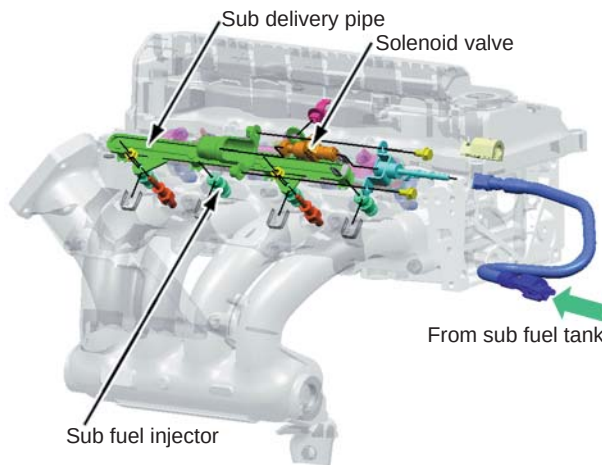


Fig. 5 Sub-fuel system for CIVIC FFV

and the vast increase in the number of components is also a major obstacle.

The third issue is that ethanol is highly corrosive to metal and rubber. This should be managed by increasing the resistance to corrosion of engine and fuel supply components⁽³⁾.

5. Fuel Injection Amount Control for Flexible-Fuel System

5.1. Issues for Fuel Injection Control

Figure 6 shows the air-fuel ratio (A/F) that results in an air excess ratio $\lambda = 1$, for the range of ethanol concentrations between pure gasoline and 7% hydrated ethanol. The A/F at which $\lambda = 1$ is 14.6 for gasoline, but 8.2 for 7% hydrated ethanol. Figure 7 shows the rate of change in the fuel injection amount at an air excess ratio $\lambda = 1$, for different ethanol concentrations relative to gasoline (ethanol concentration 22%). The fuel injection requirement increases together with the ethanol

concentration, and 100% ethanol requires a fuel injection amount approximately 1.5 times that of gasoline (ethanol concentration 22%). This shows that the fuel injection amount should be adjusted by a wide margin according to the ethanol concentration contained in the fuel. Thus, the issue for fuel injection control in a flexible-fuel system is to adjust to the ideal fuel injection amount that provides good engine performance.

5.2. Motorcycle Engine Characteristics

Most ordinary FFV use the oxygen sensor output to perform O_2 feedback control for the fuel injection amount. These results are then used to estimate the ethanol concentration, and the fuel injection amount is adjusted by applying a constant correction magnification according to the ethanol concentration estimated from a fuel injection amount map based on the reference ethanol concentration. O_2 feedback control detects whether the air-fuel ratio is rich or lean according to the oxygen concentration in the exhaust emissions, and performs control to constantly finely adjust the fuel injection amount to cancel this richness or leanness and converge

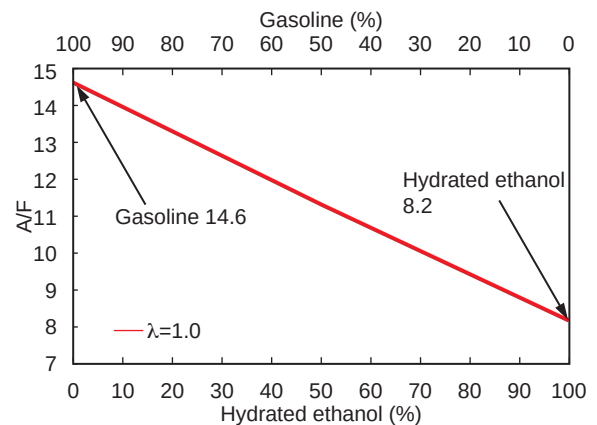
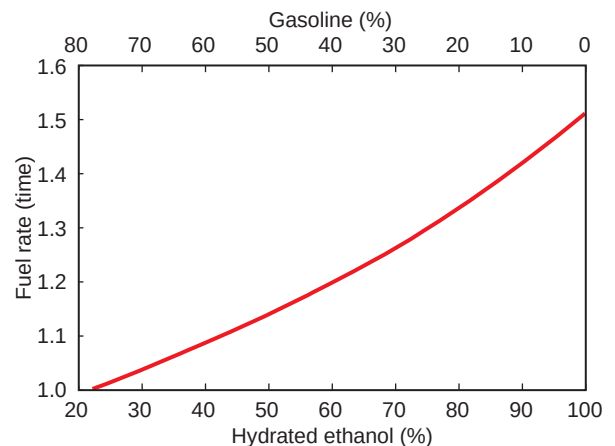
Fig. 6 Relation between A/F and ethanol concentration for $\lambda=1$ 

Fig. 7 Change in amount of injection demanded due to changing concentration of ethanol

to the stoichiometric air-fuel ratio. The adjustment magnification relative to the fuel injection amount map used as the reference for this O_2 feedback control is called the O_2 feedback correction coefficient K_{O_2} . When using only the reference gasoline fuel, only a very small K_{O_2} adjustment width is needed for O_2 feedback control. However, when ethanol is added to the fuel, the adjustment width increases. The unique correction value of ethanol concentration (K_{et}) for the fuel used can be determined by statistical processing to equalize this O_2 feedback correction coefficient K_{O_2} . The ethanol concentration correction value K_{et} is theoretically determined by only the ethanol concentration, so this enables the ethanol concentration in the fuel to be estimated. The ethanol concentration does not change until additional fuel is supplied to the fuel tank. Therefore, a good engine operating state can be secured by normal O_2 feedback control, by determining the fuel injection amount from the map obtained by applying the ethanol concentration correction value K_{et} to the basic fuel injection amount map. Figure 8 shows a schematic diagram of an FFV engine and O_2 feedback system, including the fuel injector and oxygen sensor.

Figure 9 shows the air excess ratio λ characteristics for the CG150 Titan engine when fuel injection is adjusted by the theoretical magnifications determined from the respective ethanol concentrations, when the ethanol concentration is varied using the gasoline (ethanol 22%) fuel injection amount as the reference. The same λ

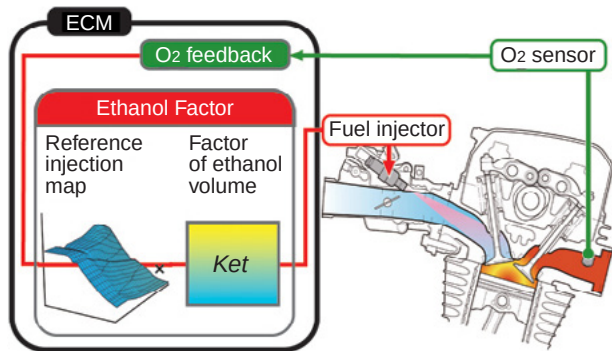


Fig. 8 Ethanol factor control diagram image of FFV

characteristics were expected regardless of the ethanol concentration, but λ varied greatly in the low load area with a throttle opening of 20 deg or less. That is to say, the change magnification for the required fuel injection amount is not constant, depending on the operating conditions, even at the same ethanol concentration. This characteristic is presumed to be due to the intake system layout peculiar to motorcycle engines, which have large valve overlaps and do not have a surge tank. This characteristic raised the issue that the appropriate amount of fuel injection cannot be supplied using the simple

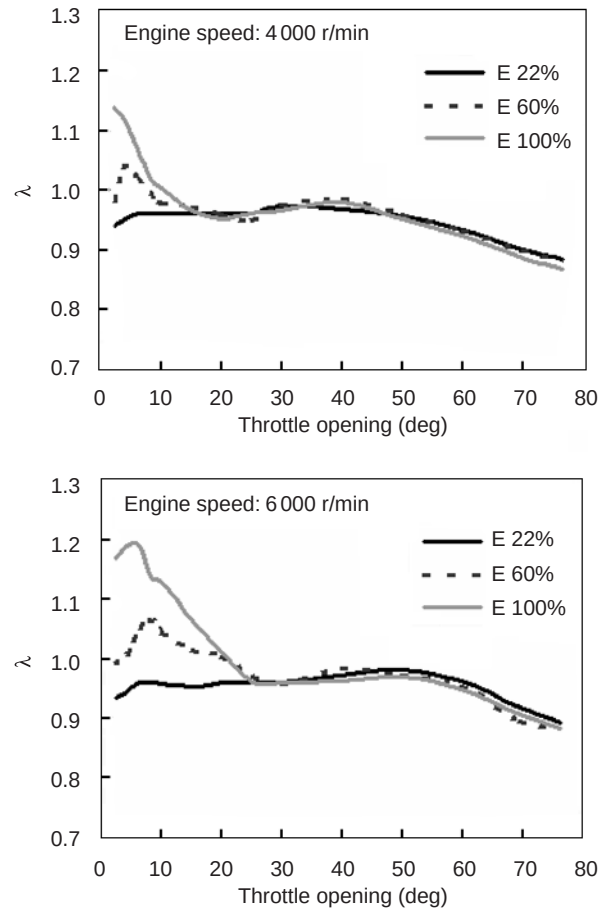


Fig. 9 λ when injection amount was multiplied at fixed rate based on difference in ethanol

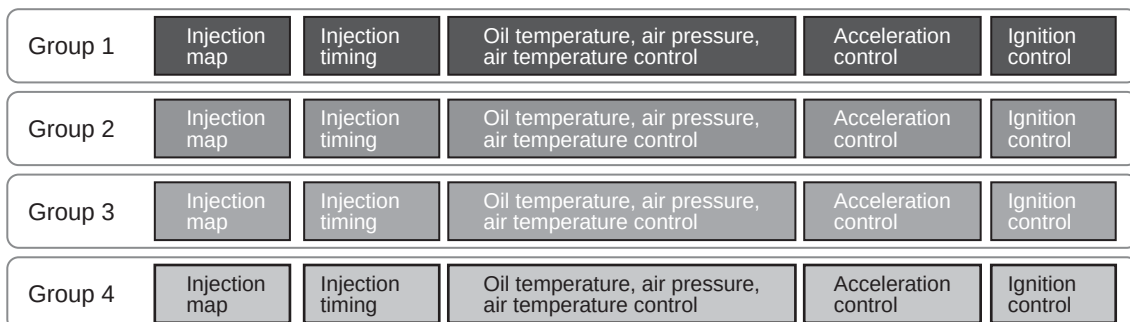


Fig. 10 Schematic diagrams of four control groups

control method of setting the fuel injection amount by adjustment using a single magnification determined according to the fuel ethanol concentration, regardless of the operating conditions.

5.3. Group Switching Control

A system that selects and switches to the appropriate fuel injection amount from among four control groups, according to the ethanol concentration, was used as the method to support the motorcycle engine characteristics. Figure 10 shows the schematic diagrams of the control groups. These control groups are packages of the various control items to be adjusted according to the ethanol concentration, and include the fuel injection amount map, injection timing, correction in start injection and engine warm-up processes, correction in transient period, ignition timing, and other control items. Four packages were prepared.

The feature of this system is that instead of directly estimating the ethanol concentration value, proper fuel injection can be performed by selecting the control group according to the set ethanol concentration range. The reference concentrations for the four control groups were spaced so that the rate of change in the magnification required for the fuel injection amount is approximately equal between gasoline (22% ethanol) and 100% ethanol. Figure 11 shows the reference ethanol concentration for each group added to the graph in Fig. 8. By dividing into four levels and setting the fuel injection amount map for each reference ethanol concentration, operation can be performed at the ideal conditions for that concentration. Correction control for other than the fuel injection amount map is also performed in the same manner. In addition, it was confirmed that even at intermediate concentrations other than the reference ethanol concentrations, the corrective effects of O₂ feedback control using the oxygen sensor output enable operation with little or no loss in performance.

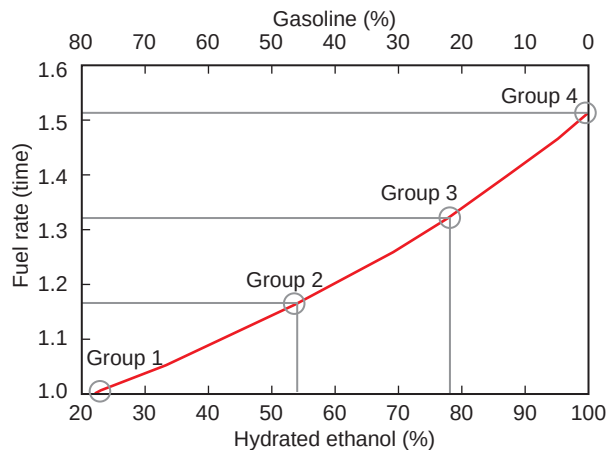


Fig. 11 Required injection multiplication based on 22% ethanol

Figure 12 shows the range of ethanol concentration for each control group. Providing areas where the concentrations overlap enabled frequent switching to be avoided, even at intermediate ethanol concentrations.

5.4. Judgment Control Using Maps

To perform the appropriate fuel injection for the fuel used, it is necessary to select the most suitable control group for the ethanol concentration. That is to say, when the ethanol concentration changes due to refueling and the control group becomes inappropriate, the control group should be switched quickly. An algorithm that selects the control group using the oxygen sensor output is used as the method of switching the control group. Figure 13 shows the group switchover concept diagram. When a certain control group is selected, typical feedback control that repeatedly alternates between rich and lean is performed by applying the O₂ feedback correction coefficient K_{O_2} to the reference fuel injection amount map based on the oxygen sensor output, so that operation converges to the stoichiometric air-fuel ratio.

When certain conditions are met, the map judgment value (K_{ref}) is continuously calculated using Eq. (1), by statistical processing to obtain the moving average of the O₂ feedback correction coefficient (K_{O_2}) for a certain time.

$$K_{ref} = \left(\sum_{i=m-n}^n (K_{O_2i}) \right) / n \quad (1)$$

K_{ref} : Map judgment value

m : Current fuel injection times

n : Fuel injection amount calculation times to be processed

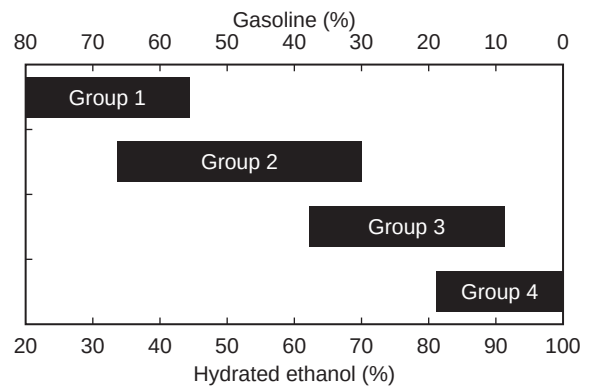


Fig. 12 Allocation of respective control groups

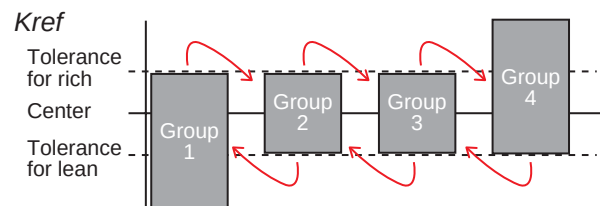


Fig. 13 Group switchover diagram

When that map judgment value (K_{ref}) is larger than the rich switching judgment value (Tolerance for rich), or smaller than the lean switching judgment value (Tolerance for lean), this means that the fuel injection amount map of the currently selected control group is inappropriate. In this case, the system switches to the adjacent control group in the direction that corrects the map offset, and operation is performed using the fuel injection amount map for that control group. When the map judgment value (K_{ref}) is still outside the tolerance for rich and lean, the system switches to the map for the next adjacent control group, and so on until the system ultimately settles on the map of the control group where the map judgment value (K_{ref}) is within the tolerance range. This type of operation to select the most appropriate of the four control groups by selecting the most appropriate fuel injection map according to the results of O_2 feedback control is called judgment control using maps. Figure 14 shows the operational schematic diagram for judgment control using maps.

This control constantly selects the ideal control group, even when the ethanol concentration of the fuel changes. Judgment control using maps is performed under various driving conditions, and achieves swift response. When the ethanol concentration within the fuel tank changes, the appropriate control group is selected within approximately 3 minutes. The most recently selected control group is

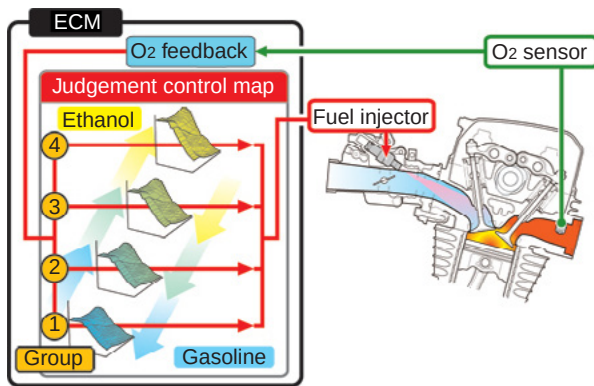


Fig. 14 Judgment control diagram map

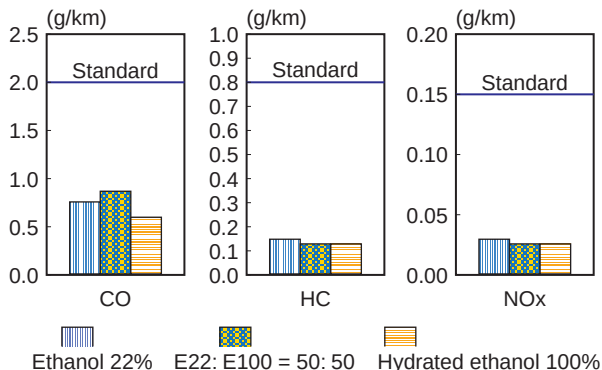


Fig. 15 Achieved exhaust emissions

Table 4 Emission standards for motorcycles
(g/km)

Stage	Class	CO	HC	NOx	Model
PROMOT 3	$V < 150 \text{ cm}^3$	2.0	0.8	0.15	CG150 Titan
	$V \geq 150 \text{ cm}^3$	2.0	0.3	0.15	

always stored in the ECM, and is selected first during the next engine start and warm-up operation.

5.5. Exhaust Gas Performance

Table 4 lists Brazilian motorcycle exhaust emissions standards. The PROMOT3 regulations, which are on the same level as Euro-3, were implemented from 2009. In case of a four-wheeled FFV, these regulation values should be satisfied for gasoline (22% ethanol), 6.8% hydrated ethanol, and fuel consisting of an equal mixture of the two. There are currently no exhaust emissions regulations aimed specifically at flexible-fuel motorcycles, but it is thought that similar exhaust emissions performance is required.

Figure 15 shows the exhaust emissions measurement results for fuels with different ethanol concentrations. This shows that exhaust emissions 50% or less of the PROMOT3 regulation values were achieved for all ethanol concentrations, indicating that proper fuel injection and exhaust emissions processing were performed.

6. Engine Start at Low Temperatures

6.1. Startability Test Results

The issue concerning the engine start performance of ethanol fuel is that engine start performance decreases as the temperature drops. When using only ethanol, engine start is not possible at sub-zero temperatures. This is due to the fact that ethanol has a high ignition point of 13°C , and that its latent heat of vaporization is also approximately 3 times that of gasoline. However, it is a challenge for motorcycles to use the same type of sub tank system as a four-wheeled FFV, so the aim was to secure startability without a sub tank. Figure 16 shows a graph

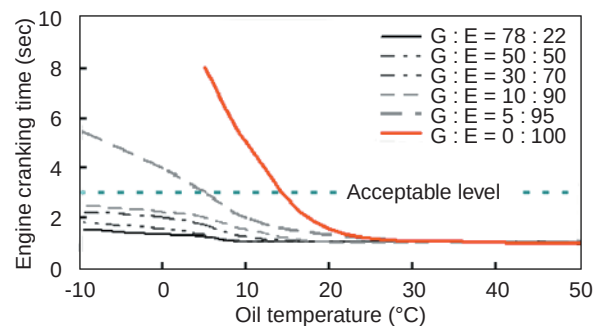


Fig. 16 Engine start time at different ethanol concentrations

comparing the cranking time until engine start for different gasoline and ethanol mixing ratios at different oil temperatures. Here, the engine was cooled completely until the oil temperature was the same as the outside air temperature. Engine startability for 100% ethanol dropped rapidly when the temperature fell below 15°C, and engine start became unlikely at temperatures below 5°C. On the other hand, when the ethanol concentration of the fuel was 90% or less, that is to say when the gasoline concentration exceeded 10%, engine start performance was found to be within the tolerable level. This indicates that when a certain concentration or more of gasoline is mixed into the fuel during engine start, stable engine start performance can be secured without the use of gasoline for engine start, even at low temperatures.

6.2. Mounting of an Alcohol Injector

If users can properly manage the alcohol concentration of the fuel in the tank according to the outside air temperature so that the engine startability does not drop, then engine startability can be secured at low temperatures, and the sub tank system can be eliminated. To achieve this, users should be able to accurately know the ethanol concentration of the fuel currently in the tank, and be able to select the appropriate fuel for refueling based on that information. An alcohol indicator consisting of the two lamps “MIX” and “ALC” was installed in the instrument panel to convey that information to users. Figure 17 shows the location of the alcohol indicator.



Fig. 17 Location of alcohol indicator

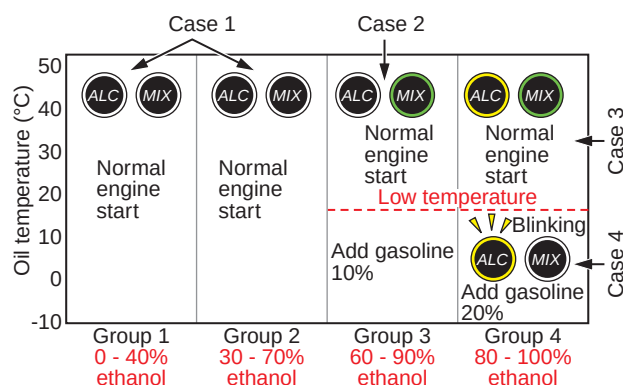


Fig. 18 Indicator functions

6.3. Indicator Display

The two lamps “MIX” and “ALC” are used in combination to indicate four different cases, to inform users of the ethanol concentration of the fuel currently in the tank, and the proper refueling method to secure good engine startability the next time the motorcycle is operated. Lamp lighting operation is linked to the control group selected as a result of map switching control, which determines the fuel injection control during operation. Figure 18 shows an overview of the indicator display.

The display contents and corresponding refueling information for each of the four cases are described below.

Case 1: Control groups 1 and 2

Both lamps off

The ethanol concentration is between 0 and 70%, and startability is good even at low temperatures.

Case 2: Control group 3

“MIX” lamp lighted

The ethanol concentration is between 60 and 90%, and startability may drop at low temperatures.

During periods when the temperature falls, additional refueling with approximately 10% or more gasoline is required when refueling.

Case 3: Control group 4

“ALC” lamp lighted

The ethanol concentration is 80% or more, and startability is poor at low temperatures. During periods when the temperature may fall, additional refueling with approximately 20% or more gasoline is required when refueling.

Case 4: Control group 4 (before engine start)

“ALC” lamp flashing

This indicates that the ethanol concentration is 80% or more and the temperature is 15°C or less, so engine start may already be unlikely.

Users can secure good startability by refueling in accordance with these indicator displays.

6.4. MIX Fuel Injection

When using gasoline and ethanol mixed fuel, the sub tank system for engine start can be omitted by performing control that secures good operability using control groups and judgment control using maps, and by mounting an alcohol indicator to help ensure a proper fuel mixture for engine start. This flexible-fuel system was named the MIX fuel injection system.

7. Fuel Supply System Components

7.1. Rust-Proofing of the Fuel Pump

One issue for the fuel supply system components is dealing with the characteristic of the corrosiveness of ethanol fuel to metal. The ethanol sold in Brazil is hydrated ethanol with water content of approximately 7%. The component most affected by this is the fuel pump, and when a gasoline-only fuel pump is used with ethanol

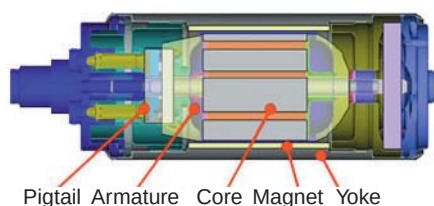
fuel, cases have been confirmed where corrosion of the metal components led to rust, resulting in malfunction. Figure 19 shows the rust-proofing performed on the various metal components of the fuel pump.

7.2. Injector

Figure 20 shows the structural diagram of the injector, and Table 5 lists the injector flow rate characteristics and materials. When using alcohol fuel, the maximum required fuel flow rate increases, even for the same engine displacement, so a larger injector flow rate range was set. In addition, the structure is the same as that for gasoline specifications, but the materials and surface treatment have been changed to increase resistance to corrosion.

7.3. Dust Deconcentration of Ethanol Fuel

The addition of ethanol is known to more finely deconcentrate the dust in the fuel. This means that the dust deconcentration in ethanol mixed fuel may promote filter



Parts	Gasoline	Flexible fuel
Pigtail	Sn plating	Sn plating
Armature	None	Resin molding
Core	None	Cu-Sn plating
Magnet	Epoxy electro-deposition painting	Epoxy electro-deposition painting
Yoke	Zn plating	Cu-Sn plating

Fig. 19 Areas of fuel pump treated with rust-preventive measures

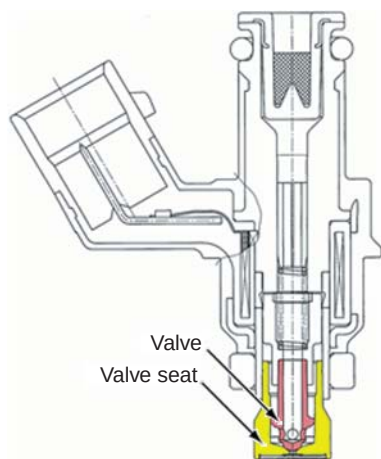


Fig. 20 Fuel injector for CG150 Titan

Table 5 Flow rate of injector and injector material of each model

		Gasoline	MIX fuel
Fuel		E20-E25	E20-E100
Fuel pressure (kPa)		294	294
Flow rate at 24 msec (mm ³ /st)		52.5	61.2
Material	Valve	S440C	S440C Passivating treatment
	Valve seat	S440C	S440C Passivating treatment

clogging. Figure 21 shows the cumulative distribution by dust particle size for gasoline and ethanol. Figure 22 shows the state of dust deconcentration in commercially available fuels. These show that ethanol contains finer dust.

7.4. Use of an Exchange Type Fuel Filter

When the existing fuel filter is used in ethanol and gasoline, the filter becomes clogged approximately three times faster with ethanol than with gasoline, and the flow rate drops. Therefore, a large capacity exchange type fuel filter was additionally installed as a countermeasure. Figure 23 shows an external view of the exchange type fuel filter. Figure 24 compares the fuel supply system with that of a conventional gasoline-only vehicle. In the system for a small motorcycle, the pressure regulator is often integrated with the fuel pump. In contrast to this,

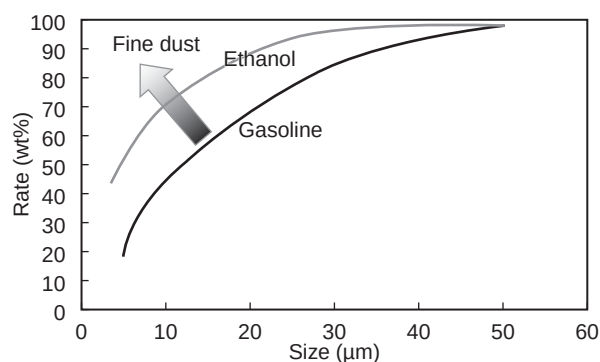


Fig. 21 Cumulative distribution of dust in fuel

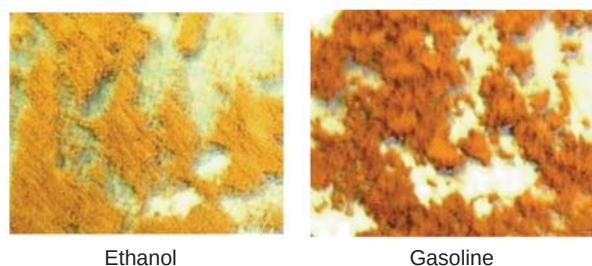


Fig. 22 State of dispersion of dust in fuel



Fig. 23 External view of stream of replacement filter

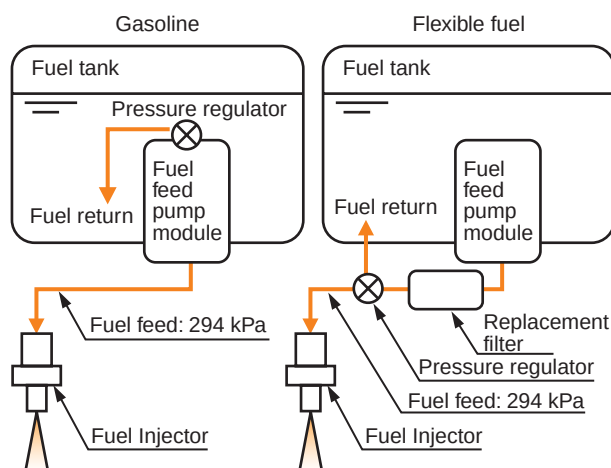


Fig. 24 Comparison of fuel feed system

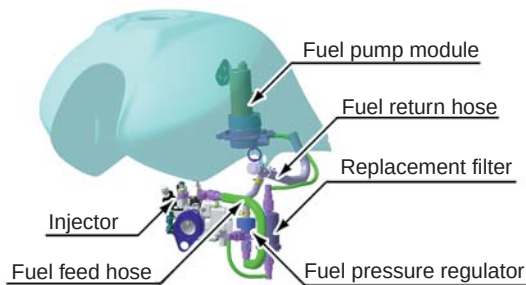


Fig. 25 Overview of fuel supply system

the pressure regulator is separate from the fuel pump in the flexible-fuel motorcycle, and is located downstream from the secondary filter. Figure 25 shows the layout of the fuel supply system components.

8. Conclusion

A flexible-fuel motorcycle was developed that matches Brazilian motorcycle user needs. The MIX fuel injection system for small motorcycles has a simple configuration

suited to the characteristics of motorcycles, and realizes flexible-fuel functions at an affordable price. The features are as follows.

- (1) Group switching fuel injection control suited to the engine characteristics of a small motorcycle is used.
- (2) An indicator is used to inform users of the ethanol concentration of the fuel and the appropriate refueling method. This eliminated the gasoline sub tank for engine start, enabling a system configuration that can be fitted to a small motorcycle.
- (3) Fuel system components that support hydrated ethanol were developed.

The CG150 Titan MIX is the first flexible-fuel motorcycle to be released in Brazil. It is hoped that the CG150 Titan MIX will delight numerous customers, and become the standard for Brazilian motorcycles in the same way that FFV have become the standard for four-wheeled vehicles.

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Development of Pianta Gas Canister-fueled Compact Cultivator for Kitchen Garden

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ABSTRACT

A compact cultivator called the Pianta that uses a gas canister was developed for use in kitchen gardens.

The butane in the gas canister undergoes phase transition between vapor phase and liquid phase at approximately 0°C under atmospheric pressure, so that fuel supply control and removal of fuel from the gas canister become theoretically difficult at an air temperature of around 0°C. The gas supply system uses the method of removing butane in the liquid phase. It also has a vaporizer placed between the cylinder head outlet and the muffler so that users can start and operate the cultivator during the planting season from March to April, when they start working with the cultivator in outside air temperatures of 5°C.

Compared to the FG201, a gasoline-fueled compact cultivator with the same engine displacement (49.4 cm³), the Pianta showed an approximately 10% reduction in CO₂ emissions. The Pianta's emission performance also met EPA Phase II regulation levels and Japan Land Engine Manufacturers Association self-regulating levels.

The overall width between the outer tines was reduced by 22% relative to the FG201 in order to make the Pianta easier to maneuver in the garden. However, the plow power was raised approximately 15% relative to the FG201 by the adoption of the new model tines and enhancement of the drag bar. The issue of noise when using the cultivator close to residential areas was also addressed by reducing the noise level at the operator's position by 1.5 dB(A) during operation.

1. Introduction

The population in Japan that engages in gardening and kitchen garden work has shown an annual increasing trend in recent years, bolstered by the active senior population, referred to as the baby boom generation, as well as by users who engage in these activities for pleasure or other such reasons.

Most of these people, however, have practically no experience in using engine-driven agricultural machinery, including cultivators. Although they may have the desire to purchase a cultivator, they hesitate to purchase one for some reasons. The followings were found to indicate the prioritized needs for which these people seek solutions in the cultivator.

- “High performance as a work machine”
- Ease of handling of fuel (acquisition, refueling, storage)
- Ease of storing and transporting the cultivator
- Consideration for the surrounding environment when operating near residential areas

It was our desire to respond to these demands in order to provide a cultivator to users who do not yet have a

cultivator and have not yet used one.

Given this kind of background, development of the present product was carried out with a focus on using a gas canister that is easy to acquire and easy to handle, and with attention to the key phrases of “threefold simplicity” and “going from a work machine to a gardening tool.”

Mounting a gas engine also enabled reduction of CO₂ emissions relative to a gasoline engine. This makes the product environmentally friendlier, as well.

However, this was Honda's first attempt to develop a product that uses a gas canister, much less one that uses a butane canister. It was therefore necessary to build a new gas supply system.

This is to introduce the Pianta, a compact cultivator for use in kitchen gardens.

2. Development Guidelines and Issues

2.1. The Pianta Concept

2.1.1. Product orientation and name

Figure 1 shows a design sketch of the Pianta.

“Pianta” in the Italian language has the meanings of

* Power Products R&D Center

vegetation and plants. The Pianta was named to express the desire to sow new seeds and bring flowers to bloom, in Japanese domestic kitchen gardens and in its gardening market. It is an affectionate nickname for Honda's first gas cultivator and it conveys the image of the great future growth that is envisioned for this product.

The Pianta is built on the base of the FG201⁽¹⁾, a compact cultivator with a gasoline engine, which has the following advantages:

- (1) A highly reliable engine
- (2) A compact transmission
- (3) Mass distribution appropriate for cultivation work
- (4) A large air cleaner with long maintenance intervals and superior cleaning efficiency

Development proceeded in emulation of these points while refining the focus on target users and following the previously mentioned key phrases of "threefold simplicity" and "going from a work machine to a gardening tool." "Threefold simplicity" refers to simplicity of fuel, simplicity of transport and storage, and simplicity of operation.

2.1.2. "Threefold Simplicity"

(1) Simplicity of fuel

In the case of cultivators equipped with a conventional gasoline engine, acquiring fuel, storing it, and carrying it from place to place ordinarily required the use of a special carrying can. Refueling was done using a nozzle or other such device to transfer fuel from the carrying can to the gasoline tank. This operation generally appeared troublesome, and was one reason why customers who had never used a cultivator found it difficult to take the step towards purchasing one.

Commercially available gas canisters were used for the Pianta's fuel with the intention of heightening the users' convenience. In other words, people have to go to a gas station to buy gasoline, but gas canisters can be bought at convenience stores and other such establishments, and the use of replaceable gas canisters further allows people to refuel without getting their hands dirty by switching



Fig. 1 Design sketch

canisters (Fig. 2).

(2) Simplicity of transport and storage

It is very hard work to pick up and move a cultivator that weighs nearly 20 kg by hand, even for just a short distance. This is not just true of the Pianta. Up to now, therefore, either the cultivators moved by the power of their own engine, using the tines in place of wheels, or optional travel wheels could be attached and the cultivator pushed by hand. The former method, however, consumes fuel while the latter requires the separate purchase of wheels. With the Pianta, therefore, it was decided to resolve this issue by including a stand to keep the machine upright and a travel wheel as standard equipment.

One change that has been taking place in the environment of compact cultivator use is an increase in use in allotment gardens and other such locations in suburban areas in addition to their use around people's own homes. There have also been survey results showing that approximately 50% of the people use automobiles as their means of travel to allotment gardens, indicating that the frequency of loading cultivators into automobiles is increasing. When cultivators are stowed on board an automobile, it is desirable to minimize their exterior silhouette as much as possible. The target values for this cultivator were therefore set so that the total height with the handle folded would be equal to or lower than the FG201.

There was also a common issue involved when loading the cultivator on an automobile and when storing it at home: That dirt and mud on the tines would come off and soil the vehicle interior and the storage location. It was therefore decided to create a dedicated storage case that would help prevent dirt from falling off.

(3) Simplicity of operation

With conversion to a gas-fueled engine, it was no

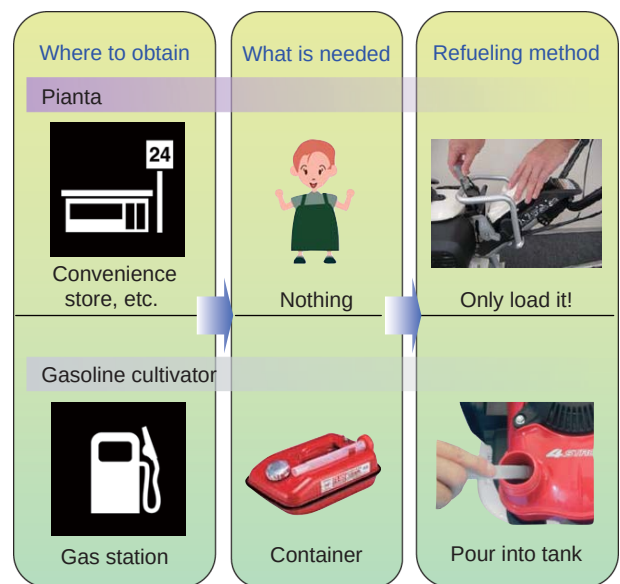


Fig. 2 Comparison between gas canister and gasoline

longer necessary to have a conventional choke operation. Further aims were to have a structure that allows users to fold the handle and to unlock the drag bar to adjust its height, which regulates plowing depth, without using tools. A system that allows cultivator operation using only the throttle lever was also adopted with the aim of simplifying operation.

2.2. Target Users

The population that engages in gardening and kitchen garden work is trending upward every year, without regard to age or gender, due to such factors as the increasing number of baby boomers who enjoy these activities as “a new interest” as well as the growing concern for food safety among the broader population. Among the population that does not own a cultivator and is inclined to take up agricultural work in the future, there are approximately 680 000 people (in Japan) who are interested in working on fields that are 9.9-105.8 m² in area, the appropriate size for a compact cultivator. These customers have been defined as the main target.

2.3. Pianta Styling Design

The basic concept of styling design is that of “going from a work machine to a gardening tool.”

(1) A simple bean form that is not intimidating

Taking the adzuki bean as a motif, the styling design was aimed to achieve a rounded effect to the greatest extent possible (Fig. 3). The exterior silhouette of the Pianta engine is larger than that of the FG201, on which it is based, but the styling design was further aimed at conveying an overall impression of compactness.

(2) An emblem that conveys quality

A fabrication technique known as potting was used for greater thickness and transparency of the mark compared to ordinary marks. The font and color used for the logo were also intended to give the impression of a step higher in high quality (Fig. 4).

(3) A cute, stylish white for the body color

The white keynote conveys a sense of cleanliness and sprightliness. This was intended to free the Pianta from the general image of work machines as heavy and dirty.

2.4. Butane Gas Engine Issues

Figure 5 shows a vapor pressure diagram^{(2),(3)} of the butane filling the gas canister and the gasoline and propane that have generally been used as engine fuels. As will become clear, butane undergoes a phase transition between vapor phase and liquid phase at approximately 0°C under atmospheric pressure. Consequently, there is concern that it will become difficult to exert control to feed the necessary amount of fuel to the engine at around 0°C. In other words, the question whether the limit temperature for fuel control on the low temperature side will be able to support the operating environmental temperature range envisioned for the cultivator becomes

an issue. The fact is that the lower limit of the theoretical operating temperature, as noted above, is an air temperature of 0°C, but there is a tendency for startup to become unstable even in the vicinity of temperatures as high as 10°C in actual operation.

In portable gas stoves, the butane is removed from the gas canister in the vapor state. In that case, the butane is vaporized inside the gas canister, and the temperature of the gas canister drops to a level lower than 0°C because of the latent heat of evaporation. The pressure inside the gas canister then drops to atmospheric pressure or lower. If left in this state, the canister becomes unable to discharge the fuel, and the fuel supply is interrupted. Therefore, a plate known as a heat panel is installed to transmit heat from the burner to the gas canister and prevent this from occurring. An engine, however, is unlike a portable gas stove that constantly carries on a certain level of combustion. In an engine, the amount of heat



Fig. 3 Bean-form design



Fig. 4 New emblem

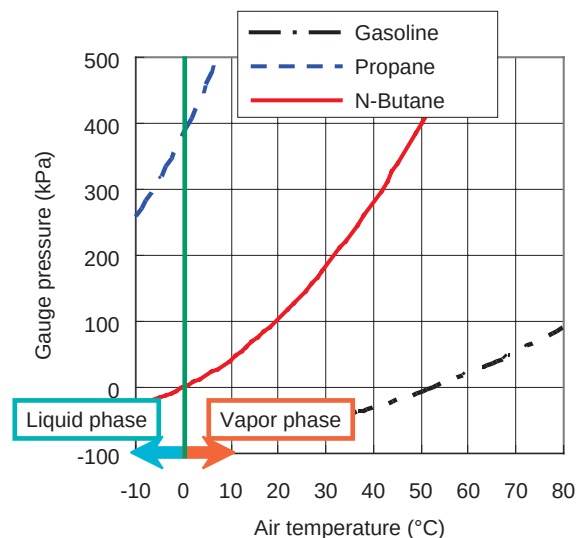


Fig. 5 Vapor pressure curve

generated will vary according to the work load, making temperature control difficult so that the gas stove approach cannot easily be adopted.

The method adopted with the Pianta, therefore, is always to take the fuel from the gas canister in its liquid phase and then to vaporize it. With this method, less of the fuel vaporizes inside the gas canister so that there is virtually no drop in the temperature of the gas canister, making it less likely that fuel-feed instability will occur. Specifically, this system will require a device to remove butane in its liquid phase, then to heat it to convert it to the vapor phase. This device is the vaporizer.

One further issue is that the butane in the gas canister contains some residue, though in extremely small amounts. This residue is separated out when the butane vaporizes and remains as a deposit within the butane pathway. Systems that remove fuel from the gas canister in the vapor phase, such as with portable gas stoves, do not experience this phenomenon because the residue remains inside the gas canister. When the fuel is removed from the gas canister in its liquid phase, however, the residue may block narrow places along the pathway, be deposited in valve seats, or the like, which may have a negative impact on fuel supply control. Therefore, it becomes necessary to have a mechanism that will separate the residue from the vaporized butane and store it.

2.5. Pianta Operating Environmental Temperature Range on the Low Temperature Side

It was found from a survey of general cultivator use in kitchen garden and similar applications that the time when people begin working with cultivators is concentrated in March and April, when they are sowing. Comparison of the average air temperature⁽⁴⁾ in the areas concerned at that time in Fig. 6 shows that the outside air temperature when sowing takes place is 5°C or higher, and the objective for the Pianta was defined accordingly as the capability to start and operate in an outside air temperature of 5°C.

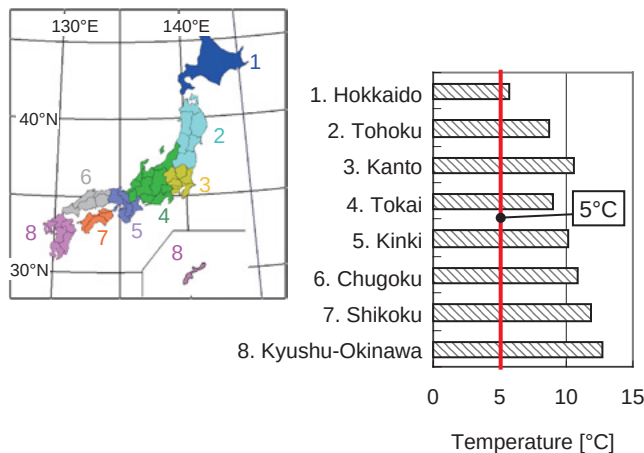


Fig. 6 Average temperature of various places from March to April

Table 1 Major specifications

Items	Developed engine
Engine type	4-stroke, single-cylinder
Displacement	49.4 cm ³
Bore × Stroke	41.8 × 36.0 mm
Compression ratio	8
Maximum power	1.2/5000 (kW/rpm) (1.6/5000) (PS/rpm)
Mixer	Side draft
Fuel	Butane

3. Overview and Features of the Gas Fuel Supply System

3.1. Gas Supply System

The engine used as the base was the gasoline-fueled GXV50 with the same displacement (49.4 cm³) as the Pianta engine. Table 1 and Fig. 7 show the major specifications and engine performance of the engine converted to burn gas.

New gas supply system parts were developed to support the use of gas canisters for fuel. Taking the flow of gas in the downstream direction, the main components in order are:

- (1) Gas canister adapter
- (2) Vaporizer
- (3) Regulator
- (4) Mixer

The layout of parts in the engine is shown in Figs. 8 and 9. Of these parts, only the gas canister adapter is attached on the frame side. The other parts are installed onto the engine itself. It is also apparent from these figures that the parts designed for compactness in order to realize the bean form are efficiently located inside the fan cover.

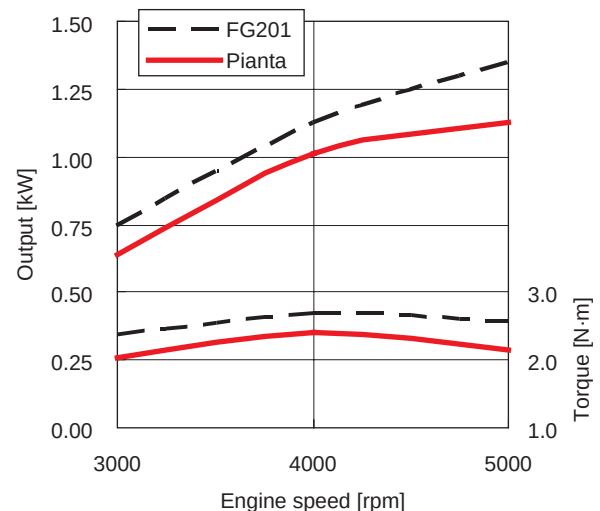


Fig. 7 Engine performance

This gas supply system also has the following two functions as its features.

(1) Fuel shutoff mechanism operated by the pressure of the fuel

...pressure detection valve

(2) Fuel cock that makes use of vacuum in the crankcase

...shutoff

The functions of the various parts are explained in greater detail in the following section.

3.2. Functions of Parts

3.2.1. Gas canister adapter

Figure 10 shows an exterior view of the gas canister adapter. The major functions of the gas canister adapter are:

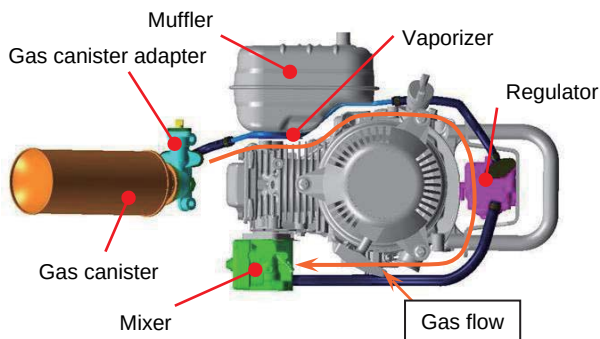


Fig. 8 Arrangement of parts

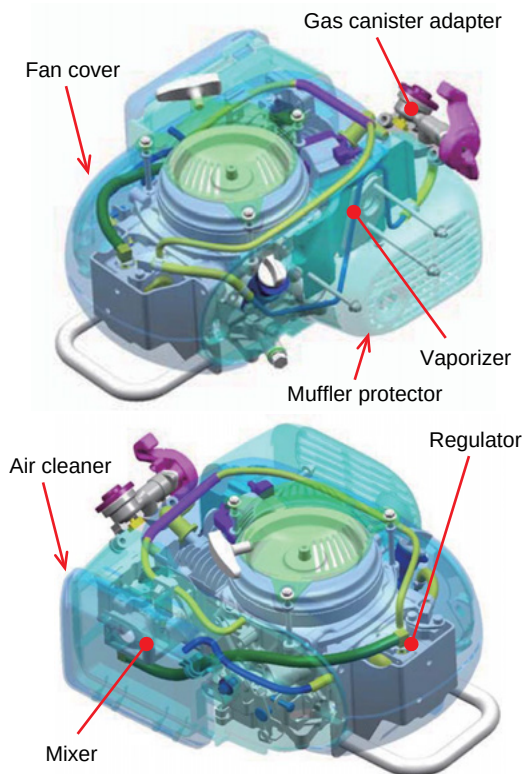


Fig. 9 Perspective view of engine

(1) Connection with the gas canister

By connecting with the gas canister, the butane is retrieved from inside the gas canister in a liquid state. The method of connection with the gas canister will be described later in connection with the gas canister connecting mechanism. The structure of the portions that connect with the gas canister and retrieve the fuel were modeled after the structures used in portable gas stoves.

(2) Manual fuel cock

Turning the knob clockwise causes the supply of fuel to be turned on and turning it counterclockwise shuts off the supply of fuel.

(3) Pressure detection valve

When the pressure in the gas canister and the tubing rises to 0.6 MPa or higher, the fuel passageways are shut down, the supply of fuel is stopped, and the engine is turned off. Figure 11 shows a conceptual image of the mechanism in operation. It is set up so that when the pressure in the tubing rises above a set level, the coned disc spring inverts and a shutoff valve shuts down the passageway. This is released by pressing the reset button. If the pressure in the tubing remains high, however, the mechanism will operate again, so the cause of the rise in tubing pressure has to be removed in order to restart the

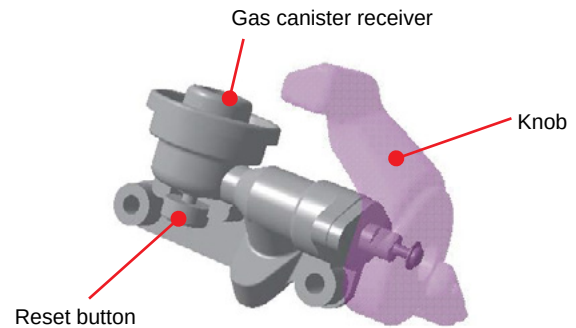


Fig. 10 Appearance of gas canister adapter

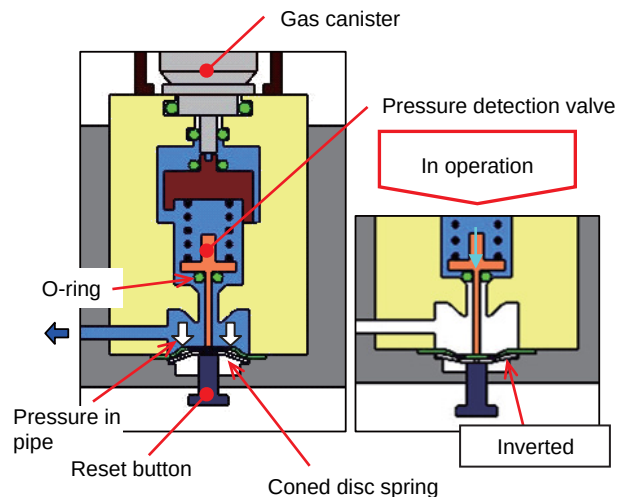


Fig. 11 Image of pressure detection valve in operation

engine. This valve mechanism was also taken from the portable gas stove system.

3.2.2. Vaporizer

The function of the vaporizer is to use the exhaust heat from the engine to vaporize the liquid phase butane retrieved from the gas canister. Figure 12 shows its external appearance. The vaporizer was placed between the cylinder head exhaust port and the muffler in order to transmit the exhaust heat efficiently (Fig. 8). Although this is a simple device, with piping attached by brazing to a steel plate formed by press piercing, it is intended to raise the temperature of the piping rapidly and promote vaporization of the butane, and this has enabled cultivator starting and operation when the outside air temperature is 5°C.

3.2.3. Regulator

Figure 13 shows an external view of the regulator. The pressure of the butane gas that is vaporized by the vaporizer becomes approximately equal to the pressure inside the gas canister (the butane vapor pressure) at the outside air temperature. The reason that it does not rise to a high pressure due to the exhaust temperature is that the vaporizer is connected to the gas canister by means of the gas canister adapter, and the vapor phase portion inside the gas canister has a damping effect. However, to have the pressure constantly fluctuating with the outside air temperature is disadvantageous in terms of supplying the proper mixture of fuel to the engine, so the fuel

pressure is adjusted to 9-11 kPa in the regulator before the fuel is sent to the mixer.

In addition to butane, there is also residue inside the gas canister. This residue remains after the gas evaporates. The labyrinth structure shown in Fig. 14 was located inside the regulator chamber so that the residue that separated out inside the regulator would accumulate in a separate chamber below it. Figure 15 shows the residue accumulated in a cup after the cultivator has been in operation for 50 hours. There was no outflow of the residue to any point past the regulator, confirming the effectiveness of the labyrinth.

There is also a fuel cock known as a “shutoff” built into this regulator. This is a so-called negative pressure cock. A tube that connects to the crankcase communicates the vacuum from the crankcase to operate a diaphragm that opens the valve while the engine is in operation. When the engine stops, the valve closes and shuts off the supply of fuel.

3.2.4. Mixer

Figure 16 shows an external view of the mixer. The butane gas, with its pressure adjusted by the regulator, is supplied to the engine from the mixer. There is a zero governor built into the mixer, and this zero governor regulates the volume of gas supplied to the engine according to the size of depression at engine manifold. A combustible gas mixture is supplied to the engine by this mechanism.

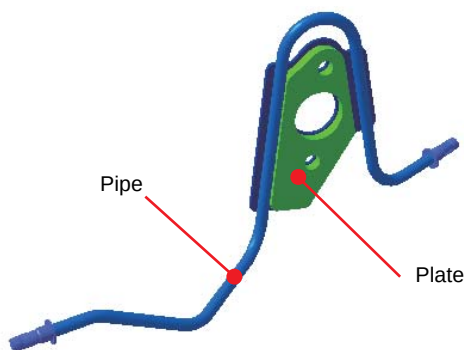


Fig. 12 Appearance of vaporizer

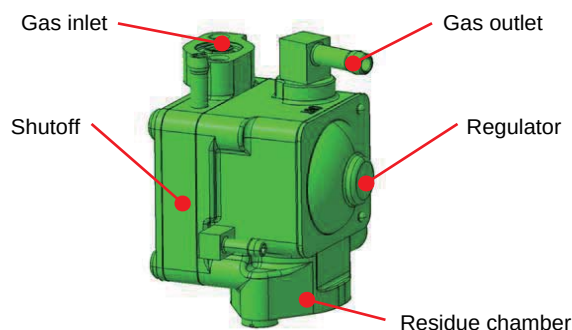


Fig. 13 Appearance of regulator

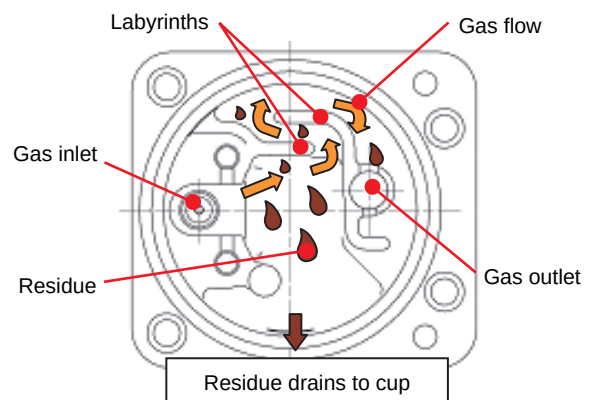


Fig. 14 Labyrinth structure in regulator chamber



Fig. 15 Residue that drained into cup (use for 50 hours)

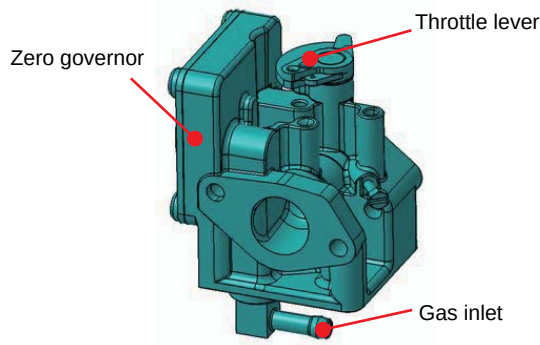


Fig. 16 Appearance of mixer

Table 2 CO₂ emission

FG201	Pianta
1.5 kg/(kW·h)	1.3 kg/(kW·h)

Table 3 Emission regulation

EPA Phase II · LEMA	Pianta
CO : 610 g/(kW·h)	286 g/(kW·h)
HC + NOx : 50 g/(kW·h)	24 g/(kW·h)

3.3. Environmental Performance

Tables 2 and 3 show CO₂ emissions and emission performance of the Pianta. The conversion to a gas-fueled engine has reduced CO₂ emissions by approximately 10% relative to the FG201 equipped with a gasoline engine. In terms of emission performance, the Pianta engine met the EPA Phase II and Japan Land Engine Manufacturers Association (LEMA) self-regulating levels.

4. Overview of Gas Canister Connecting System

4.1. Gas Canister Interior Structure and Liquid Phase Supply

The gas canisters that are commercially available for use with portable gas stoves have JIS-specified⁽⁵⁾ shapes, dimensions, content gas constituents, and the like, and the Pianta uses these canisters. As shown in Fig. 17, the interior of a gas canister has an L-shaped nozzle that is

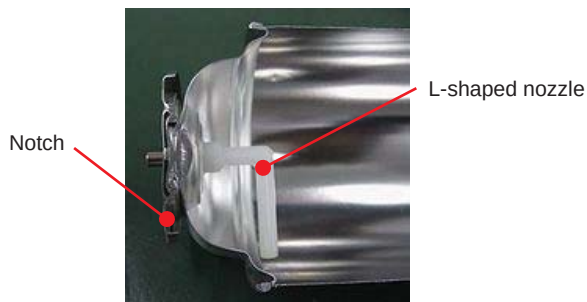


Fig. 17 Internal structure of gas canister

located in the same direction as the notch in the gas canister flange. In order to remove butane in its liquid phase, the cartridge needs to be connected with the nozzle (and notch) facing down, as in Fig. 17. This allows removal of fuel in its liquid phase.

4.2. Overview of Connecting System and Method of Attachment

A cultivator may sometimes be left outside. Therefore, it requires a system for connecting the gas canister that is better suited to outdoor environments than the method found on portable gas stoves.

For the Pianta, therefore, a gas canister case was devised into which the gas canister is placed (Fig. 18). This protects the gas canister from direct sunshine, rain, and other such factors, and allows users to make sure that the notch is oriented properly. The gas canister adapter intake is also protected by a shutter mechanism. This structure was adopted to make the intake dustproof, even when stored with the gas canister removed.

The gas canister is inserted into the gas canister case. When the case is slid into the receiver and the fastener is affixed, the gas canister connection is complete. Figure 19 shows the connected gas canister.

With this connecting system, the gas canister is

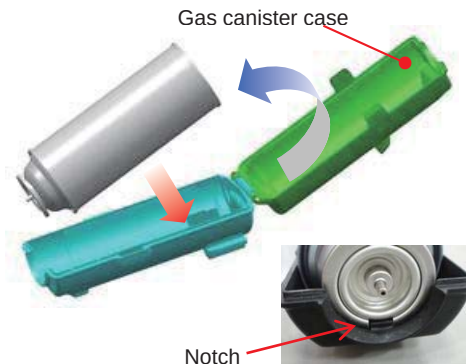


Fig. 18 Method of connecting gas canister

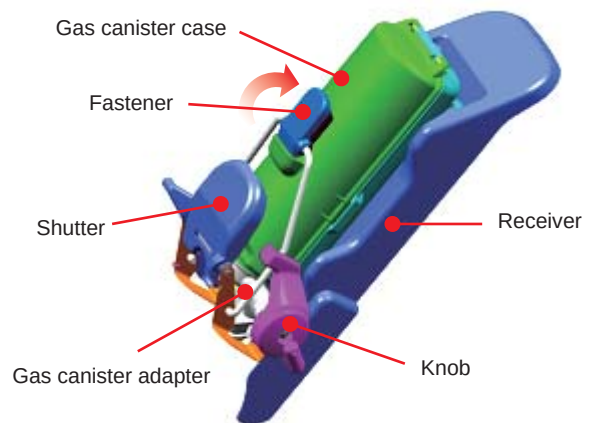


Fig. 19 Gas canister connected

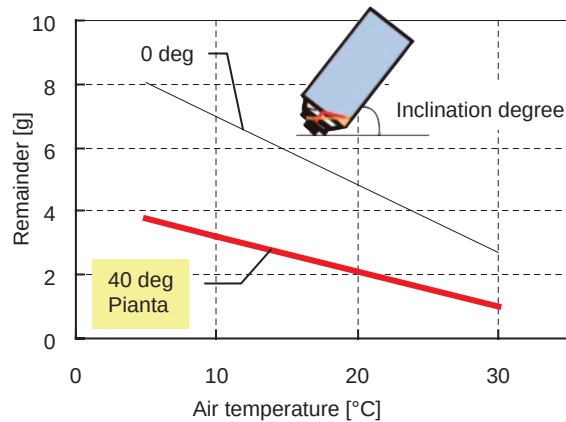


Fig. 20 Amount of gas remaining at various air temperatures

connected at an angle of 40° from the horizontal. This enables complete use of the gas down to a remainder of 3.7 g (liquid phase) even when the outside air temperature is 5°C (the lower limit of the operating temperature). Figure 20 shows the relationship between the amount of gas remaining in the gas canister when the engine runs out of fuel and the outside air temperature for canister inclinations of 0° and 40°.

5. Component Technologies on the Cultivator Side

5.1. Reduction of Body Size and Simplification of Operation of Various Parts

Figure 21 and Table 4 show the external appearance and major specifications of the Pianta, respectively. In keeping with the Pianta's development concept, the simple bean form and white color were adopted, conveying the intended image as a gardening tool.

The Pianta tines were made approximately 4% shorter



Fig. 21 Appearance of Pianta

Table 4 Comparison between Pianta and FG201

Items	Pianta FV200	FG201
Overall length (mm)	1055	1050
Overall width (mm)	485	475
Overall height (mm)	990	995
Storage height (mm)	530	635
Dry mass (kg)	20	16.5
Tine speed (rpm)	135	135
Tilling width (mm)	350	450
Tine diameter (mm)	φ 250	φ 260
Starting system	Recoil starter	Recoil starter
Main clutch type	Centrifugal clutch	Centrifugal clutch
Transmission speeds	1Forward	1Forward

and 22% narrower in total than the tines on the gasoline-fueled FG201 compact cultivator. This was done to make the body more compact and more easily maneuverable during operation. In addition to these changes, the layout of the handle column components was also revised so that the total height with the handle folded was reduced from 635 mm to 530 mm, a reduction of approximately 17% (a reduction of 20% when the stand is not used) (Fig. 22).

Manually loosening a bolt with a large knob was adopted as the method of releasing the lock when folding the handle. The mechanism for releasing the lock when changing the height of the drag bar is also a knob to be pulled out (Fig. 23). This allows both operations to change configuration to be carried out without using tools.

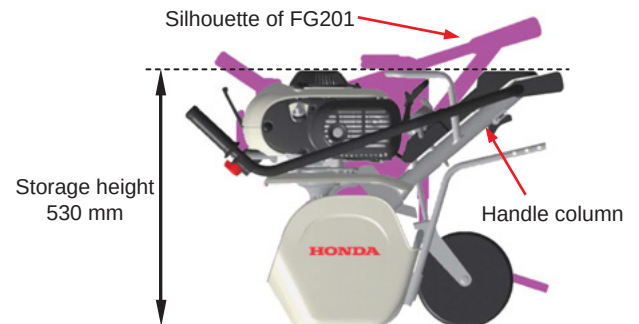


Fig. 22 Appearance of storage configuration



Fig. 23 Height adjustment mechanism

The system was also made so that the only operation that has to be performed in order to begin working with the cultivator after starting the engine is to grip the throttle bar. Specifically, gripping the lever causes the engine speed to increase. At approximately 2700 rpm, the centrifugal clutch engages, the tines begin to rotate, and work can be done.

The adoption of mechanisms such as those above realized simplification of controls for “simplicity of operation.”

5.2. The Carry Stand and Travel Wheel Integrated with the Stand

The Pianta was equipped with a dedicated carry stand (Fig. 24). With this, users can put down the cultivator in a more stable position even though the overall width between the outer tines is narrower than on the FG201. This stand can also be configured to raise the body of the cultivator, making it easier to perform maintenance on the tines, wash the cultivator, and carry out other such operations. The stand is also equipped with an integrated travel tire, to help reduce the frequency with which the cultivator body must be lifted up and moved by hand. Furthermore, a storage holder for the drag bar was also placed on the left side of the stand. Enabling this integration of the stand, travel wheel, and drag bar with the main body makes the cultivator even more convenient to put away.

5.3. Manufacture of a Carry Box

A carry box as shown in Fig. 25 was devised for the Pianta. The box was shaped so that the cultivator could be placed in and removed from the box from in front while on its stand, without having to lift up the cultivator. As a result, the box is distinctive for how easy it is to fit onto the Pianta (Fig. 26). With this approach, dirt on the tines or other parts of the cultivator can be kept from soiling the surroundings when the Pianta is loaded into a vehicle or placed in storage at home.

The carry box is also made so that the tines are in contact with the inside surface of the box. This means that

the box will not be unsteady or shift balance, and it does not require buckles or other such attachment devices to keep it on the cultivator. As shown in Fig. 27, this carry box also serves as a protective cover that keeps the tines from hitting against the user’s leg when the user is carrying the cultivator by hand.

5.4. Adoption of New Model Tines and Enhancement of Drag Bar

The tines were made shorter and narrower, as discussed earlier, but ordinarily changes like these would also cause some loss of plow power (the power to move forward while breaking the earth). Therefore, the cutting angle at the tips of the tines was made larger on the Pianta than on the FG201, and the projected area of the tines was increased by approximately 6%. This increased the amount

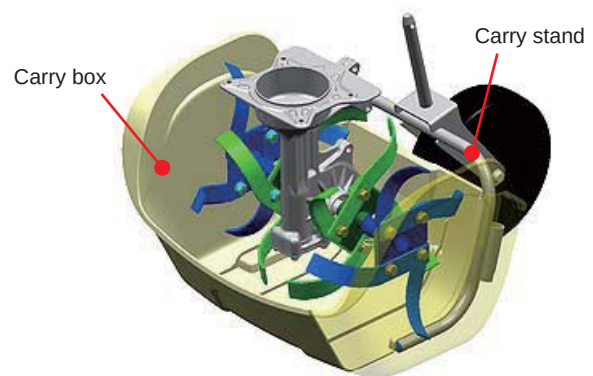


Fig. 25 Cutaway view of carry box



Fig. 26 Method of fitting on carry box

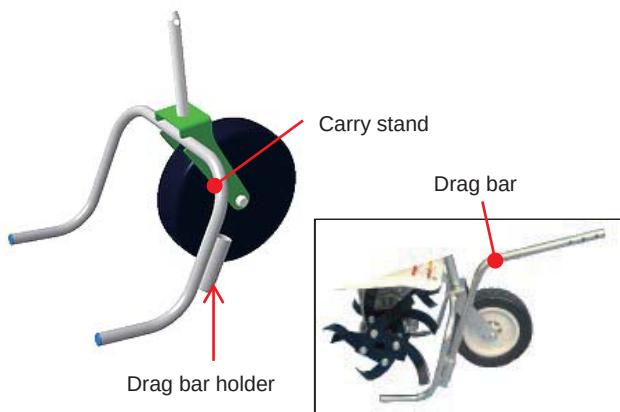


Fig. 24 Appearance of carry stand



Fig. 27 Pianta configuration for carrying by hand

of soil that is able to be scraped out by the tines and provided plow power equal to or greater than the FG201 (Fig. 28). The shape of the drag bar was also given a bending angle 3.4° greater to lessen resistance from the soil. Combined with the change in the tine shape, this enhanced the Pianta's plow power (Fig. 29).

Figure 30 shows the results from measurement of work speed for different plowing depths. The Pianta has

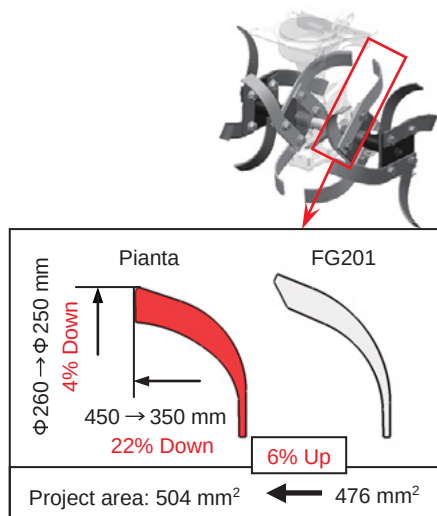


Fig. 28 Comparison of tine project area

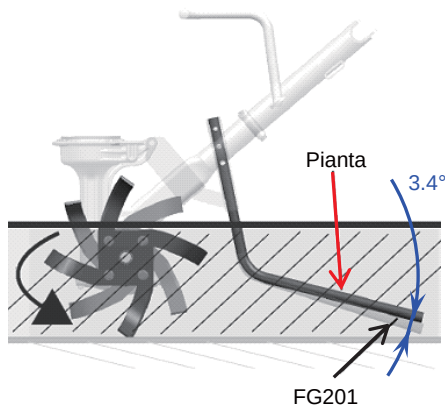


Fig. 29 Drag bar angle comparison

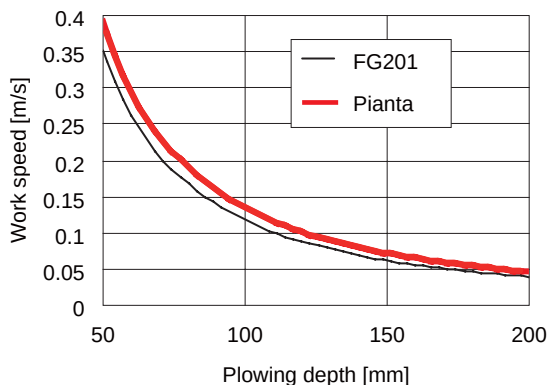


Fig. 30 Work speed

working speeds, on average, approximately 15% greater than those of the FG201, regardless of plowing depth.

5.5. Noise

The envisioned use of the Pianta is in kitchen gardens about 9.9-105.8 m² in size, commonly adjoining residential areas, so that consideration of noise heard in surrounding areas is necessary. The capacity of the Pianta's muffler was increased from the 370 cm³ of the FG201 to 790 cm³, approximately a twofold increase. The engine was also fully covered. Figure 31 shows the resulting 1.5 dB(A) decrease in noise level at the operator's position while the cultivator is in operation.

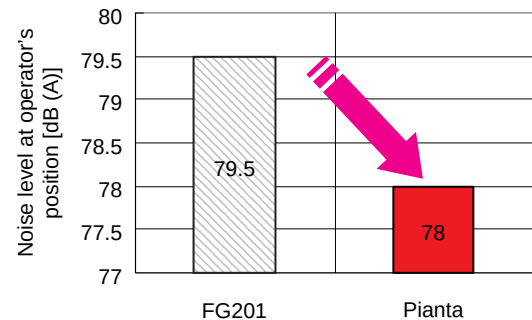


Fig. 31 Comparison of noise

6. Conclusion

The Pianta compact cultivator was developed with a gas supply system that presupposes that butane will be removed from the gas canister in its liquid phase.

(1) Realization of simplicity of fuel

The use of a gas canister reduced the time and trouble of acquiring, storing, and transporting fuel.

Furthermore, a labyrinth structure was located inside the regulator chamber to separate and remove the residue that is left after butane vaporizes.

(2) Realization of simplicity of transport and storage

An integrated travel wheel and carry stand was devised to allow stable placement of the cultivator during storage and to reduce the labor in lifting and carrying the cultivator. A carry box was also devised to keep dirt and mud from falling off the cultivator in the storage location.

(3) Realization of simplicity of operation

The conversion to a gas-fueled engine made choke operation unnecessary. The Pianta also allows the handle to be stored and the plowing depth to be changed without any need for tools. Moreover, a method of operation was devised that, once the engine has been started, only requires the throttle bar to be gripped in order to begin working. A new gas canister connecting mechanism that is suited to use in an outdoor environment was also created.

(4) “Going from a work machine to a gardening tool”

The adoption of a simple bean form and white color convey the intended image as a gardening tool.

(5) Environmental performance

The Pianta has CO₂ emissions approximately 10% lower than the gasoline-fueled GXV50, and the CO, HC+NO_x emissions met EPA Phase II regulation levels and LEMA self-regulating levels. Changes to the muffler and other changes also achieved a reduction of 1.5 dB(A) in the noise level at the operator’s position when working with the cultivator relative to the FG201.

(6) Engine startup at low temperature and removal of residue

The vaporizer was placed between the cylinder head outlet and the muffler to warm the piping more quickly and enable starting and working with the cultivator when the outside air temperature is 5°C.

(7) Increased plow power

The adoption of new model tines, with a projected area approximately 6% larger, together with enhancement of the drag bar increased the Pianta’s plow power, on average, approximately by 15% relative to the FG201.

7. Epilogue

The adoption of gas canisters for fuel and other such measures were taken in order to develop a cultivator that would be easy to use and not intimidating. As a result, Honda believes that even users who have never worked with a cultivator before will find this product more approachable. The appearance of this product will enable further market expansion, and it is the developers’ profound hope that the Pianta will increase the number of customers who feel “the joy of using the product” even if just by one.

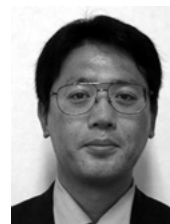
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Introduction of Micro-combined Heat and Power Generation Unit with Backup Function

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ABSTRACT

A micro-combined heat and power generation (micro-cogeneration) unit which can be used as a backup power generator in an emergency has been developed. A battery, DC-DC converter unit, and inverter unit were newly developed to enable autonomous operation of the generator. The DC-DC converter unit converts power from the battery when backup operation commences, and supplies power to the starter. It also applies charging control to extend battery life. In addition, the inverter unit is the same size as the model currently on the market, which does not have a backup power function, but it incorporates both grid-connected and backup generation functions. Output power as an emergency generator during backup operation has been increased 1.5 times against the previous model. The realization of hybrid power generation through the use of battery assist has reduced voltage sag when an electrical load is connected, and thus, the amount of usable electric load and types increased.

1. Introduction

The G8 Leaders Summit held in Japan in 2008 expressed their intention to reduce the amount of greenhouse gas emissions in the entire world to at least half by 2050, spurring their full-fledged efforts toward the realization of low-carbon society. However, energy consumption in the civil sector (household) is growing steadily, with a skyrocketing rate, which accounts for a key factor in the growth of energy consumption as a whole. In the future, it will be necessary to establish more stable power supply in order to meet the increasing demand for electric power due to the electrification of mobility and other factors.

Cogeneration system, which uses a generator to produce electricity, while simultaneously recovering and reusing the heat generated, has already been used in large-scale facilities, including factories, and is expected to effectively reduce CO₂ emissions⁽¹⁾. Nonetheless, we have been facing the issues for the practical use of small-scale cogeneration system, such as its cost, service life, and other issues. Using unique technologies based on small gasoline engine and inverter generator, Honda has

overcome those issues, launching the sales of the world's first small gas engine cogeneration unit for household (hereinafter called "micro-cogeneration unit")⁽²⁾ in February 2003 in Japan, and 2007 in the U.S. In the U.S., because natural disasters, such as flooding of rivers caused by heavy rains, large-scale hurricanes, and blizzards frequently lead to power interruptions⁽³⁾, market for backup generator was firmly established. Since the household cogeneration unit is a power generation system for everyday use that places a very low burden on the environment, it will benefit our customers to use the unit as an backup generation equipment in case of power outage from the perspective of home security.

In this paper, we will introduce Honda's micro-cogeneration unit, backup power generator in case of power outage, which Honda launched in January 2009 in the U.S.

2. Main Specifications of the Product

The micro-cogeneration system is a household energy supply system that consists of Honda micro-combined heat and power generation unit and cogeneration unit with

* Power Products R&D Center

recuperator that was jointly developed by a city gas company and water heater manufacturer. It was considered that there is demand for micro-cogeneration unit with backup power generation function in the U.S., where the electrical power condition is different from that of Japan.

Figure 1 illustrates how the system is utilized in a household. Electricity generated by the Micro Combined Heat and Power Generation unit goes through a power distribution board, and is consumed by the electric appliances in the household. In the system that is used in Japan, for example, when the engine unit generates electricity, the heat that is recuperated from the engine is temporarily kept as hot-water in a hot-water storage tank, which not only supplies hot water, but also contributes to underfloor heating, heater and dehumidifier for the bathroom, and other uses. In the U.S., on the other hand, the heat is directly exchanged with the air through a hot-air heater, and is used for hot-air heating.

Figure 2 shows the appearance of Micro Combined Heat and Power Generation unit with a gas engine generator, heat exchanger, grid-connected inverter, and other components. Table 1 shows the main specifications of the unit. The housing of previous model was equipped with new battery and DC-DC converter unit.

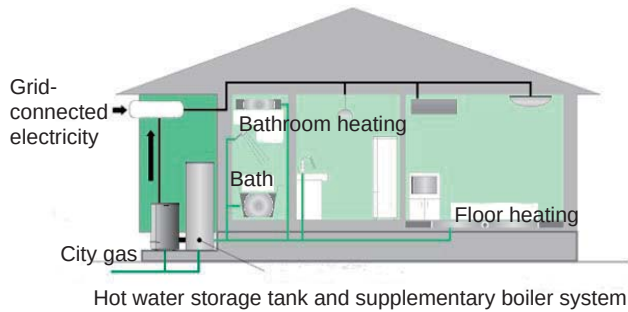


Fig. 1 Micro-cogeneration system



Fig. 2 External view of micro-cogeneration unit

Table 1 Specifications (US model)

		Normal	Boost	Backup
Output	Electricity	1 Φ 3W 240 V/120 V 60 Hz		1 Φ 2W 240 V 60 Hz
		1.2 kW	1.8 kW	1.8 kVA
	Heat	3.2 kW or more		
Power supply		Grid connection by inverter		Inverter
Heat recovery		80 °C Hot water		
Efficiency	Electricity	23.0% or more		
(LHV)	Heat	62.5% or more		
Dimensions (LxWxH)		380 × 580 × 880 mm		
Mass		82 kg		
Noise		47 dB(A)	55 dB(A)	
Engine	Type	Liquid-cooled 4-stroke OHC vertical single cylinder		
	Displacement	163 cm ³		
Starting system		Starter generator		

3. Technological Issues and System Configuration

In addition to the grid connection mode, which was the only operating mode used in the previous model, the new model features two new operating modes, grid connection boost mode and backup generation mode. The grid connection boost mode refers to the system that sells electricity in response to the request from power company, when there is a demand for power from extensive area, where power plants do not cover. In this situation where power is insufficient, higher power output is required. The backup generation mode, on the other hand, refers to the mode that the unit autonomously generates power as a backup generator during power outage as indicated in the above. In the backup mode, higher generator output is also required to allow the user to use more electrical load. According to the survey conducted by Honda in the U.S., 23% of purchasers of Honda gasoline engine generator, EU2000iA (rated output: 1.6 kVA), needed it as a backup power supply during power outage. Therefore, the output of new model in backup mode as well as grid connection boost mode was set at 1.8 kVA. Because the rated output of grid connection mode remains 1.2 kW, the same as that of the previous model, the output of the engine, which functions as the input source to increase generator output, is increased by accelerating engine speed, and thus, the output performance of inverter is also facilitated. In order to increase electrical load that can be used in backup mode, battery assists generator in producing more output.

Figure 3 shows the system configuration of previous model. Power output from the alternator (hereinafter called “ALT”) is converted to DC in the rectifier, and then to

constant DC voltage in the boost converter of the grid-connected inverter (hereinafter called “inverter”) installed in the micro-cogeneration unit. In the MOSFET section, the power is further converted to a form, which can be connected to the commercial power supply, to complete electric interconnection. When starting the engine, the use of rectifier as a starter driver with the system as the power source, enables the inverter to function as a starter driver as well. This configuration enables the inverter unit to use the power line in both directions⁽⁴⁾, thus eliminating dedicated starter devices, switching relays, etc. The engine control unit (hereinafter called “ECU”) is the master unit of Micro Combined Heat and Power Generation unit, issuing commands, organizing operation, and communicating with the externally connected water heating unit or heater. Although it was possible to eliminate the electronic unit for startup in the configuration of previous model, the engine could not start during power outage, since it used the system as its power

source. In order to realize autonomous startup and power generation, and to fulfill the performance requirements for backup generation, the following items were placed on our development agenda.

(1) Power source for autonomous startup

The unit should be fitted with Ni-MH battery to help ensure a power source for engine startup during power outage. Long-life battery is desirable to avoid frequent maintenance. Also, it is necessary to check the battery condition in order to help ensure engine start in case of power outage.

(2) DC-DC converter unit

DC-DC converter unit (hereinafter called “DC-DC converter”) is necessary to convert the power from low-voltage battery to the equivalent voltage to the system voltage in order to provide it to the inverter. The DC-DC converter deals with high-current, which generates heat and electromagnetic noises. This promotes us to develop highly efficient and low-noise DC-DC converter.

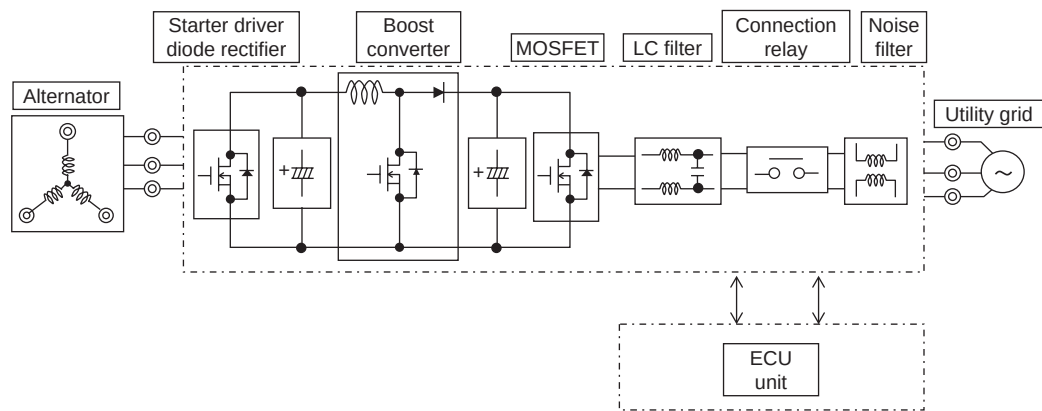


Fig. 3 Diagram of previous system

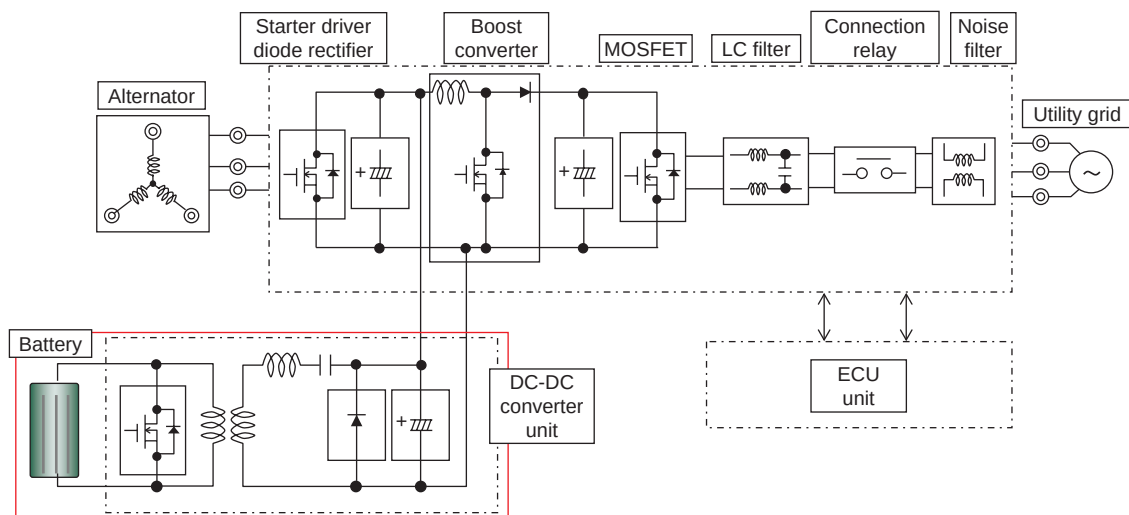


Fig. 4 Diagram of newly developed system

- (3) Inverter unit which is capable of electric interconnection and independent generation

Another issue is the fact that all electric interconnection, electric boost interconnection, and backup generation are performed in a single hardware. With regard to the performance of backup generation, the LC filter settings that enable electric interconnection need to meet the requirements for backup generation, and output should be 1.5 times higher than that of the previous model in the same size. In addition, hybrid generation should be available by means of battery assist in order to increase electrical load during backup operation.

Figure 4 shows the configuration of newly developed system. In the following chapter, we will discuss actual operation of this system in detail.

4. Function of Each Component

4.1. Ni-MH Battery

4.1.1. Battery specifications

A small Ni-MH battery, which is capable of high-output, is employed in the system to maintain sufficient power to start engine during power outage. Figure 5 shows the appearance of the battery with 12 V of rated voltage and 6.4 Ah of rated capacity, equipped with built-in current and temperature fuses and a temperature sensor. Figure 6 indicates required battery output to start the engine along with the temperature characteristic of the battery output. It suggests that high output is necessary for engine start, because engine friction increases at low



Fig. 5 Ni-MH battery

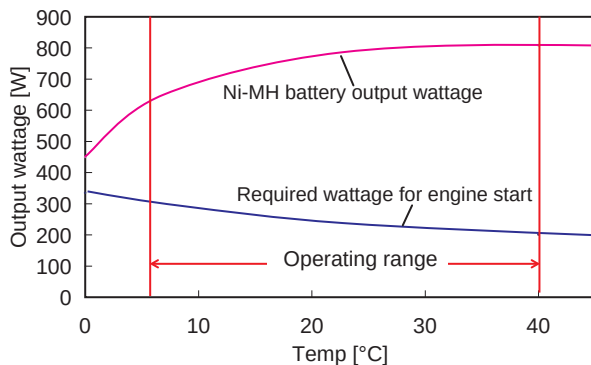


Fig. 6 Ni-MH battery output wattage

temperatures on the one hand, the battery output declines at low temperatures on the other. Therefore, we decided the battery specifications on the basis of the temperature characteristics of the battery to fulfill the output requirements in the most severe conditions for the battery.

4.1.2. Technologies to increase battery life

We employed Ni-MH battery, which has a twice longer lifespan than that of lead battery. Since the lifespan of Ni-MH battery declined with a rise in temperature, the battery was positioned by the vent that admits cooling air, as shown in Fig. 7, to control the rise of temperature below 10°C. In order to minimize battery degradation due to charging, intermittent charging method was also adopted, as shown in Fig. 8. The DC-DC converter constantly monitored battery voltage, and applied charge control to help ensure sufficient state of charge (SOC) to start the engine. When the battery was used to start the engine, the DC-DC converter calculated the amount of power taken out of the battery to start the engine, and conducted a fundamental charge to cover the loss. Following this, trickle charge was conducted to help ensure uniform charge throughout the cells, and to maintain a hundred percent charge. Compared to the previous model in which the battery was constantly

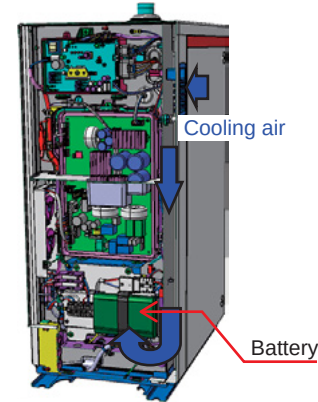


Fig. 7 Ni-MH battery layout

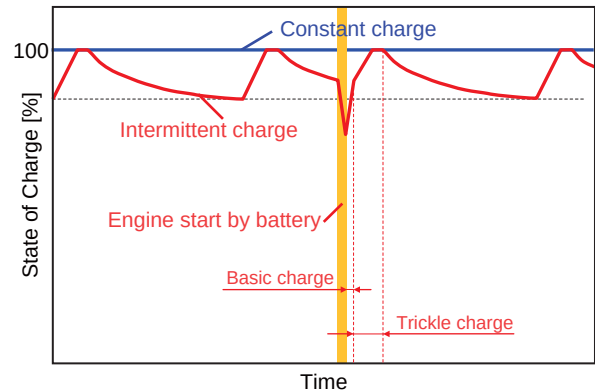


Fig. 8 Ni-MH battery intermittent charge

charged, this system maintains sufficient SOC to start the engine even in the worst-case scenario, while reducing battery degradation due to overcharging.

4.1.3. Checking battery degradation resulting from internal resistance

For the new model, the state of battery should be checked periodically, and monitored on a routine basis, by starting the engine with battery power, in order to help ensure that the engine can start during power outage without fail⁽⁵⁾. The status of battery degradation is checked based on Eq. (1). Using previous voltage and current before discharge, voltage and current at discharge, and current correction factor and temperature correction factor, the internal resistance of battery, R , is calculated based on the above equation. Note that the internal resistance is calculated, when the discharge current reaches or exceeds a predetermined figure.

$$R = k_i k_t (V_0 - V_1) / (I_1 - I_0) \Omega \quad (1)$$

V_1, I_1 : Voltage and current at discharge

V_0, I_0 : Voltage and current before discharge

k_i, k_t : Current correction factor, temperature correction factor

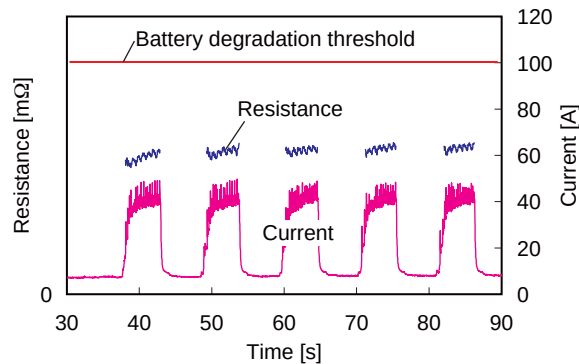


Fig. 9 Battery degradation threshold and resistance

The internal resistance of battery at the limit for engine start in the engine startup tests was deemed to be the threshold value of battery degradation. In cases of exceptional degradation of battery, this periodic calculation of internal resistance also enables us to detect it in advance.

Figure 9 shows the results of calculations of internal resistance, using a battery that exceeded the assumed battery lifespan of new model. Based on the considerable gap between the threshold and the battery's internal resistance, we confirmed that the battery had a sufficient length of battery life.

4.2. DC-DC Converter

In order to allow the micro-cogeneration unit to autonomously operate during power outage, the following functions are necessary for DC-DC converter:

- (1) Detection of power source outage in the power grid
- (2) Charging control of battery
- (3) Power source to start engine during the engine's autonomous operation

Figure 10 shows the detailed system configuration of the DC-DC converter outlined in Fig. 4. The unit consists of grid voltage detect circuit, which monitors the status of the normal grid power supply and power outage, battery charge control circuit, which controls charge, and DC-DC converter section, which boosts battery voltage, and supplies power to the inverter.

4.2.1. Grid voltage detect circuit

The grid voltage detect circuit reduces the grid-supplied voltage to low voltage with insulated transformer, and then, the CPU monitors the grid voltage to constantly make a judgment whether the status of the normal grid power supply should be recovered or not. When an outage in the grid power supply is detected, the ECU unit sends a command to boost the battery voltage in order to supply the inverter unit with power to start engine. If

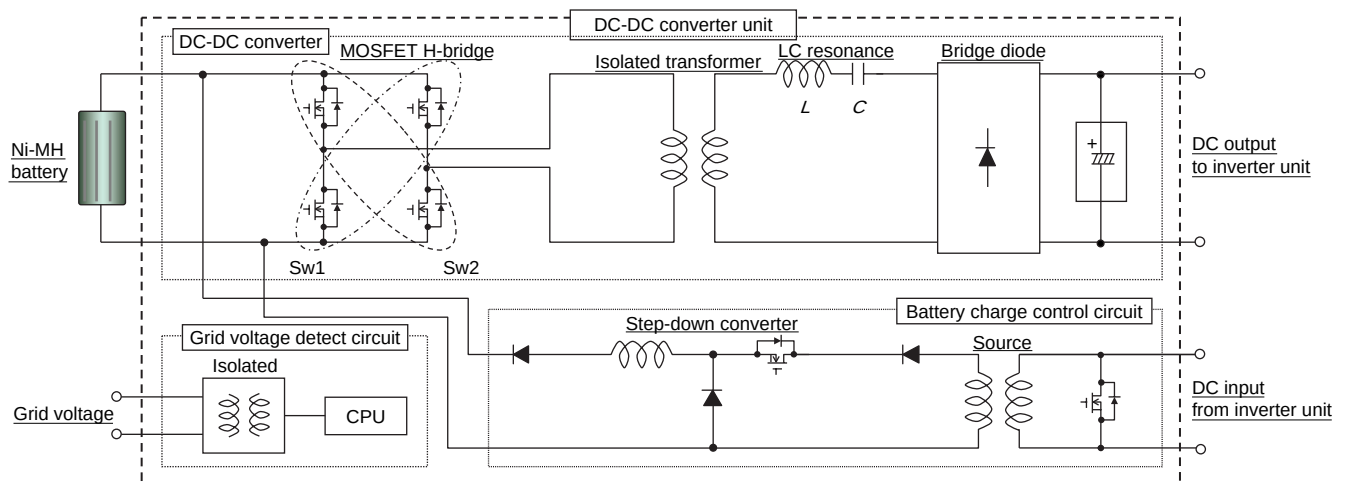


Fig. 10 DC-DC converter unit

disconnection or short-circuit occurs in the grid voltage detection lines, the self-diagnostic function of DC-DC converter allows the user to aware of anomaly.

4.2.2. Battery charge control circuit

The battery charge control circuit applies charge current control by means of a step-down converter, with DC voltage rectified from the grid power input by the inverter, or DC voltage rectified from the ALT output during engine operation, as the power source.

4.2.3. DC-DC converter

In a state of normal grid connection, the inverter starts the engine, using the grid voltage as a power source. During power outage, however, the battery is used as the power source to start engine. In order to share the inverter hardware, it was necessary for the DC-DC converter to boost the voltage input from the battery to close to the grid voltage. Considering the DC voltage of 340 V rectified from the grid voltage ($340 \text{ V} = 240 \text{ V} \times 1.414$), the battery voltage in the newly developed model was set to be 270 V, approximately a 20-fold increase, to share the parts. In addition, it was necessary to use an insulated DC-DC converter in order to provide inverter unit, which is isolated from the casing, with power from the battery, which is connected to the engine earth and the casing earth. By switching between MOSFET (metal oxide semiconductor field effect transistor) H-bridges Sw1 and Sw2, as shown in Fig. 10, the voltage supplied from the battery impresses a rectangular AC voltage in the transformer.

As a result, a voltage representing the voltage ratio between the primary and secondary coils is output from the secondary coils of the transformer as a rectangular AC voltage. Conversion of this rectangular AC voltage waveform into an isolated DC voltage is achieved by its full-wave rectification and transformation into a DC voltage by the bridge diodes. Elements with a low level of ON resistance were selected for the MOSFET section to cope with low voltage and high current. However, when switching is conducted in the high DC current range, increased switching loss leads to generate heat and noise. For this issue, in order to realize high efficiency and low noise in the newly developed model, a resonance converter and resonance coils were employed, as shown in Fig. 10, to enable current resonance type of zero current switching (ZCS). The resonance frequency, f , can be expressed by Eq. (2), using the capacity of the resonance condenser, C , and the inductance of resonance coils, L as shown below.

$$f = 1/2\pi\sqrt{L \cdot C} \quad (2)$$

Switching at 0 A by means of current resonance is enabled by synchronizing the carrier frequencies of the H-bridges, Sw1 and Sw2, with the resonance frequency, f . As a result, switching loss was reduced, and high

Table 2 Specifications (DC-DC converter unit)

Boost type	Current resonance type isolated converter
Switching type	Zero current switching
Rated input voltage	14 V
Rated output voltage	270 V
Rated output power	440 W
Switching frequency	40 kHz
Dimensions (LxWxH)	277 × 187 × 32 mm
Mass	1510 g

efficiency and low noise were achieved⁽⁶⁾.

In addition, each of the input circuits was designed for high-impedance input, in order to reduce standby energy in the state of normal household, where the unit stood by for long time. As a result, the standby energy of DC-DC converter was reduced to a negligible level of 1/100 less than the battery's self-discharging level of 0.3 mW.

4.2.4. Test results

Table 2 shows the specifications of DC-DC converter, and Fig. 11 shows its appearance. Figure 12 shows the measured waveforms of the switching voltage and the transformer input current in the DC-DC converter. The measured current waveform on the primary side of the



Fig. 11 DC-DC converter unit

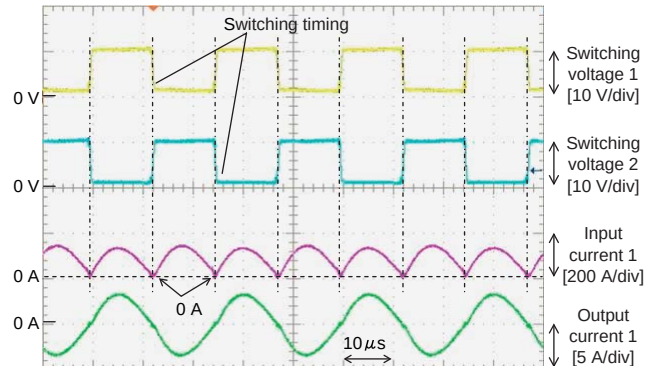


Fig. 12 Zero current switching

Table 3 Test results of DC-DC converter unit

Input voltage	14 V
Output voltage	273 V
Efficiency (rated output power)	91.6 %
Maximum output power	1168 W
Output voltage (no load)	297 V

isolated transformer (Input current 1) suggests that the ZCS operation was conducted with switching at 0 A. Because manufacturing variations in the resonance condensers and the resonance coils resulted in variations in resonance frequency, a correction term for the switching frequency was set with software. The correction term was set in the inspection prior to shipping the DC-DC converter to enable the ZCS operation. Figure 13 shows the load efficiency of DC-DC converter for 12 V and 14 V of input voltage. Table 3 shows test results for the unit. The ZCS operation achieved 91.6% of efficiency at the rated output of 440 W. In addition, even the input voltage achieved an efficiency of 89.5% at the engine start-up, when the maximum power was used. The realization of high efficiency in the isolated DC-DC converter continuously enabled rated power output, using only natural heat dissipation, without necessitating external cooling.

4.3. Inverter

Figure 14 shows the system configuration of the inverter outlined in Fig. 4. The system is composed of starter driver / diode rectifier, which enables the engine to start, and converts the power from the ALT to AC or DC during power generation; boost converter that raises DC voltage; a MOSFET section that converts DC voltage rectangular voltage based on pulse width modulation (PWM); LC filter that converts rectangular voltage to sine voltage; relay that connects to or disconnects from the grid; a noise filter that removes noise; a current sensor that detects output current; current limiters for autonomous operation and grid-connected operation, which limit the currents used in these operating modes; voltage sensor that

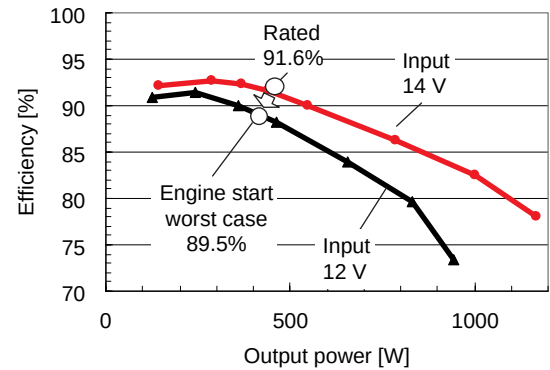


Fig. 13 Load efficiency characteristics of DC-DC converter

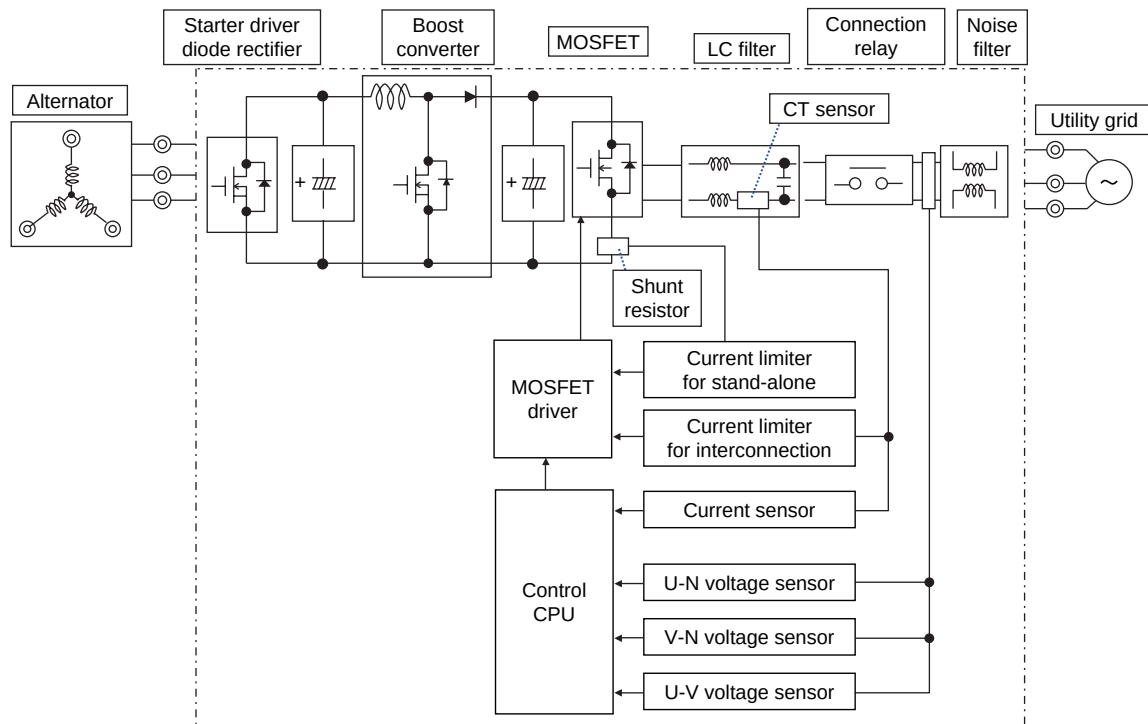


Fig. 14 Block diagram of interconnection inverter with backup function

detects U-N, V-N, and U-V voltages; control CPU that controls generation; and drive circuit that controls drive of the MOSFET section.

By contrast with the grid-connected inverter installed in the previous model, the newly developed model includes a backup generation function for power outage. Also, while using a base plate in the same size as the previous model, the new model generates more power in the backup mode and grid connection boost mode. The hardware and software used to achieve this will be discussed in the following sub-sections.

4.3.1. Increasing power output

When backing up, the power output of newly developed model is 1.8 kVA, 1.5 times higher than the output, when connected to the grid. In order to increase output as high as 1.5 times, the size of the LC filter coil (L) was increased to make maximum flux density higher, and the diameter of coil wire was also increased. The more the output increases, the more the ripple voltage of the DC voltage input to and output from the boost converter become higher. Because of this, the ripple current to the electrolytic condenser also increases, and heat generation shortens the lifespan of condenser. In order to help prevent this, the inductance of the boost converter coils and the capacity of the electrolytic condenser were increased to reduce ripple current, and to control temperature increases in the condenser. As a result, the lifespan of electrolytic condenser was doubled from that of the assembled micro-cogeneration unit. Because the heat generated by the boost converter and MOSFETs also increases in proportion to power, a dedicated inverter cooling fan, which operated in high temperature, was also added to the unit to facilitate its cooling performance. Despite the same size as the previous one, in this way, the new model successfully generates 1.5 times more output.

4.3.2. Addition of backup functions

(1) Addition of U-V voltage detect circuit

As shown in Fig. 15, when the system was connected to the grid, U-N voltages and V-N voltages were separately detected to find irregular grid voltages and to increase the resolution of voltage detection. By adding these voltages, we found the voltage between the U and V phases, which could be used for the proportional, integral, and differential control (PID control) of voltage feedback. However, as shown in Fig. 16, the N phase became disconnected due to the output from two-wire single-phase operation during the backup operation as a standalone generator. This is because the MOSFET section that converts output from DC to AC was a single-phase full bridge. For this reason, the addition of U-N to V-N voltages did not simply give the U-V voltage. Detection of U-V voltage is therefore conducted to enable voltage feedback during backup generation.

(2) Addition of current limiter circuits

Current limiter circuit was installed for high current load during backup generation in addition to the current limiter for grid connection in the newly developed system. The threshold value of current limiter circuit for grid connection was set at 150% of the rated current, during the grid connection boost operation. The threshold value of the current limiter circuit for backup operation was set at 250% or more than the value of the limiter circuit for grid connection to sustain the load of mercury lamp or compressor, which required high-current. The threshold values were determined based on the results of tests and simulations, in order to help prevent the FETs used as the inverter switching elements from suffering heat damage, when high current of electrical load was required, or short circuit occurred. During backup generation, the grid connection current limiter circuit was set not to operate following the setting of the software.

(3) Modification of current detection circuits

A single current sensor was used to detect both the currents in the grid connection operation and backup operation. In the previous inverter generator, the current of FET bridge arm was detected. However, the shared use of current detection circuit for detection of current downstream from the LC filter during grid-connected operation in the new model enabled the

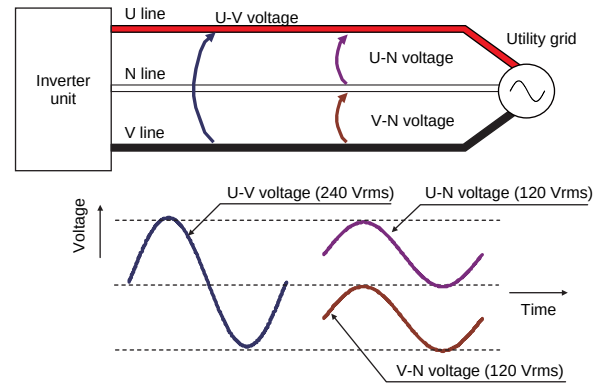


Fig. 15 Three-wire single-phase (grid connection)

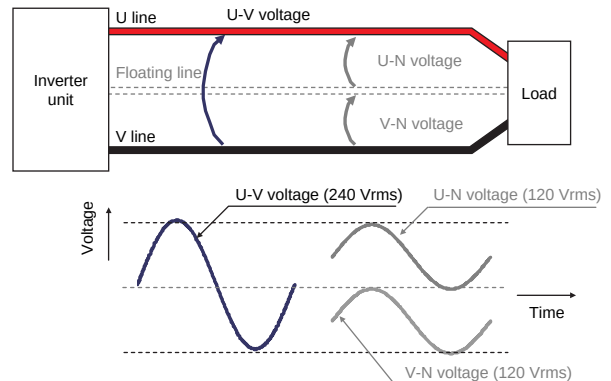


Fig. 16 Two-wire single-phase (backup)

number of circuits to be reduced. Because the system handles high currents during its backup operation, the size of conducting wire in the current sensor was enlarged to increase the rated current from 10 A of the previous model to 30 A. This rated current was set to include a sufficient margin in relation to the excess current limiters discussed in the above.

4.3.3. Grid connection control and backup generation control

Three control modes, grid connection control, grid connection boost control, and backup generation control, are employed in the new model, with the same CPU as the previous model. As Fig. 17 shows, sharing of software for the input and output levels of each mode allowed to share hardware for each operating mode. Because backup operation is carried out during power outage, the grid voltage is not input, which is supposed to provide a benchmark for this control. Because of this, a benchmark that modeled the grid voltage (an internal standard sinusoidal wave) is formulated in the computation section of the control system, to output sine wave.

The actual program implemented two unique types of control: 1) fixed current control in the grid connection that controlled output current by superimposing the output waveform on the grid voltage, 2) fixed voltage control in the backup generation that outputs rated sinusoidal voltage, no matter what loads are connected. Judgment to which mode should be applied is based on the data of power interruptions provided by the externally connected devices and DC-DC converter.

4.3.4. Generation performance during grid-connected operation and backup operation

Table 4 shows generation performances when the unit

Table 4 Power generation performance of interconnection

Output power		1.2 kW / 1.8 kW	
Engine speed		1950 rpm / 2800 rpm	
Rated voltage		AC 120 V / 240 V (1 Φ 3 W)	
Rated frequency		60 Hz	
Efficiency		92% or more	
Power factor		97% or more	
Output current distortion		5.0% max	
Total			
Individual harmonic of odd order	3-9 order		4.0% max
	11-15 order		2.0% max
	17-21 order		1.5% max
	23-33 order		0.6% max
	35-39 order		0.3% max
Individual harmonic of even order	2-10 order		1.0% max
	12-16 order		0.5% max
	18-22 order		0.375% max
	24-34 order		0.15% max
	36-40 order		0.075% max

is connected to the grid. The system operates in two modes, when connected to the grid: normal grid connection operation (1.2 kW) and grid connection boost operation (1.8 kW). In both modes, the unit generates a high-quality power output that meets the UL 1741 safety standard for grid-connected inverters⁽⁷⁾ established by Underwriters Laboratories Inc. in the U.S..

In addition to the grid connected operation, because the system also operated, using the settings for the LC filter constant in the backup mode, the output voltage waveform for the load that rapidly varied currents, such as diode rectifier load, was distorted with approximately 14% of distortion rate. The system therefore identifies the diode

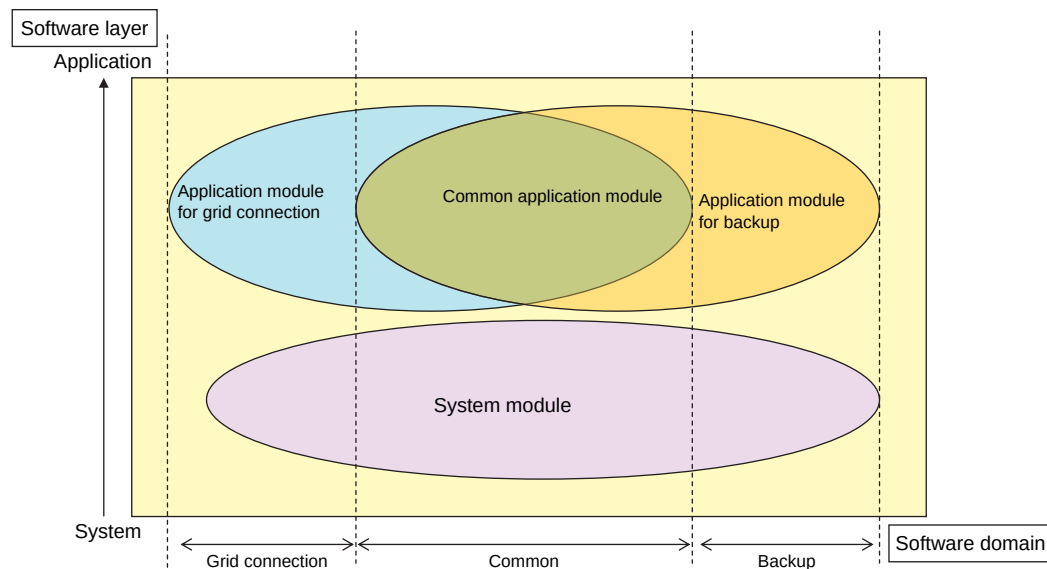


Fig. 17 Software architecture

rectifier load based on the magnitude of the crest factor (maximum current / effective current), and applies feedback control to minimize distortion rate. As shown in Fig. 18, we reduced the distortion rate by 4.7 points to 9.2%, achieving equivalent performances to those of Honda inverter generator⁽⁸⁾. Table 5 shows its generation performances during backup operation. During backup operation, the system supplies power at its rated power of 1.8 kVA, which meets the UL2200⁽⁹⁾ standard for stationary generators.

4.3.5. Battery assist performance

Engine generator converts engine output to electricity, and supplies this power to load.

For this reason, we can make the unit more commercially appealing by increasing the usable amount and type of electric load based on enhanced instantaneous responsiveness to rated output, or to the inrush current at

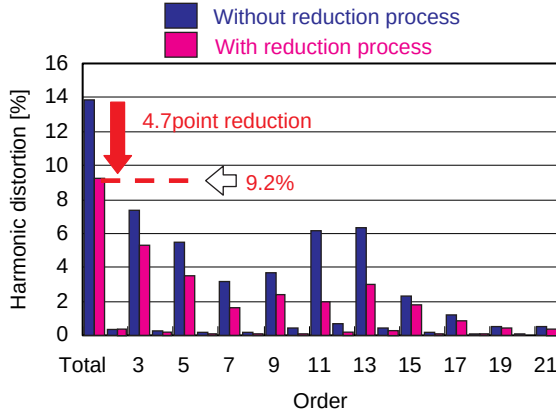


Fig. 18 Output voltage harmonic distortion With and without reduction process

Table 5 Power generation performance of backup

Output power		1.8 kVA
Rated voltage		AC 240 V (1 Φ 2 W)
Rated current		7.5 A
Rated frequency		60 Hz
Efficiency		92% or more
Output voltage distortion	Resistance load	3.0% max
	Rectifier load	10.0% max

startup of an inductance load, such as a motor. The newly developed model is fitted with a battery and a DC-DC converter, which enables hybrid generation with engine power and battery power. As shown in Fig. 19, when instantaneous excessive power is demanded on the engine during backup operation, a command from the inverter increases the battery voltage through the DC-DC converter, and the battery supplies power to the inverter⁽¹⁰⁾. When receiving more than the rated load, or inrush current of high-load, in this way, the battery assists the engine output by engaging in hybrid generation. This facilitates the transient response of the engine, and makes the unit more commercially available as an engine generator. Figure 20 shows the change in the voltage waveform, when a load is input. Voltage sag was evaluated based on the index expressed by Eq. (3) below.

$$\text{Voltage sag} = (V1 - V2)/V1 \times 100\% \quad (3)$$

Figure 21 shows the differences in the same load, which resulted from the presence of battery assist. As Table 6 shows, voltage sag reduced by approximately 40 points, and stabilization time reduced by 0.8 sec, when 120% of the rated load was input.

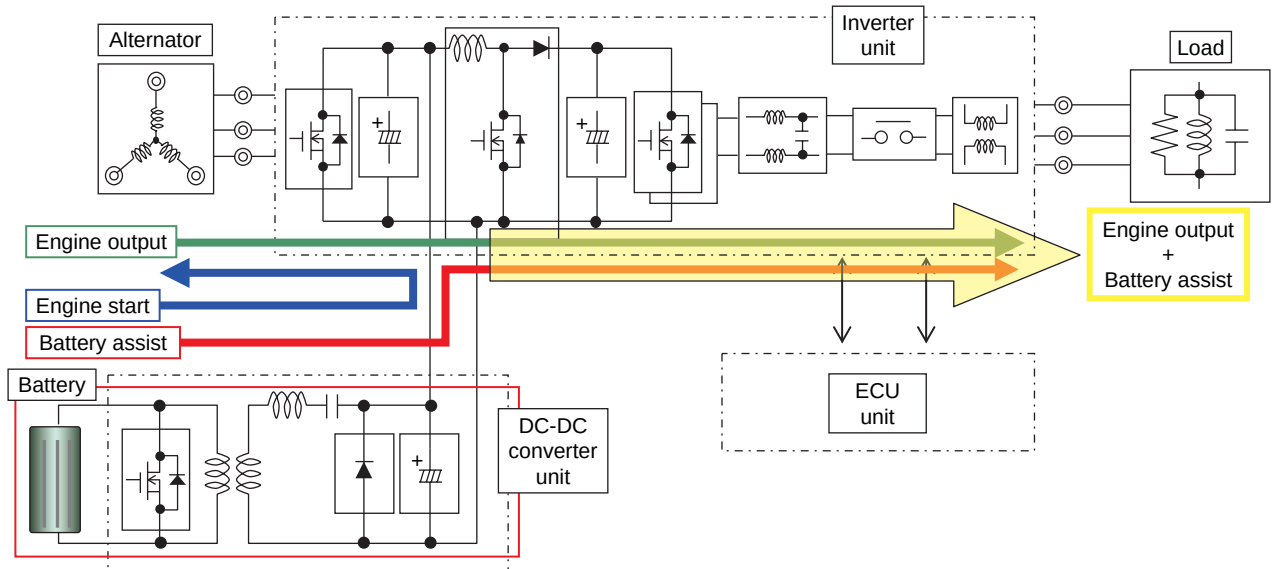


Fig. 19 Hybrid power generation

Table 6 Comparison of battery assist on-off

	Assist off	Assist on
Voltage sag	59.3%	16.6%
Stabilization time	2.54 s	1.71 s

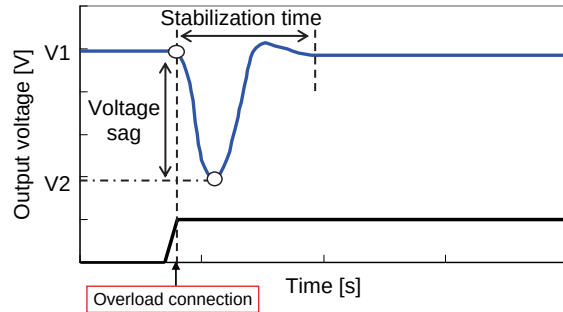


Fig. 20 Voltage sag and stabilization time

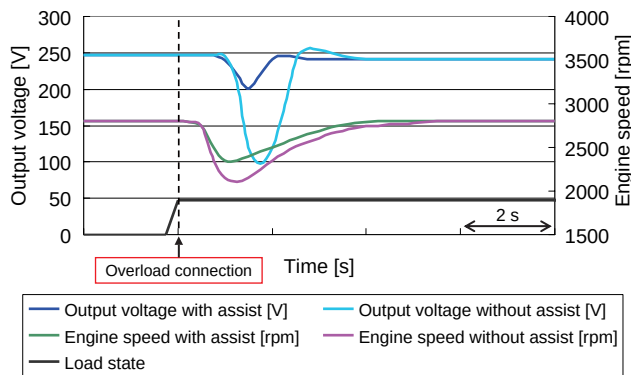


Fig. 21 Comparison of battery assist on-off

5. Conclusion

A micro-cogeneration unit for domestic use with the capacity for autonomous power generation was developed to function as a backup generator during power outages. Increasing the speed of the engine for standalone power generation in power outages increased output 1.5-fold in comparison with the previous model, which only operated based on the grid connection. Because the unit is also able to recover heat as a micro-cogeneration unit, when used as a backup generator, achieving total efficiency of 85.5% or more of primary energy. The features of the newly developed unit are further outlined below:

- (1) The realization of automatic switching between grid connection and autonomous operation as an inverter, in addition to the development of highly efficient isolated DC-DC converter, enabled both autonomous generation and hybrid generation in the same size of housing as that of the previous model.
- (2) By increasing engine speed, we increased output 1.5 times more than that of the previous model, while keeping the same size of circuit board.

- (3) The realization of current resonance ZCS operation enabled the development of highly efficient isolated DC-DC converter that achieved 91.6% efficiency at 14 V of input voltage and 440 W of output.
- (4) In addition, the use of long-life Ni-MH battery, optimization of component layout, and intermittent charging allowed us to actualize a maintenance-free battery.

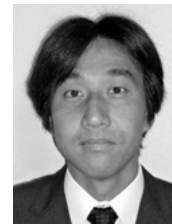
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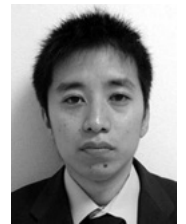
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Development of Air-cooled, 4-stroke V-twin Cylinder General Purpose Engine GX690/GXV690

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ABSTRACT

Honda has developed GX690/GXV690, a small, high-performance, air-cooled, 4-stroke V-twin cylinder general purpose engine with an outstanding environmental performance.

In this new model, the enhanced shapes of combustion chamber and port, upgraded cooling capability around the combustion chamber, and variable ignition timing effectively suppress knocking, while increasing the compression ratio to 9.3 from 8.3 of previous GX670/GXV670, which results in 8% increase in output. Without using any catalysts, this engine with 10% of increased fuel efficiency has cleared the EPA exhaust emissions regulations. Both the decreased size of air cleaner, which was resulted from enhanced filter, and the adoption of oil filter base, which also had an oil cooler function, eliminating previous oil cooler, allowed us to reduce the total height and width of the engine, as well as the volume by 18%. The modified shape of cooling fan and fan cover, configuration of muffler, and other parts are effective to decrease the measured and perceived noises that occurred in the previous engine in operation.

As new features, we have also added an hour meter and oil alert indicator to enhance the usability of engine. Furthermore, we advanced battery charging performance to offer a diverse use in working machines.

1. Introduction

V-twin cylinder gasoline engines are the mainstream in 10-20 kW general purpose engines that are employed as the power sources for business working machines, such as generators, construction equipments, and ride-on lawnmowers.

Honda launched the GX series of V-twin cylinder engines with GX610/620 in 1993, adding GX670 to it in 1999. Since 2000, other engine makers have commenced offering their V-twin cylinder engine line-ups with higher output than that of Honda's GX engines. As a result, high-output gasoline engines have come to be employed in a various type of business working machines; at the same time, the demand for more fuel-efficient and smaller engines is strong, due to the users' increasing environmental awareness and limited space available for fitting an engine in a working machine.

In order to cope with this background, the new GX690/GXV690 air-cooled, 4-stroke V-twin cylinder general purpose engine has been developed. In this paper, we will introduce our developmental efforts to give more power to the previous GX670/GXV670 engines by achieving higher fuel efficiency, lower hazardous exhaust emissions, and reduced engine size.

2. Development Goals

When we developed the new engine, we set three main goals to achieve sufficient output to meet the work load that was demanded for business working machines, higher fuel efficiency, and reduced engine size, while decreasing hazardous exhaust emissions and noises, and enhancing equipments, as elaborated below:

(1) Output

- 5% more output (16 kW or more) than the previous engine (Fig. 1)

(2) Fuel efficiency and exhaust emissions

- 10% more efficient fuel consumption than that of the

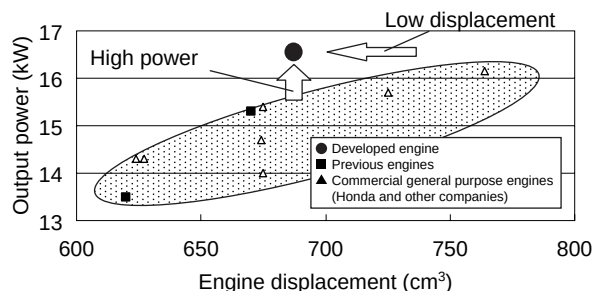


Fig. 1 Positioning of developed engine

* Power Products R&D Center

Table 1 Engine specifications

Item	Previous engine (GX670)	Developed engine (GX690)
Engine type	4-stroke, V-90° twin-cylinder	4-stroke, V-90° twin-cylinder
Displacement (cm ³)	670	688
Bore × Stroke (mm)	77 × 72	78 × 72
Compression ratio	8.3 : 1	9.3 : 1
Valve train	2-valve OHV	2-valve OHV
Valve inclination angle (deg)	0	29
Valve diameter (mm)	Inlet: ϕ 35, Exhaust: ϕ 31	Inlet: ϕ 30, Exhaust: ϕ 26
Combustion chamber shape	Wedge type	Hemispherical type
Lubrication system	Forced feed system	Forced feed system
Ignition system	Transistorized magneto (fixed)	CDI (advanced)
Dimension (L × W × H) (mm)	412 × 471 × 457	405 × 410 × 438
Volume (cm ³)	88680	72730

previous model in the EPA mode for general purpose engines⁽¹⁾

- Compliance with the exhaust emissions regulations (EPA Phase 3 Small Nonroad Spark Ignition Engine Class 2)

(3) Engine size

- 3% reduction in total height and 10% reduction in total width from those of the previous model

(4) Noises

- Equivalent to or lower than those of the previous model
- Enhanced noise feeling

(5) More equipment with advanced usability

- Addition of hour meter and oil alert indicator
- Enhancement of charge output

3. Basic Performance of the Engine

Table 1 shows the main specification of the developed GX690 engine, a V-90° twin OHV engine in a uniblock cylinder structure that consists of cylinder heads and cylinder block⁽²⁾.

A horizontal-type engine in which the output shaft faces in a horizontal direction and a vertical-type engine in which the output shaft faces in a vertical direction were developed simultaneously with the aim of sharing parts between both types. Figures 2(a) and 2(b) display the

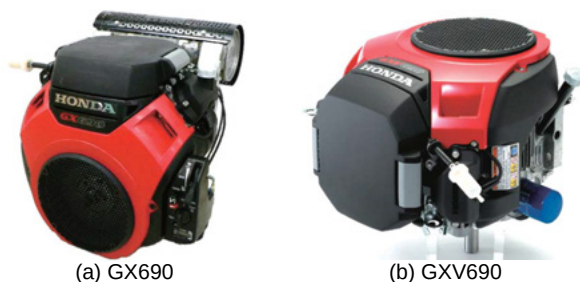


Fig. 2 External view of developed engines

external appearances of the horizontal and vertical types, respectively.

In the following sections, we will discuss engine output, fuel efficiency and exhaust emissions, and engine size.

3.1. Engine Output

In order to reconcile high output with reduced size, we set the displacement of new engine to be 688 cm³, 3% larger than the previous model. The bore was increased by 1 mm without altering the stroke distance to produce a bore/stroke ratio of ϕ 78/72 mm, and to minimize the total height.

As discussed later in Chapter 4, also, enhanced combustion, variable ignition timing, and increased cooling capability around the combustion chamber reinforced knocking toughness and enabled the compression ratio to be increased to 9.3 from 8.3 of the previous model.

By replacing non-advanced ignition system which was conventionally employed in general purpose engines with electronically-advanced capacitor discharge ignition coil, variable ignition timing became available to each engine speed. As Fig. 3 shows, this has increased torque in the entire operating range more than the previous model; the maximum torque has increased by 5% and maximum output by 8%, as observed in the engine performance curve.

3.2. Fuel Efficiency and Exhaust Emissions

Figure 4 shows the achieved figures in fuel consumption and exhaust emissions of new engine. As discussed later in Section 4.1., the use of technologies to facilitate combustion contributed to higher fuel efficiency by 10% in comparison with that of the previous model, while keeping HC + NO_x emissions in the same level, when the engine was operated in the EPA fuel efficiency mode for general purpose engines. Thus, the engine has

met the exhaust emissions regulations for general purpose engines (EPA Phase 3).

3.3. Engine Size

The intake manifold and carburetor of the new engine were lowered to a height enabling maximal reduction of the length of the inlet port. Also, the size of air cleaner was reduced without causing a decline in its filtering performance by using a filter material, which had a higher

dust holding capacity per unit of area as an air filter in the air cleaner. In this way, the total height of engine has been reduced by 19 mm.

In addition, the use of an oil filter base that has an oil cooling function (Fig. 5) has allowed us to remove the motorcycle-type oil cooler, which was used in the previous model, and reducing the total width of the engine by 61 mm and reducing the number of parts used.

As shown in Figs. 6 and 7, these contributed to reduce the total height by 4%, total width by 13%, and volume by 18% from those of the previous model. This enables the engine to be easily fitted in construction equipments, generators, and other working machines in which engines are installed in narrow spaces under the bonnets.

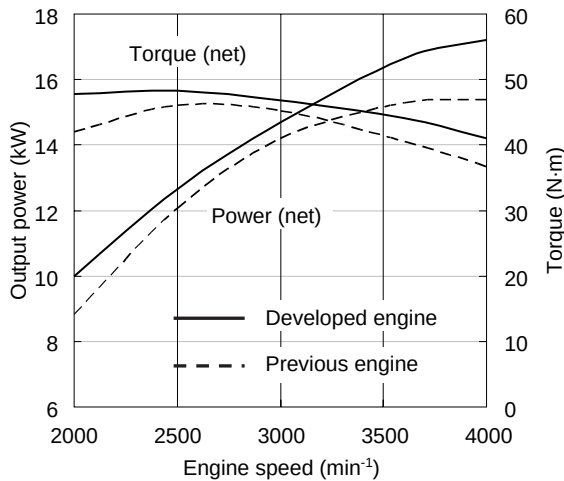


Fig. 3 Engine performance

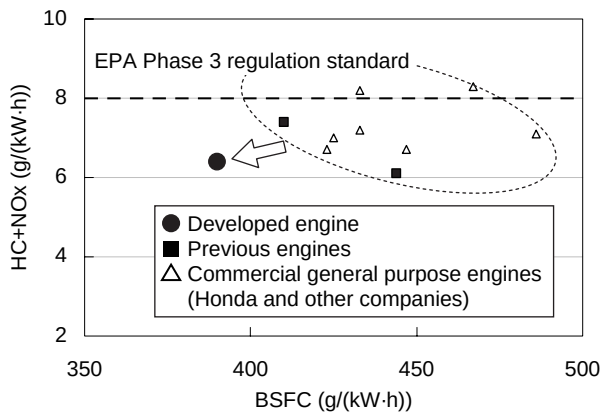


Fig. 4 Fuel consumption and mass emissions in EPA emissions mode

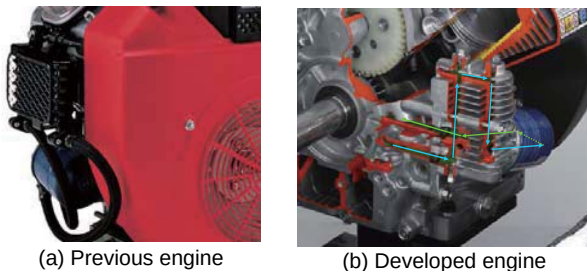


Fig. 5 Oil cooler

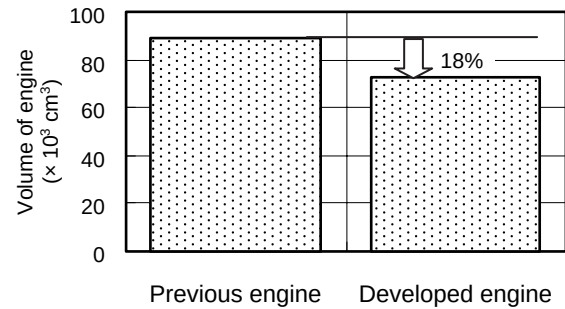


Fig. 6 Engine volume

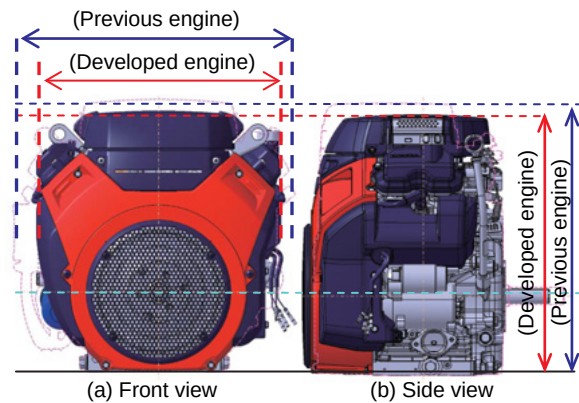


Fig. 7 External shape

4. Technologies to Facilitate Combustion and Enhance Cooling Performance

As seen in a generator, because most general purpose engines are air-cooled, the work load is high during stationary operation. For this reason, it was challenging for us to increase the compression ratio. Based on the knocking limit, therefore, the compression ratio was set at 8.3 in the previous model. In the new engine, on the other hand, the compression ratio was increased to 9.3 to help ensure higher thermal efficiency by suppressing knocking, based on the modification of the shape of

combustion chamber, which is discussed in the following section, the use of variable ignition timing, and the enhanced cooling capability around the combustion chamber.

4.1. Technologies to Facilitate Combustion

4.1.1. Combustion chamber/port configuration

Figure 8 shows the valve arrangements and port configurations of new engine. In the previous model, a parallel valve arrangement was adopted in the wedge-type combustion chamber. The new engine employs a valve arrangement with a valve included angle of 29° and hemispherical combustion chambers on the cylinder head side, in addition to concave piston heads, resulting in enhanced flaming.

Further, the angle between the valve shaft and the incident direction of inlet port has been reduced to 60°

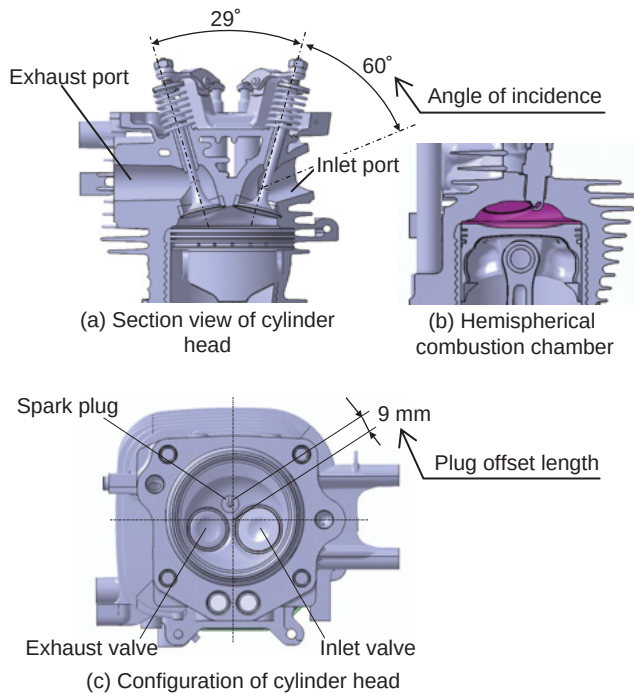


Fig. 8 Cylinder layout

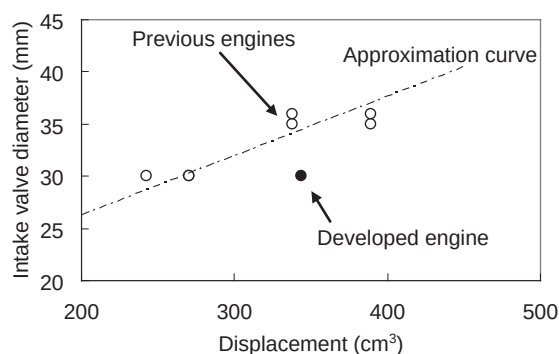


Fig. 9 Intake valve diameter

from 90° of the previous model to decrease duct resistance in the inlet port, and thus reducing pumping loss (losses that occur during intake).

As Fig. 9 shows, the inlet valve diameter has also been reduced to 30 mm (5 mm smaller than that of the previous model) to facilitate the boost flow velocity, and activated the in-cylinder flow. Similarly, the distance between the spark plugs and the center of combustion chamber has been decreased from 20 mm of the previous model to 9 mm to minimize the flaming distance in the combustion chamber. Based on these technologies to facilitate combustion, we have successfully increased combustion speed and enhanced knocking toughness.

4.1.2. Electronically-advanced capacitor-discharge ignition coil

In order to suppress knocking without affecting startability or engine speed stability during idle operation, the transistor magneto ignition system, which was used in the previous model, was replaced by an electronically-advanced capacitor-discharge ignition coil, which allowed the engine to vary the settings of ignition timing based on the engine speed. In this way, suppression of knocking is followed by the advanced ignition timing based on the engine speed, and which increased both the output and fuel efficiency of new engine (Fig. 10). Moreover, setting an acceleration map has increased the responsiveness of the engine, when it is accelerated.

4.2. Technologies to Facilitate Cooling Capability

4.2.1. Cylinder head

Because the previous model employed a split cylinder head configuration, which entailed bolts to fasten and bosses to fix in the cylinder head, the flow of cooling air was disturbed. Considering this issue, we adopted a uniblock cylinder, which integrated cylinder heads and cylinder blocks, in the new engine, in order to enhance cooling capability around the combustion chambers (Fig. 11). This uniblock cylinder obviates the necessity for the bolts and fixing bosses around the combustion chambers,

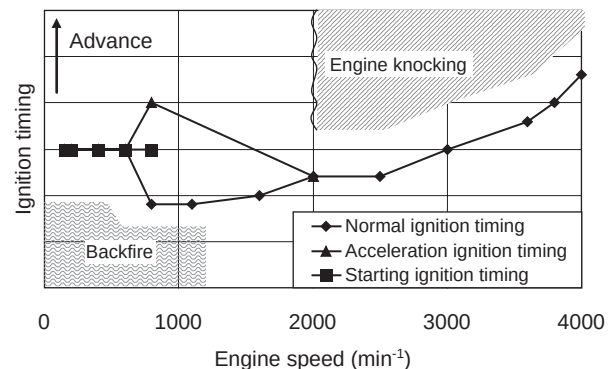


Fig. 10 Ignition timing

facilitating the flow of cooling air around the chambers.

In addition, the pushrod chamber of previous model consisted only of aluminum cylinder heads. The fixing bosses that coupled this aluminum pushrod chamber with cylinder head, which was mentioned in the above,

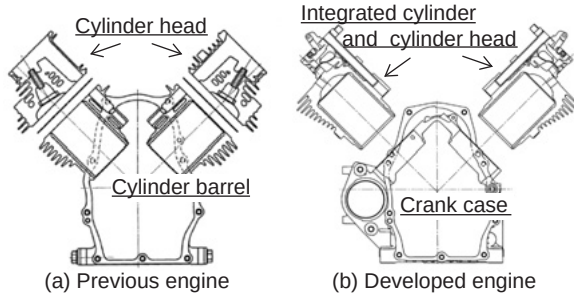


Fig. 11 Engine configuration

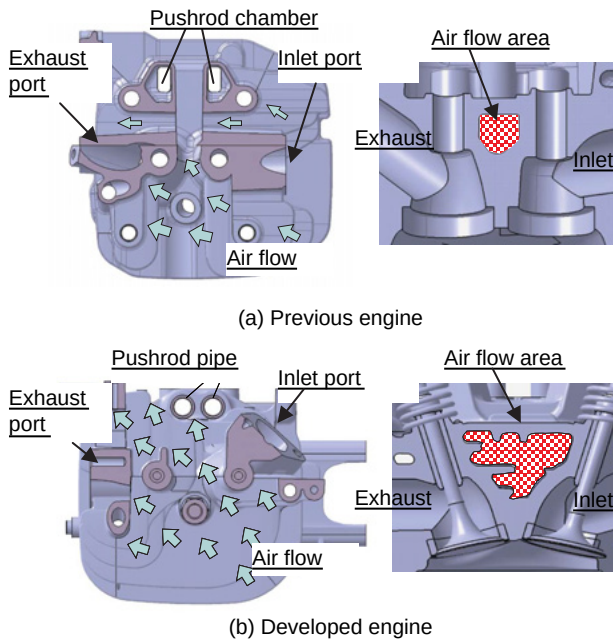


Fig. 12 Section view of air jacket

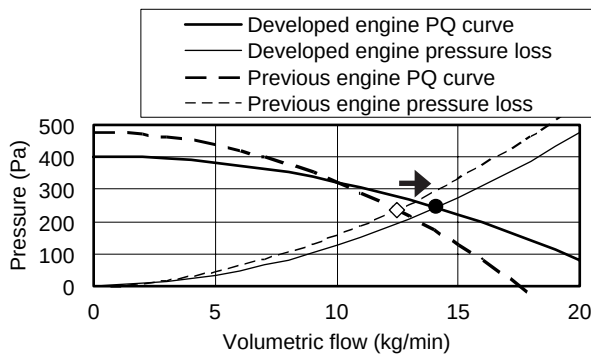


Fig. 13 P-Q curve of fan

involved excessive thickness of aluminum, due to the die-casting manufacturing method. This eventually narrowed the flow path for cooling air. In the new engine, the fixing bosses have been removed, and separate aluminum pipes have been used as the pushrod chambers. As a result, while die-casting method is still employed, the amount of excessive aluminum has been decreased, expanding the flow path of the cooling air in the upper section of the cylinder head (Fig. 12).

In addition to the above modifications, the use of a radial valve arrangement has made the cross-sectional area of flow path for cooling air between the valves 2.8 times larger than the previous one. By securing the flow path for cooling air in the exhaust side of combustion chamber, which reaches high temperatures, and assisting the cooling air to flow more efficiently, we have successfully increased the cooling capacity of new engine.

4.2.2. Cooling fan

The external diameter of cooling fan has been increased from 228 mm of the previous model to 241 mm.

As discussed later in Section 5.1., the stud bolts, which impeded the flow of cooling air within the scroll of fan cover in the previous engine, have been removed. Also, a resin fan cover and shroud have formed a smooth scroll shape, enabling optimal allocation of cooling air around the combustion chamber of each cylinder and around the cylinders, which resulted in the reduction of airflow resistance in the engine.

The volume of the air produced by the fan in operation, which is indicated in the intersection of the pressure/quantity curve and the engine airflow resistance curve in Fig. 13, has eventually increased by 14% with the same pressure as that of the previous model.

5. Technologies to Reduce Noises

As Fig. 14 shows, the noise level of new engine has been reduced by 1.5 dBA from that of the previous model, when the engine is operated under three-quarters of the rated load, at an engine speed of 3000 min⁻¹ and output of 8.6 kW.

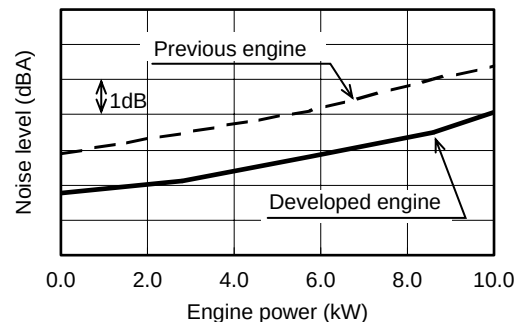


Fig. 14 Noise level (3000 min⁻¹)

As indicated by the noise attributable ratios in Fig. 15, this reduction of engine noise level has been actualized mainly by a reduction of radiation noises resulting from an increased surface stiffness of crankcase, of mechanical noises, including those attributed to the resin cam gears, of cooling fan and fan cover noises, and of exhaust noises.

The technologies employed to reduce the noises from cooling fan and fan cover as well as the exhaust noises are discussed in the following sections.

5.1. Cooling Fan and Fan Cover Noises

As Fig. 16 shows, the structure with a sub-plate at the top of cooling fan blade has prevented air recirculation from the tip of the blade, and reduced fan noise.

In addition, a high-stiffness resin, which has approximately 1.5 times higher bending elasticity modulus than that of the resin material used in the previous model, used for the fan cover, has increased the surface stiffness

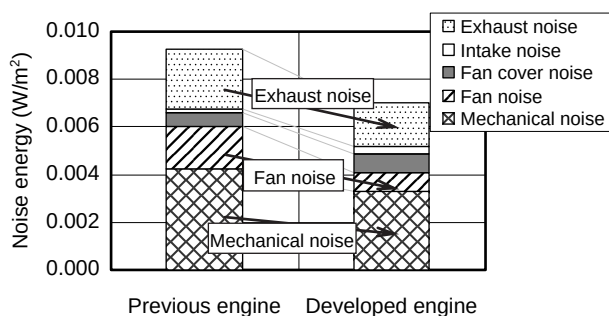


Fig. 15 Noise contribution

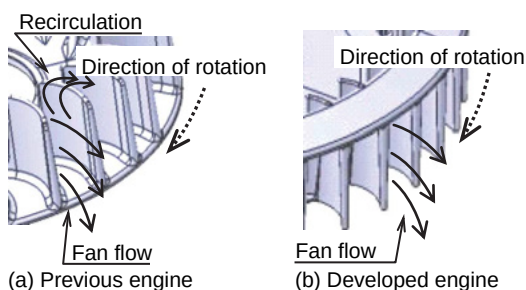


Fig. 16 Fan cover layout

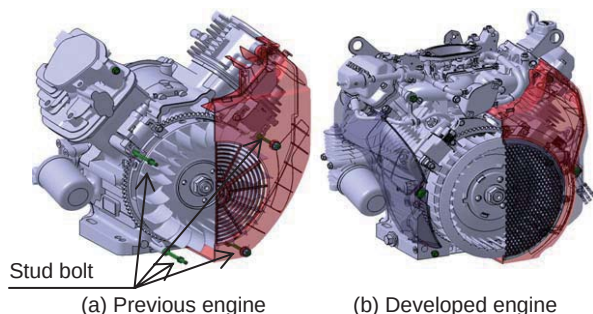


Fig. 17 Fan cover layout

of the fan cover. As shown in Fig. 17, this has allowed us to remove the stud bolts that supported the fan cover in the previous model. In this way, we minimized the wind roar produced by the cooling fan that struck the stud bolts, and thus decreased the level of fan noise.

The technologies employed in the cooling fan and cooling fan cover noises, as discussed in the above, have achieved the reduction of the noise level by 1.5 dBA (Fig. 18), while providing a 14% larger volume of wind than that of the previous model.

5.2. Exhaust Noises

We display the muffler configuration of new engine in Fig. 19, and its effects and details below.

- (1) Three-chamber muffler configuration in the exhaust path of each cylinder has reduced exhaust pulsation noise to 100-200 Hz.
- (2) Double-plated wall has reduced the higher frequencies of noise radiation than 2000 Hz, which was produced from the muffler wall.
- (3) Glass wool, which was arranged in the exhaust pipe, has reduced the higher frequencies of exhaust discharge noise than 2000 Hz.

Measures (2) and (3) above have reduced the harsh frequency components of 2000 Hz and higher (Fig. 20), resulting in a noise feeling with minimal harshness. In addition to this, the structure that was described in (1) in the above has effectively decreased 100-200 Hz exhaust noises, and have achieved the reduction of the exhaust noise level by 1 dBA.

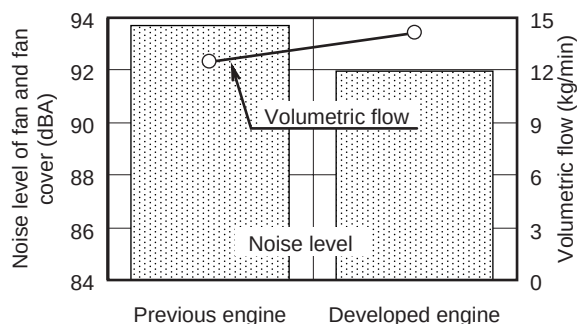


Fig. 18 Noise level of fan

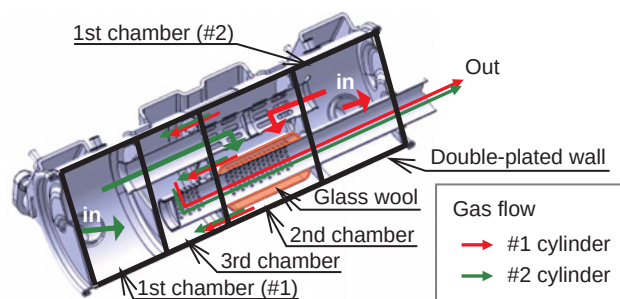


Fig. 19 Internal configuration of muffler

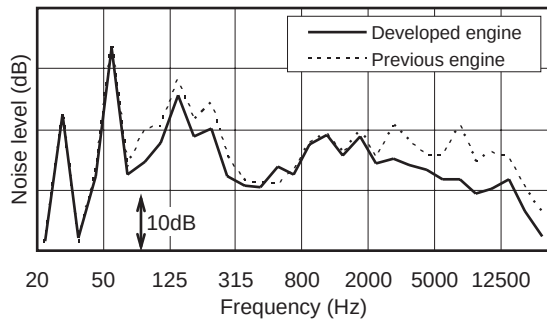


Fig. 20 Frequency characteristic of muffler

6. Enhanced Usability

In this chapter, we will discuss main features of the equipments mounted in the new engine.

6.1. Control Box

As Fig. 21 shows, the operating controls, such as throttle lever, choke knob, and engine switch have been concentrated in a control box in new engine. This has eventually enhanced visibility of the engine operating controls, and enabled the user to start-up and shutdown the engine with the same panel.

Also, a new oil alert indicator and hour meter have been fitted in the control box. When oil runs low during engine operation, the oil alert is activated. The oil alert indicator lights concurrently with engine shutdown. This makes the user instantly aware that the oil is insufficient.



Fig. 21 Control box

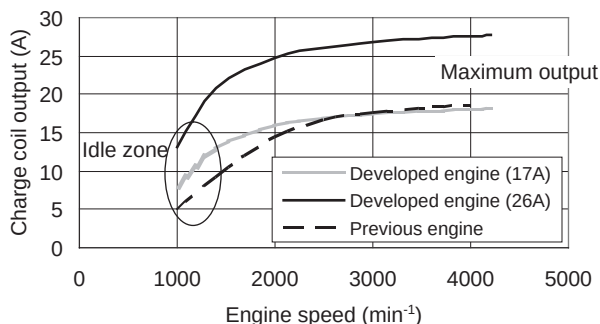


Fig. 22 Charge coil output

In addition, the LCD display clearly indicates cumulative operating time of engine, which the user can rely on for their maintenance of the oil, air cleaner filter, etc.

6.2. Increased Low-speed Output and Maximum Output of Charge Coil

For the charge coil which is used for battery charging, a multi-pole winding configuration is adopted instead of single-pole winding used in the previous model. By this, the charging frequency is raised and then the charging efficiency is increased. As a result of this, the charge output characteristic has increased by approximately 1.6-fold against that of the previous model at the idling speed of 1000 min^{-1} , while the maximum output of the charge coil has remained the same. This increases charging performance and enables more electrical loads to be used in working machines that are operated for long periods at idling speed.

In addition, a new charge coil has been added as an option. This new charge coil is enabled to output 26 A at maximum engine speed, as shown in Fig. 22, by adopting a three-phase winding structure instead of a single-phase. This enables the engine to be used in working machines that have electrical parts with high electrical loads, such as machines with large headlights or electric power tools.

7. Conclusion

The technologies, which were employed in a newly developed air-cooled 4-stroke V-twin cylinder 688 cm^3 general purpose engine, allowed us the following performances that enhance combustion, increase cooling capability, and reduce noises:

- (1) Maximum output has been increased by 8% and maximum torque by 5% in comparison with those of the previous model.
- (2) Fuel efficiency has been increased by 10% in the EPA operating mode for general purpose engines.
- (3) Exhaust emissions clear the figures stipulated in the EPA Phase 3 Small Nonroad Spark Ignition Engine Class 2 regulations, without using catalysts or any other devices.
- (4) While interchangeability has been enhanced, the volume of the new engine has been reduced by 18% in comparison with that of the previous model.
- (5) The noise level of engine during operation has been reduced by 1.5 dBA, and noise feeling has also enhanced, in comparison with that of the previous model.
- (6) Usability has been enhanced by adding the following equipments:

- Operating controls have been concentrated in a control box with a new hour meter and an oil alert indicator.
- The low-speed charge output performance of charge coil has been enhanced, and a new charge coil with a maximum output of 26 A has been added as an option.

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ABSTRACT

This paper discusses a novel walking assist device that assists users in adopting a more efficient posture, muscular usage and walk ratio. An assist method was developed that coordinates the walk ratio of users while increasing their propulsive force. This assist method was implemented through a hardware system that consists of low-profile actuators and compact electrical components. The device is light and adaptable to users of various shape and size. A long-term experiment showed that elderly subjects using the walking assist device were eventually able to walk with a wider stride, at a higher speed, and with a lower heart rate, without help from the device. Their balance of muscular usage also changed accordingly. Energy consumption increased according to the increase in the subjects' speed. This result suggests the possibility of using the walking assist device as a tool for increasing elderly peoples' physical activity, while reducing the level of stress this would normally produce.

1. Introduction

According to a survey conducted by the Ministry of Internal Affairs and Communications, the number of Japanese citizens aged 65 or over reached 28.19 million (12.03 million men and 16.16 million women) in 2008. This represents 22.1% of the total population, indicating that Japan has become a full-fledged elderly society⁽¹⁾. Many of Japan's elderly citizens are living their lives without concern for their age, and are actively involving themselves in social activities in their particular communities. The maintenance or enhancement of the individual's physical functions can be considered an important factor in the ability to live this type of active life.

The physical functions of elderly individuals decline as their physical strength declines with advancing age. This not only reduces their level of activity, but produces a vicious circle in which insecurity regarding going out and other issues lead to greater declines in physical function. Insufficient muscular strength can be considered to be the main factor in the decline of physical function among the elderly. Muscle training has been recommended for the elderly in the United States since the 1990s, and

this practice is also becoming more widespread in Japan⁽²⁾.

Extensive research has been done on compensating for this lack of muscular strength using robotic technology, and on power assist technologies that would further boost muscular strength. Devices have also been developed that measure the amount of force the individual wishes to generate using electromyographs and force sensors, and boost their strength with power assist⁽³⁾.

Meanwhile, some reports have indicated that the level of stress associated with a particular amount of exercise can be reduced simply by altering the way in which the individual moves⁽⁴⁾⁻⁽⁷⁾. Rather than exerting force constantly from the beginning to the end of a movement, concentrating force at the appropriate time and then relying on inertia reduces heart rate, blood pressure, energy consumption⁽⁴⁾⁻⁽⁷⁾.

In the case of walking also, research has commenced on a two-axis walk, which effectively uses changes in the center of gravity⁽⁷⁾. In this mode of walking, virtual axes passing through the foot making contact with the ground, the knee, the hip joint, and the shoulder blade, move forward alternately on the left and right like a pair of stilts. The center of gravity moves forward without the upper and lower bodies twisting. This two-axis walk has

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recently been used by Japanese athletes who have been said to be at a disadvantage in terms of physique and muscular strength. This technique has enabled them to supplement their muscular strength with gravity and inertia, and to achieve good results in world championships⁽⁸⁾.

Robots are also being used while patients who have been paralyzed by strokes are being retrained in how to move their shoulders and elbows, in this case not to increase muscular strength but to teach patients the correct movements⁽⁹⁾. The robot assists patients in moving their shoulders and elbows in the correct trajectory to enable them to grasp objects, generating a load if they move outside the appropriate trajectory. In this type of training process, results achieved using a robot are indicated as being superior to those achieved by normal training⁽⁹⁾.

The aim of the research discussed in this paper was to develop a system that would induce an effective mode of walking in the user without reliance on assist power, thus reducing the exercise stress associated with walking. Another aim was to attempt to help ensure that this effect was lasting, and that the user eventually became able to walk under their own power, thus establishing a positive cycle in which the amount of exercise taken by the user

would increase naturally and muscular activity would be beneficially stimulated. It was believed that by this means, it would be possible to assist elderly individuals in leading healthy and active lives.

The balance between the stride and the cadence (steps/min) is termed the walk ratio (stride/cadence). Experiments have shown that energy consumption increases unless this walk ratio is close to 0.0063⁽¹⁰⁾. Figure 1 shows the results of a verification of this phenomenon. The graph shows that energy consumption changes at the same walking speed when the walk ratio is varied. As Fig. 2 shows, among the elderly the walk ratio declines at both normal and maximum speed^{(10),(11)}. In other words, there is a tendency for energy consumption when walking to increase among the elderly. A means of inducing an appropriate walk ratio in the elderly is therefore important in inducing efficient walking. With this concept in mind, the research discussed here based itself on the two-axis walk and realized a new assist method that would assist with propulsive force to propel the body forward, and would induce a walk ratio while adjusting stride and cadence⁽¹²⁾. This paper will introduce this assist method and the assist device developed on the basis of the method, in addition to discussing the results of test verification with elderly subjects.

2. Assist Method

The computer used for control of the assist device contains a rhythm pattern generator^{(13),(14)} that generates walking trajectories in response to predetermined rhythms. Assist is realized using a control flow in which the user's walking rhythm and stride, which are input to the generator, are modified (Fig. 3).

2.1. Mutual Adaptation of User and Device

When two people walk side by side, they may unconsciously adapt the cadence of their walks to each other. This is known to be a phenomenon of mutual adaptation in which the individual rhythms of the walkers mutually influence each other to create a new overall rhythm, and each individual is unconsciously entrained by this rhythm⁽¹⁵⁾. The assist method discussed here uses this phenomenon to entrain users' cadences into new rhythms that are produced as a result of mutual interaction between the user and the assistance.

Reflexive and periodic motions such as the gait of animals are believed to be controlled by rhythm pattern generators in the spine⁽¹³⁾. The rhythm pattern generator used in the assist device models these rhythm pattern generators, and generates assist patterns using reflexive, predetermined rhythms while adapting to the input user rhythm measured by the angular sensors. These rhythms synchronize with the user's walking, and change in accordance with the walk ratio control

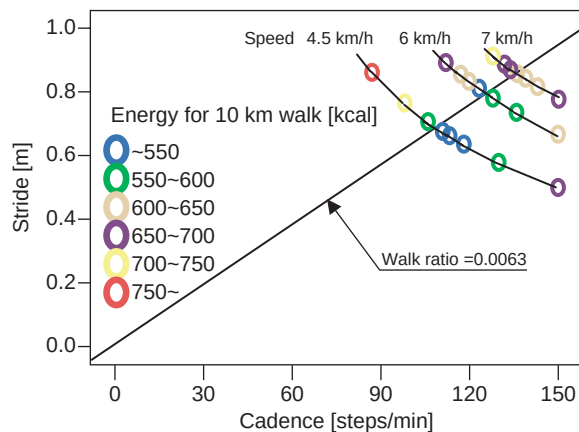


Fig. 1 Map of energy consumption by walk ratio

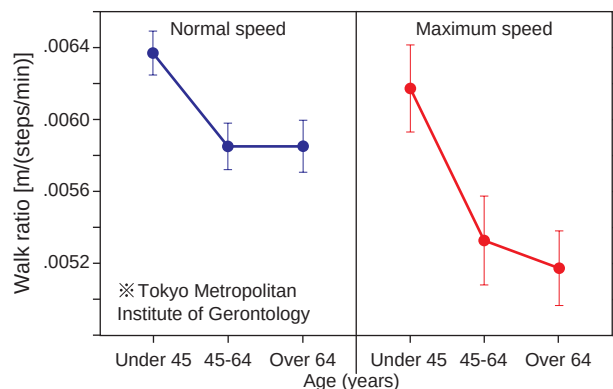


Fig. 2 Change in walk ratio with advancing age

to be discussed in the next section, enabling the device to induce a cadence in the user.

2.2. Walk Ratio Control

The rhythms generated by the rhythm pattern generator are produced by a pacemaker in the control computer. First, the walking rhythm of the user, as measured by the angular sensor, is input to the pacemaker. The pacemaker is entrained by this rhythm, and oscillates in synchrony with it. The phase difference between the rhythm produced by the pacemaker and the input rhythm is measured at this time. This phase difference is a result of mutual adaptation, and cannot be directly controlled⁽¹⁵⁾. For this reason, the phase difference is controlled by evaluating the measured phase difference and correcting the rhythm of the next step of the assist device. This corrected rhythm becomes the next rhythm of the pacemaker.

The device reads changes in the area in which the user

is walking as changes in the walk ratio. On flat ground and when climbing stairs or slopes, the phase of the device will be accelerated slightly beyond that of the user to give the user a sense of forward propulsion; when going down, the phase of the device is retarded by the application of brakes. In this way, the device induces cadences in the user. When the detected phase difference is retarded in relation to the ideal phase difference, the pacemaker will speed up the pace of the rhythm, and when the detected phase difference is advanced in relation to the ideal phase difference, it will reduce the pace of the rhythm⁽¹⁵⁾.

By establishing the appropriate phase difference, it is possible for users to excite their legs, while controlling their stride, using a minimal assist force that they are able to stop under their own power. A relatively large assist force is applied during the turn-over phase, when the leg starts moving forward or pushes off the ground, as if pushing a child on a swing. Other motions are left to inertia, reducing the amount of assist force required⁽⁴⁾⁻⁽⁶⁾.

The stride is determined by the relationship between the cadence as set by phase control and the ideal walk ratio, and is used to derive a target hip joint angle. At this time, the stride is adjusted to attempt to eliminate asymmetry between right and left. The rhythm pattern generator outputs torque to enable this hip joint angle to be realized by the thigh frame.

2.3. Assist for Supporting Leg

In order to facilitate displacement of the center of gravity by pushing the hips forward while supporting the body, the device synchronizes assist to extend the supporting leg to the rear and assist in swinging the idling leg forward. In a repeated cycle, the reaction force generated by this assist for the supporting leg advances the center of gravity^{(7),(16)}, the idling leg swings forward as if attempting to follow, and touches down on the ground.

The force generated by the assist is transmitted in sequence to the extremities, from the hip joint to the knees and ankles⁽¹⁷⁾, and indirectly assists in the flexion and extension of the knee. Tests showed that the provision of assistance to the hip joint of the supporting leg has the effect of maintaining the extension of the knee and keeping the knee from bending. Before the foot touches the ground, assist begins to increase to push the thigh to the rear, in order to help ensure that the knee is extended at the point at which the heel makes contact with the ground. After the foot touches the ground, the upper body is supported while the center of gravity is maintained in a high position with the knee extended, and the force that causes the upper body to topple forward is the propulsive force⁽¹⁸⁾. Even if the foot touches the ground with the knee bent, the extension of the knee is compensated for with assist that pushes the thigh to the rear. The main propulsive force is generated at the hip joint, where large

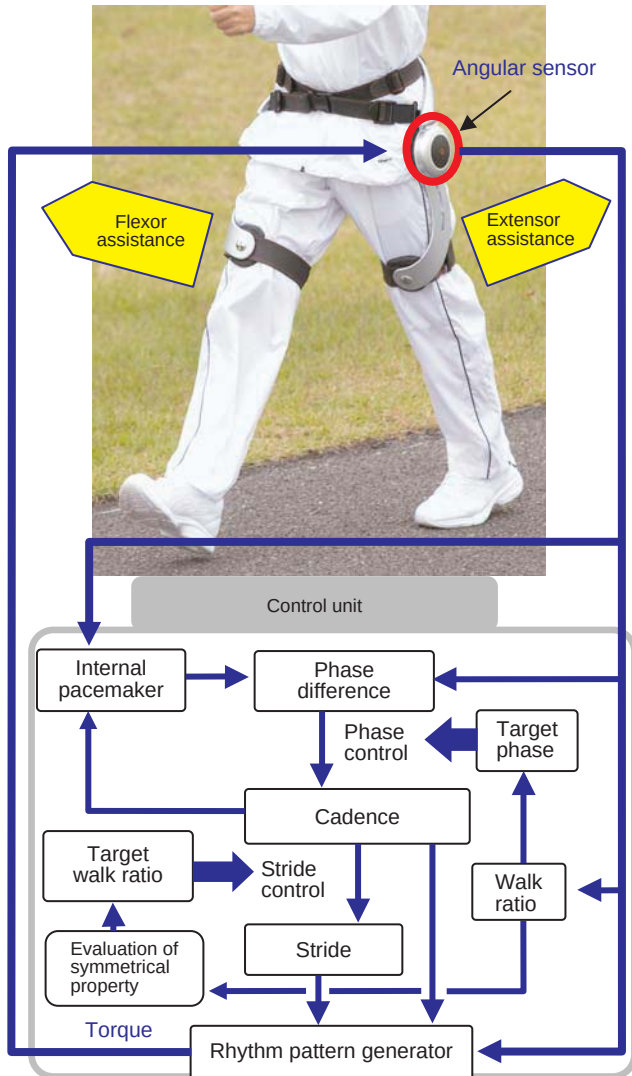


Fig. 3 Control flow for walking assist

muscles are concentrated, and is transmitted to the extremities^{(4)-(6),(17)}. The aim for this assist method was to show users this mode of walking with every form of assistance, and to enable them to learn the mode of walking through their own bodies⁽¹²⁾.

3. Assist Device

3.1. Mechanism

The assist device that implements this method of walking assist (Fig. 4) is made up of two actuators positioned on the axis of the hip joints (a), a lumbar frame that supports them (b), and a thigh frame that can be attached or disconnected with one touch (c)⁽¹⁹⁾. The actuators are connected to the lumbar frame by coupling joints that possess a degree of freedom in adduction and abduction⁽¹⁸⁾. Assist is provided for the flexion and extension of the thigh during walking by assist force transmitted from the actuators to the thigh frames.

The small, lightweight actuators (Fig. 5) are a combination of a multi-polar brushless motor and a planetary gear mechanism⁽¹⁹⁾. Low-profile actuators have been used in an attempt to ensure that they do not interfere with the wearer's arms or get caught on surrounding objects. Angular sensors in the actuators monitor the status of flexion and extension of the user's thighs⁽¹⁹⁾. Angular sensors are the only sensors employed.

The control circuits and batteries are located in the lumbar frame (Fig. 6). Table 1 shows the specifications of the device. The use of a mechanism that only assists

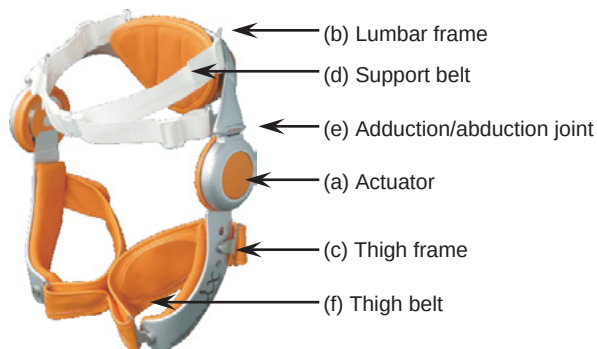


Fig. 4 Overview of walking assist device



Fig. 5 Low-profile actuator

Table 1 Key specifications of walking assist device

Size	3 sizes (small, medium, large) Distance between motors: (S) 312 mm; (M) 342 mm; (L) 372mm
Weight (kg)	2.8 (medium)
Drive system (motor/reduction ratio)	Brushless DC motor /10
Battery	Lithium-ion battery/ 22.2 V-1 Ah
Operating time per charge	2 hours (when walking at 4.5 km/hour)

the hip joint has enabled the total inertia on the legs with the device fitted to be reduced, and the weight of the device to be controlled to 2.8 kg.

3.2. Fitting

To fit the device, the lumbar frame is first fitted around the hips. The front support belt [(d) in Fig. 4] is fastened in place by a buckle at the base of the abdomen, and the thigh frames are fastened around the thighs by thigh belts [(f) in Fig. 4]. From considerations of ease of fitting and removing the device and of the possibility of the user sitting in a chair, and the like, the thigh frames only extend from the sides to the front of the thighs, and are fastened with a belt at the back of the thighs.

The upper belt passes over the pelvis, and keeps the lumbar frame from coming away from the body due to the reaction force to assist force. In order to maintain the transmission efficiency of the assist force, the lumbar frame, which supports the actuators, is highly rigid; cushioning has been used on the side that makes contact with the user's body. A front belt has been employed to ensure that the lumbar frame makes solid contact with the pelvis; the belt presses on a point 5 cm below the navel, increasing abdominal muscle pressure⁽²⁰⁾. The configuration here was modeled on the belt of a *hakama*. It has long been known that in addition to tilting the pelvis forward and stabilizing it, these belts guide the spine into the correct position, causing the weight of the upper body to ride on the pelvis, and directing it through the skeleton

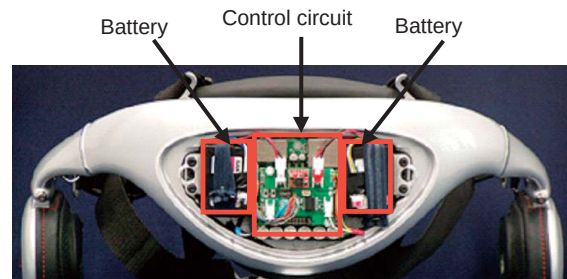


Fig. 6 Layout of control circuit and battery

to the surface of the ground. It was considered that by realizing these same functions in the harnesses of the assist device, it would be possible for assist to be provided after the user had adopted a comfortable posture in a standing position prior to going out walking.

To enable the device to be adapted to changes in the physique with advancing age and to different body types, the lumbar frames and thigh frames are available in small, medium, and large sizes; the type most suitable for the user's particular body type can therefore be selected from among nine variants. This enables the device to be used by 95% of Japanese adults⁽²¹⁾. Employing size adjustment mechanisms for each of the two frames would have made the configuration complex, and would also have added to the weight of the device. The nine variant sizes were adopted to avoid these issues.



Fig. 7 Design proposal



Fig. 8 Color variation model



Fig. 9 Walking assist device

3.3. Design

The design of the device focused on the theme of a “wearable man-machine interface,” and considered the feeling of integration between the user and the device to be the most important design factor. Use of the device in a variety of actual environments, including nursing homes and parks, was projected, and the ability of elderly users to easily fit the device themselves before going out was considered. The aim was for a simple and easy-to-understand design like a pair of headphones or a waist pouch (Figs. 7 through 9).

The basic layout employed was one in which the configuration of the buckles, waist belt and supporters enables the tightness of the lumbar frame to be adjusted at the lower abdomen⁽²⁰⁾ (Fig. 4).

People go out wearing clothes of a variety of forms and made of a variety of materials. There are also considerable differences in physique and body type between different individuals. In addition, different individuals display different levels of resistance to wearing this type of device close to their bodies. In order to minimize the discomfort experienced by these individuals and the physical and psychological lack of fit between themselves and the device, stylings were developed that would result in a greater level of harmony between the users and the use environments of the devices. Designers aimed for stylings that could be used irrespective of age or gender.

4. Verification Tests

Tests were conducted in which elderly subjects wore the assist device to enable verification of its short-term induction effects^{(11),(19),(22)} and its long-term induction effects^{(11),(19)} by studying changes in walking patterns and levels of muscle activity. These tests were approved by the Ethics Committee of the Tokyo Metropolitan Institute of Gerontology.

4.1. Verification of Short-term Effects

Ten elderly males with an average age of 76 ± 2 years were selected as test subjects. The changes in walking patterns and in muscle activity displayed by these subjects during a 50-minute period of walking on a treadmill at 4 km/h with and without the assist device were compared. Figure 10 presents a photograph of a subject wearing the assist device.

4.1.1. Verification of the device's ability to induce a walk ratio

Measurement of the test subjects' walk ratios prior to the tests revealed an average figure of approximately 0.005, and the walk ratios tended to be lower than the figure of 0.0063 discussed above. In order to verify the ability of the device to induce a walk ratio, irrespective of the differences in walk ratios between different

individuals, the initially-measured figure plus 0.0005 was made the target walk ratio for all subjects, and the walk ratio induction effect of the assist device was verified. As Fig. 11 shows, a walk ratio approaching the target ratio was achieved by 9 of the 10 test subjects.

4.1.2. Evaluation of muscle activity

In order to understand what type of effect walking assist has on muscle activity, positron emission tomography was used to measure the sugar metabolism due to muscle activity displayed by the test subjects following walking on the treadmill. This method enables the cumulative effect of muscle activity during walking to be studied even when the subject has ceased walking. The expected result here was that the walking assist would change the balance of the muscles used, and that muscle activity would increase in the muscles being assisted, the muscles close to the hip joints and around the hips.

Figure 12 shows an example of results for a representative test subject. The left and right sides of the figure respectively show visualizations of muscle activity with and without assist. The more intense the red color, the greater the level of muscle activity. Increased muscle

activity can be observed in the muscles of the buttocks, but muscle activity is reduced in the muscle group at the back of the thighs, which push the leg to the rear when it is acting as the supporting leg. It is believed that this is because the assist has reduced the burden on these muscles⁽¹¹⁾. The muscles of the buttocks have been indicated as providing support to enable the opposite side of the pelvis to the leg making contact with the ground not to sink, and it is believed that the muscle activity in these muscles increased in response to the increase in the length of the subject's stride⁽¹¹⁾.

4.2. Verification of Long-term Effects

Having verified the ability of the assist device to induce a walk ratio, 13 female test subjects with an average age of 78 ± 2 who had not taken part in the short-term study were selected for a five-month study. In this study, the test subjects would walk outside twice a week using the assist device for 30 or 40 minutes, depending on their physical condition (Fig. 13). The average walk ratio of the subjects was approximately 0.004 prior to the tests. The target walk ratio for each twice-weekly walking session was set at the initially-measured value plus 0.0005. The tests verified that there was a lasting induction effect from periodic application of the assist device.

4.2.1. Evaluation of walking

Figure 14 shows a comparison of results for stride, walking speed, and cadence measured before the commencement of the tests and after three months of regular walking using the assist device. The measurements were taken without using the assist device. Of the 13 test subjects, 11 increased their stride and 12 increased their walking speed, indicating that the assist induced lasting effects. However, because the test subjects' cadences, which should have become more relaxed with increased stride lengths, actually became faster, no increase in their walk ratios was observed. There was no major difference



Fig. 10 Experiment with elderly adult

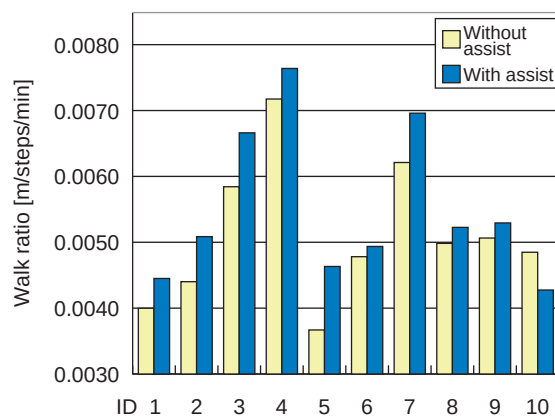


Fig. 11 Result for control of walk ratio

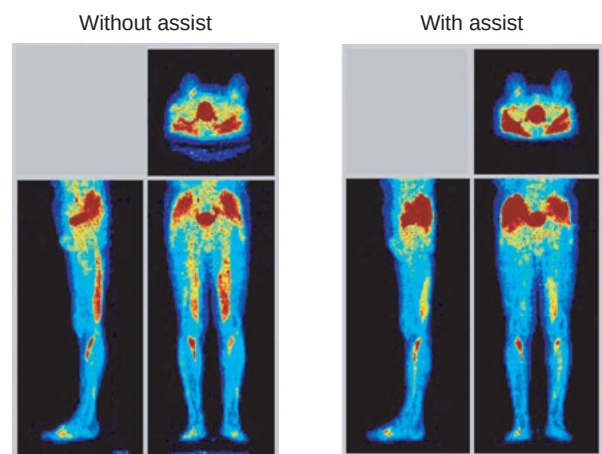


Fig. 12 Positron emission tomography muscular images



Fig. 13 Open-air long-term application for elderly subject

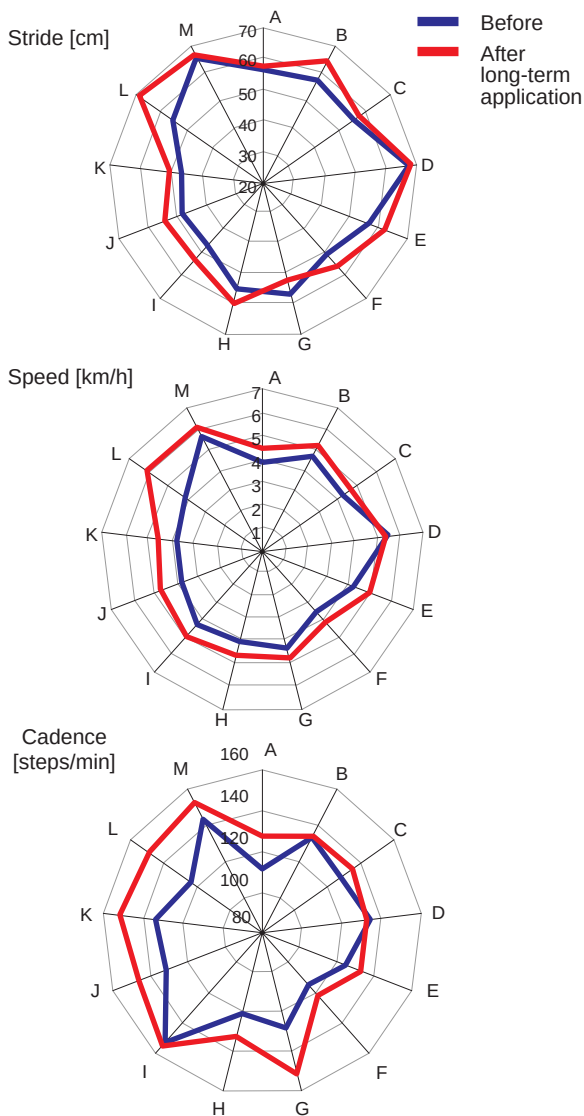


Fig. 14 Comparison of walking parameters before and after long-term application

between results after three months and results after five months⁽¹¹⁾.

Considering the changes over the course of the long-term tests, the increase in subjects' stride length was observable after only 1-2 tests, and no significant changes were observed following this⁽¹¹⁾. Considering this, the assist method can be indicated as having a nearly instantaneous effect.

4.2.2. Evaluation of muscle activity

Figure 15 shows a comparison of positron emission tomography results for a representative test subject before the commencement of the tests and after five months of regular walking using the assist device. The images of muscular activity were taken without using the assist device. It was believed that the increase in the subject's walking speed would result in an increase in activity in the muscles at the back of the thighs, which push the leg to the rear when it acts as the supporting leg, and in fact the actual results did display this tendency⁽¹¹⁾. It is thought that activity in these muscles facilitates the displacement of the center of gravity in a forward direction, and is linked to an extension of stride length and an increase in walking speed. A more detailed study of the rate of increase in activity of each muscle showed a 17% decrease in activity in the muscles at the front of the thighs that extend the knees and support the body. This is believed to be because the increased activity of the muscles at the back of the thighs reduced the burden on the knees⁽¹¹⁾. The pelvis tends to display a posterior inclination among the Japanese, and the muscular burden therefore tends to concentrate in the muscles at the front of the thighs⁽⁸⁾. These tests indicated that the assist device fulfilled its aim in enabling greater use of the muscles at the back of the thighs, and suggest that there is a possibility that it also promotes a more efficient balance of muscle activity⁽¹¹⁾.

By contrast with the results of the short-term study, activity in the muscles below the knees has increased, but this test subject walked from the beginning using these muscles. These muscles are known to be used when the area of the supporting leg below the knee moves to the rear, and the extension of the knee is maintained while

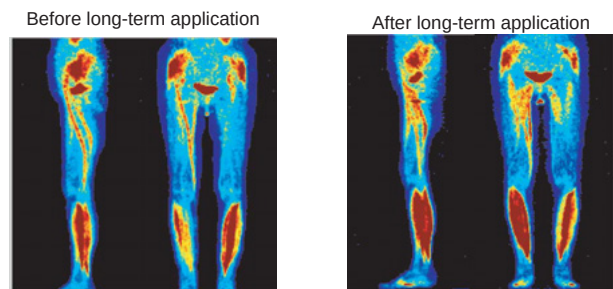


Fig. 15 PET comparison of muscular activity before and after long-term application

the thigh moves forward faster than the area below the knee⁽¹⁸⁾. It is believed that activity in these muscles for this test subject increased with increased activity in the muscles at the back of the thigh. The reduction in the activity of the muscles around the hips, which stabilize the pelvis when the leg is used as the supporting leg, is thought to be due to the length of time that each leg is used as the supporting leg becoming shorter with the increase in the subject's cadence.

4.2.3. Changes in energy consumption and heart rate per unit distance

Test subjects walked around an indoor course for 12 minutes without using the assist device to enable measurement of average energy consumption and heart rate per unit time. These figures were divided by the distance walked by the subjects to obtain average energy consumption and heart rate per unit distance. Figure 16 shows the rate of increase in average energy consumption and heart rate per unit distance from the period prior to the commencement of long-term application of the assist device. The figures were divided by the distance walked because the walking speeds of the test subjects differed before and after the long-term tests. A breathalyzer device was used to measure energy consumption.

Energy consumption naturally increased due to increased walking speed, but despite this, the subjects' average heart rate decreased by 7% after five months. Given that a reduction in the heart rate reflects a reduction in the burden on the heart, this indicates that the heart rate can be reduced despite an increase in the amount of exercise performed and the amount of energy consumed. This would enable the amount of exercise performed to be comfortably increased.

The phenomenon of a reduction in the heart rate despite an increase in the amount of exercise performed and the amount of energy consumed has already been reported⁽⁵⁾. This is believed to be because the promotion of muscle activity makes exercise easier and causes the muscles to act as secondary hearts in pumping blood, thus reducing the burden on the circulatory system⁽⁵⁾.

It has also been reported that in comparisons of the mode of exerting force during weight training, both heart rate and subjective exercise stress are lower when force

is exerted only during the turn-over phase, after which inertia is then relied on, rather than when force is exerted constantly from the beginning to the end of the exercise⁽⁴⁾⁻⁽⁶⁾. This is believed to be because when exercise is performed in this way, the duration of tonus is reduced, and the duration of relaxation is increased by the same amount⁽³⁾⁻⁽⁵⁾. The method of assist discussed here has the potential to produce the same results, and it will be necessary to conduct a more detailed study in the future using measurements of myoelectric potential, and the like.

4.2.4. Subjective comments

Test subjects commented that even when they were not wearing the assist device, "I feel more comfortable," "I feel happier," "Walking is enjoyable," "I can walk faster than before," and "I can walk for longer than I could before."

The reduction in heart rate reflects a reduction in the burden on the heart, a fact which backs up these comments. This suggests the value of the assist device as a tool to support self-reliance by enabling the amount of exercise performed to be comfortably increased and physical functions to be maintained or enhanced.

5. Conclusion

Of the various walking-related parameters, the walk ratio was selected as an indicator, and an assist method for the hip joints designed to facilitate and induce displacement of the center of gravity, along with an assist device based on this method, were developed. Short-term tests with elderly test subjects showed that when the device was worn, a walk ratio matching the target ratio was induced, and the burden on the muscles was reduced, verifying the assist effect. Tests involving periodic application of the device over a longer period confirmed that longer strides and faster walking speeds were maintained even when the device was not being worn. Activity in the muscles that move the thigh to the rear tended to be increased in these subjects, while some activity in the muscles that support the knees was reduced, indicating that the assist device also tended to enhance the balance of muscle activity. A comparison of measurements taken following the long-term tests with measurements taken at the commencement of the tests showed that subjects' heart rates had declined despite an increase in the amount of exercise performed, and this phenomenon correlated with a reduction in their level of subjective exercise stress.

6. Afterword

One of the major characteristics of the assist method discussed in this paper is the mutual adaptation of user and device, based on the human ability to learn motions. As an extension of this, the device can be expected to be

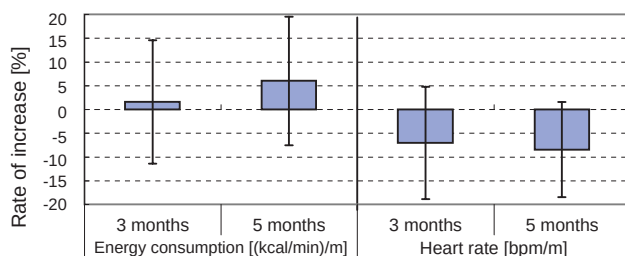


Fig. 16 Rate of increase in energy consumption and heart rate

useful in the case of patients who are experiencing difficulty in walking due to spinal cord injuries or cerebral disorders such as strokes or Parkinson's disease. At present, the value of the device in these cases is being tested in a number of rehabilitation facilities. In the future, it will be necessary to not merely study the effect of the method on muscle activity, but also on posture and on the reorganization of the brain and central nervous systems in cases of impaired walking.

The assist device was exhibited at the International Home Care & Rehabilitation Exhibition in 2007, and has been exhibited at a number of domestic exhibitions, including Barrier-Free 2008 and Welfare 2008.

Acknowledgments

Up to the present, this project has received the generous cooperation of numerous individuals, including test subjects and individuals who provided valuable comments on the device at exhibitions. The authors wish to offer all of these individuals their sincere thanks.

Associate Professor Yoshihiro Miyake of the Interdisciplinary Graduate School of Science & Engineering of the Tokyo Institute of Technology provided valuable guidance in the area of control systems that move the assist device in the same time-scale as that of a human being, taking into consideration the mutual interaction between the device and users. Guidance was also offered by numerous specialists affiliated with Wacoal Holding Corp.'s Human Science Research Laboratory, The Tokyo Metropolitan Institute of Gerontology, and the Rosai Rehabilitation Engineering Center affiliated with Chubu Rosai Hospital. The authors wish to take this opportunity to express their gratitude.

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Enhancement of Diesel Combustion Noise for Interior Sound Quality

– Transfer Path Analysis Using Principal Component Regression Method –

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ABSTRACT

An analysis focusing on the transfer paths of combustion noise from the engine to the interior of the cabin was conducted in order to enable enhancement of audible in-cabin diesel combustion noise during the development of the 2009 model year ACCORD diesel. Transfer path analysis using the principal component regression method was employed to analyze the degree of contribution to noise transfer. First, the airborne and structure-borne contribution for 920-2300 Hz radiation noise, which represents an issue from the perspective of combustion noise, was analyzed. Following this, the input paths for the structure-borne component were determined. As a result, it was judged that despite the fact that airborne transfer has been regarded as the major factor in the case of the high-frequency band, the structure-borne component also has a profound effect. Methods of enhancing interior sound were examined based on the results of the contribution analysis. Reducing the transferred components by controlling vibration in the mounts has enabled enhancement of combustion noise in the cabin.

1. Introduction

Today, diesel engines for use in passenger vehicles are necessary to produce high power, display high fuel efficiency, and conform to stringent exhaust gas regulations. From the perspective of the commercial appeal of the vehicles in which the engines are fitted, low noise and measures for the enhancement of interior sound quality represent further necessities.

In diesel engines, the noise with the greatest effect on interior sound quality is diesel combustion noise (“combustion noise” below) originating in combustion excitation force. Conventionally, combustion tuning by means of using a pilot injection and a main injection in order to reduce the combustion excitation force has been the main method of enhancing combustion noise. However, the enhancement of noise by means of combustion tuning is antagonistic to the achievement of increased fuel efficiency and reduced exhaust gas emissions, and the margin for the use of this method in reducing noise is declining with increasing demands from the market for enhanced fuel efficiency and conformity with more stringent emissions regulations.

In order to determine measures for the enhancement

of interior sound quality that do not rely on combustion tuning, the research discussed in this paper focused on measures targeting the transfer paths of noise. The project applied the principal component regression method to transfer path analysis⁽¹⁾ (a method that is termed “PCR-TPA” below). The results showed the structure of the engine mounts in the transfer path to be a major factor in the transmission of engine noise, and that the control of vibration in the mounts has enhanced combustion noise.

2. Nature and Characteristics of Combustion Noise, and Countermeasures Instituted to Date

In the vehicle interior, combustion noise generates rattling and clinking noises of fluctuating intensity. The range and level of these sounds varies with variations in the engine speed and load and the temperature of oil and intake air.

Figure 1 shows the results of an analysis of interior sound quality. The graph shows a comparison of interior sound quality with higher and lower level of combustion noise in a completed vehicle.

The vertical axis of Fig. 1 shows fluctuation intensity,

* Automobile R&D Center

an index of sound quality formulated and quantified by Honda^{(2),(3)}, while the horizontal axis shows the auditory critical band⁽³⁾.

Figure 1 shows that combustion noise is a noise that is generated within the high-frequency band between 920 and 2300 Hz (in this paper, 920 Hz and above will be termed “high-frequency”).

Conventionally, the use of sound insulating materials and acoustic insulators to dampen airborne transfer of noise has been the main method of reducing high-frequency interior noise. This is because it has been considered that, at frequencies of over 1 kHz, the higher the frequency becomes, the lower the effect of structure-borne transfer that is due to the mutual effect of declining body sensitivity and declining amplitude of vibration. Insulating materials and acoustic insulators have therefore been employed during development as an effective countermeasure against noise.

However, there have been cases during vehicle development in which the use of additional insulating materials and acoustic insulators has not resulted in an enhancement satisfying interior sound quality requirements. Recognizing the necessity for a thorough analysis of the input paths for combustion noise to the vehicle interior, the project discussed in this paper therefore set out to conduct analyses using PCR-TPA.

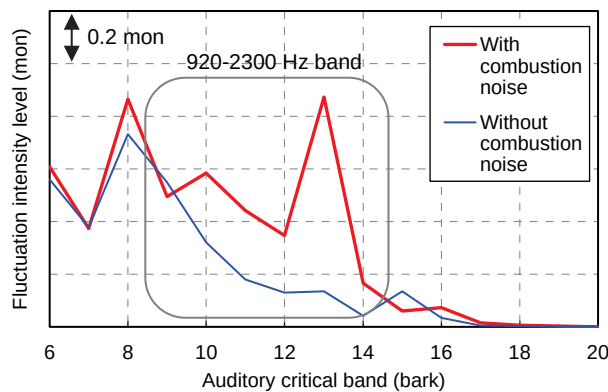


Fig. 1 Interior sound quality

3. Vehicle Interior Sound Analysis using PCR-TPA

3.1. Characteristics and Measurement Method of PCR-TPA

To date, a number of methods have been proposed for use in the analytic technique of transfer path analysis. The majority of these proposed methods have involved simultaneous measurements of structure-borne and airborne noise components in an operating vehicle. However, the separation of these components represents a challenge. When the sound pressure signal at a single

point between the engine and the vehicle body is used as a reference to enable determination of the effect of the engine radiation noise (the acoustic excitation force) on the vehicle body (the structure), even when the sound pressure signals at the reference point are identical, the excitation force transmitted to the structure can differ as a result of differences in the direction of the sound waves or the magnitude of the sound source. In such cases, the inability to accurately understand the effect of the excitation force can prevent the calculation of an accurate transfer function from the sound pressure signal at the reference point and the interior sound at the response point. Impact tests using dummy sound sources have generally been employed in order to address this issue. When researchers wish to conduct high-precision measurements of the structure-borne and airborne components of interior sound, it is necessary to utilize both impact tests and actual running tests, and this can be impractical.

PCR-TPA has been proposed⁽¹⁾ as a method of separating and analyzing components when vibration and noise have been measured simultaneously in vehicle tests. The present project employed PCR-TPA, considering that its use in contribution analyses would enable the accurate separation of airborne and structure-borne components, and the consequent clarification of the input paths of combustion noise to the vehicle interior. (Contribution analysis is a method in which the ratios of the airborne and structure-borne components of interior sound obtained through transfer path analysis are calculated.)

Measurements were conducted in a 2008 model year Accord, a 4-door sedan fitted with an inline 4-cylinder diesel engine. With regard to data measurement points, considering both solid transfer paths for excitation force and airborne transfer paths for acoustic excitation force, reference points for vibration and sound were established in the pathways shown in Fig. 2; a dummy head microphone was positioned in the front passenger seat,

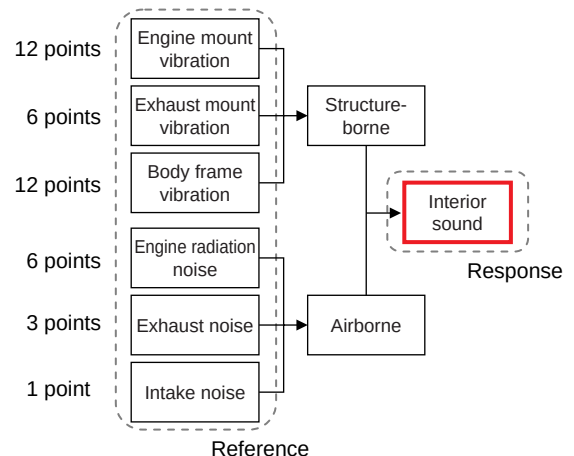


Fig. 2 Measurement setup for PCR-TPA

and response points were located at the left and right ears of the dummy. The vehicle was placed in a test jig, and simultaneous measurements were conducted at all reference and response points while the engine load conditions were varied.

Combustion varies with variations in load and temperature conditions in diesel engines, and these variations produce variations in sound quality. In order to study sound quality in relation to all these variations, the present project conducted analyses both during and after warm-up. Here, an engine water temperature of 60°C is the starting condition for measurements “during warm-up,” and an engine water temperature of 80-85°C is the starting condition for measurements “post-warm-up.”

3.2. Airborne and Structure-borne Components

Figure 3 shows the results of separation of the airborne and structure-borne components of synthesized post-warm-up vehicle interior sound using PCR-TPA.

The results show that the contribution of the structure-borne component is high for noise in the 920-2300 Hz band, the combustion noise range.

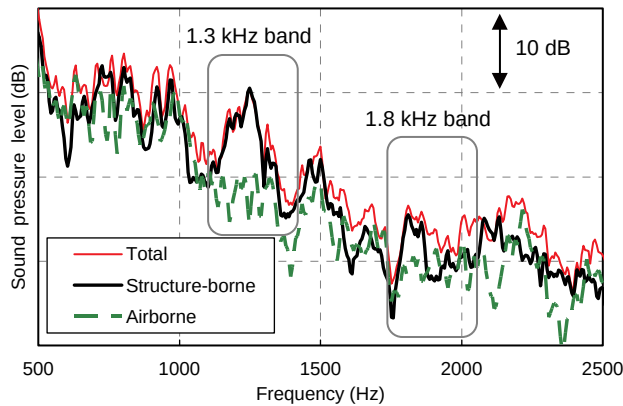


Fig. 3 Comparison of structure-borne and airborne contribution for in-cabin noise

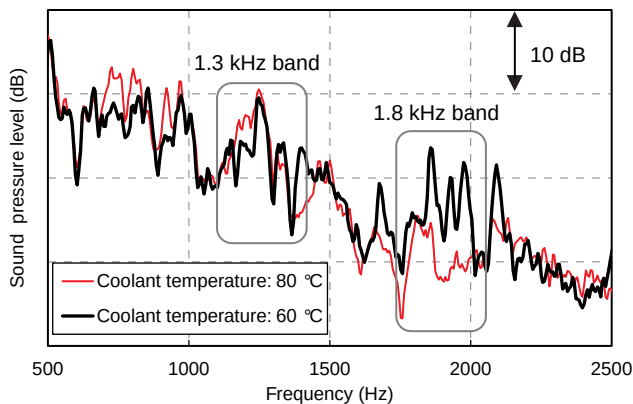


Fig. 4 Comparison of structure-borne noise by engine cooling water temperature

The contribution of the structure-borne component is particularly high in the 1.3 kHz and 1.8 kHz bands. As Fig. 4 shows, there is a significant change in the sound pressure level from warm-up to post-warm-up in the 1.8 kHz band.

3.3. Identification of Vibration Input Pathways

The results of the analysis of transfer paths indicated that the transmission mounts (Tr-Mt) and the upper torque rod mounts (Up-Mt) displayed the highest contribution of all the engine mounts (“Mt” below). The results also showed that there was a change in the noise transmission level from warm-up to post-warm-up for the Up-Mt. Figures 5 and 6 respectively compare the structure-borne component of the Tr-Mt and the structure-borne component of the Up-Mt with the total structure-borne component of interior sound.

Within the 1.3 kHz band, there is a range in which the contribution of the structure-borne component of the Tr-Mt is high, and which has a significant effect on interior sound. The level of input from the Tr-Mt changes only minimally from warm-up to post-warm-up.

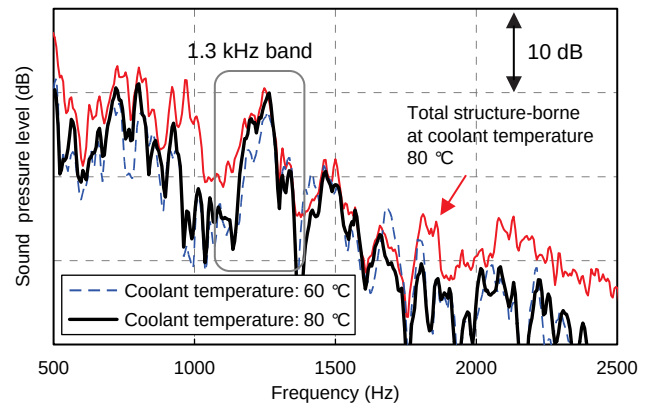


Fig. 5 Tr-Mt contribution to structure-borne noise

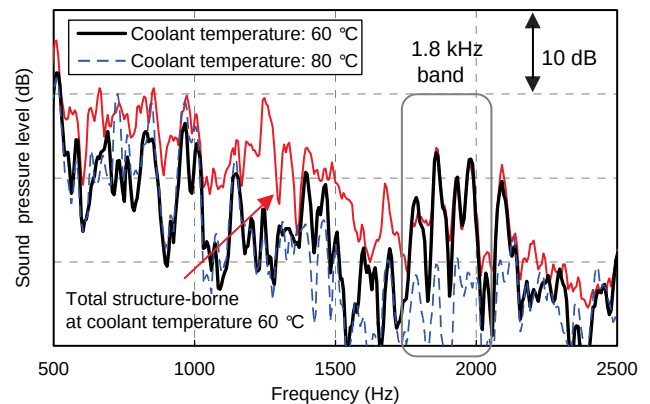


Fig. 6 Up-Mt contribution to structure-borne noise

Within the 1.8 kHz band, there is a range in which the contribution of the structure-borne component of the Up-Mt is high, and which has an effect on interior sound during warm-up. A change is observable in the level of the structure-borne component from the Up-Mt between warm-up and post-warm-up.

The reason for this change in the level from the Up-Mt is believed to be the fact that the high-frequency component of combustion, which is the excitation force, changes between warm-up and post-warm-up. Because the characteristics of the transfer paths that are affected by this change in the high-frequency excitation force have not been clarified previously, effective countermeasures for combustion noise within the transfer paths have not been implemented. The analysis discussed here indicated the existence of a structure-borne component in the high-frequency component of interior sound, identified the transfer paths, and indicated that the structure-borne transfer paths change with changes in combustion. These results enabled the study of effective countermeasures against noise in the transfer paths. The project went on to study methods of reducing combustion noise via countermeasures introduced into the transfer paths.

4. Study of Methods for Reduction of Vibration Input and Enhancement of Sound in Completed Vehicle

4.1. Measurements of Reductions in Interior Noise

The transmitted noise components obtained via PCR-TPA were resynthesized as interior sound after changes were made to the characteristics of each transfer path, and the resynthesized sound was evaluated by means of listening tests and sound quality analysis in order to enable the formulation of targets for interior sound.

Figure 7 shows a comparison of the results of sound quality analysis of interior sound measured in an actual vehicle and the interior sound obtained from resynthesizing components. The results for the resynthesized sound were obtained after changing the 1.3 kHz band of Tr-Mt vibration.

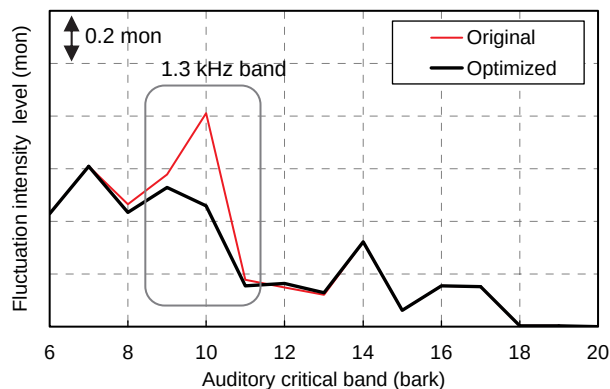


Fig. 7 Target value for optimized interior sound

The results indicated that changing Mt vibration changes the quality of combustion noise, and clarified the level of reduction that could be made a target. The level of reduction for the Up-Mt was clarified in the same way.

4.2. Reduction of the Structure-borne Component for the Mount Brackets

Analyses indicated that the forms of the Tr-Mt and Up-Mt engine mount brackets ("BRKT" below) were factors in the change in vibration within the transfer paths.

Chiefly due to the dynamic characteristics resulting from their form, the BRKT increase and decrease vibration input from the engine. Research was conducted on a method of using this characteristic in order to enhance interior sound quality by reducing vibration in the high-frequency range.

Figures 8 and 9 respectively show the Tr-Mt and the Up-Mt.

It was determined that the BRKT resonated with the frequencies that represented the issue. The following modes were identified:

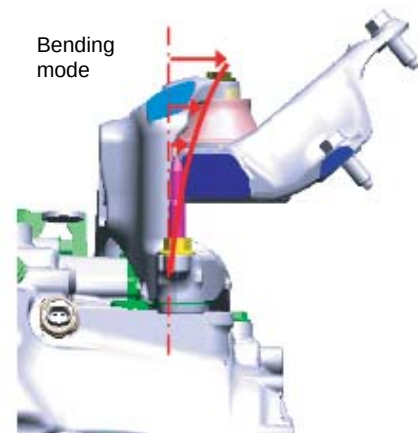


Fig. 8 Tr-Mt

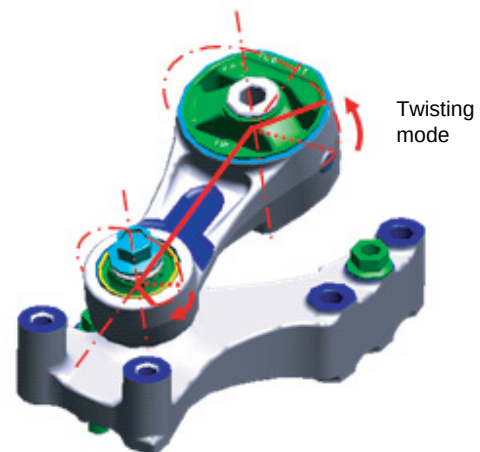


Fig. 9 Up-Mt

- (1) 1.3 kHz band: Tr-Mt BRKT right-left bending mode
- (2) 1.8 kHz band: Up-Mt BRKT twisting mode

Having identified the modes representing the major factors, measures to control vibration in each BRKT were applied in order to reduce response.

Figures 10 and 11 respectively show the results of the use of PCR-TPA to separate the structure-borne components of interior sound transmitted from the Tr-Mt and the Up-Mt before and after the application of countermeasures. Figure 10 shows results post-warm-up, while Fig. 11 shows results during warm-up.

The following enhancements in the structure-borne component of interior sound from each Mt were obtained:

- (1) The 1.3 kHz-band structure-borne component from the Tr-Mt was reduced by approximately 15 dB
- (2) The 1.8 kHz-band structure-borne component from the Up-Mt was reduced by approximately 10 dB

4.3. Verification of Enhancement in Completed Vehicle

As a final verification of the effectiveness of the countermeasures in enhancing sound quality, interior

sound measurements were conducted in completed vehicles with and without the application of the countermeasures.

Figure 12 shows the results of these measurements of combustion noise in the vehicle interior. The measurements shown in Fig. 12 were taken during warm-up.

Control of the vibration of the engine Mt BRKT, the transfer path, resulted in an enhancement in the fluctuation intensity of combustion noise in the vehicle interior in the 920-2300 Hz band. The reductions were particularly significant in the 1.3 kHz band (10-11 Bark) and the 1.8 kHz band (13 Bark). The application of the countermeasures resulted in the reduction of structure-borne components between 920 and 2300 Hz, the range in which combustion noise is audible in the vehicle interior, and enhanced the comfort of the vehicle interior.

These results have demonstrated that the control of structure-borne components is an effective means of enhancing combustion noise.

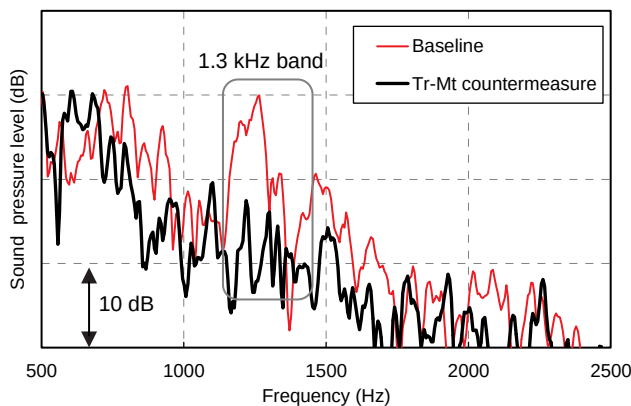


Fig. 10 Effect of Tr-Mt countermeasure on Tr-Mt's structure-borne contribution to interior sound

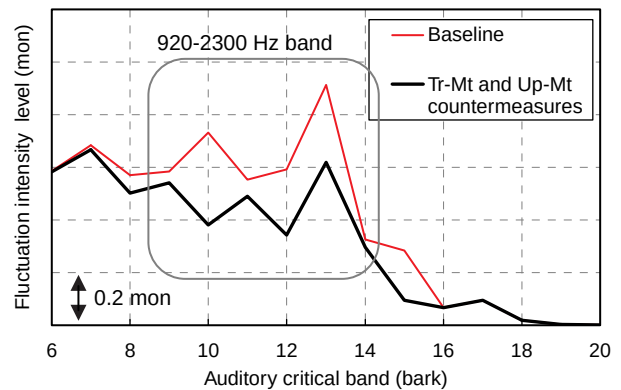


Fig. 12 Results of analysis of interior sound

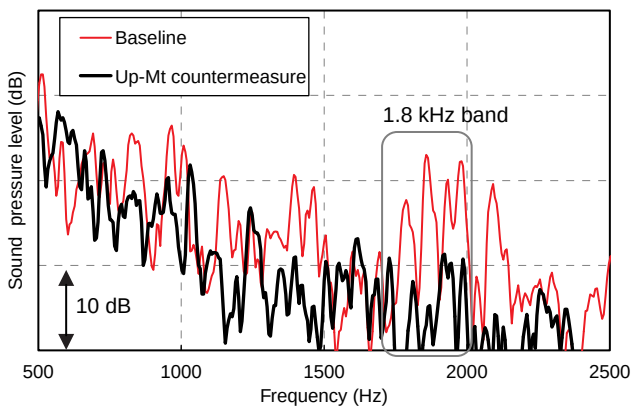


Fig. 11 Effect of Up-Mt countermeasure on Up-Mt's structure-borne contribution to interior sound

5. Conclusion

The following results were obtained from the application of transfer path analysis:

- (1) The study indicated that in addition to airborne components, structure-borne components also have an effect on the diesel combustion noise audible in the vehicle interior.
- (2) Control of the vibration of the engine mounts reduced the level of the structure-borne component, and enhanced the comfort of the vehicle interior in terms of combustion noise.
- (3) The study indicated that PCR-TPA is an effective method of analyzing combustion noise.

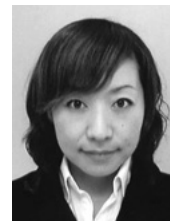
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Heat Recovery Technology of Automobile Using Thermoelectric Element and Its Effect on Fuel Economy

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ABSTRACT

Prior to the development of a heat recovery system using thermoelectric elements for automobile exhaust heat energy, simulation methods were developed to understand the current technical level and extract issues as well as key technologies.

Generated power not only has a positive effect on automobile fuel economy, but there are also the negative effects of increased weight and backpressure. Effects of fuel economy making full use of thermoelectric technology lie in optimum balance of these factors. Thus, guidelines for optimizing this balance were also developed.

The results showed that heat recovery using existing thermoelectric elements is nearly unable to enhance fuel economy. Elements that exhibit good performance within the temperature range of 100°C to 350°C should be employed, and development of new elements is found to be the key. Furthermore, investigations also showed that a heat recovery system provides approximately twice the fuel economy effects when the engine is operated at constant speed such as in a series hybrid, compared to an ordinary car. These findings provided the outlook that the combination of developing new elements, selecting the optimal car type, insulating the exhaust system, and adopting other technologies leads to enhance fuel economy by 3% or more compared to conventional levels.

1. Introduction

Technology for enhancing automobile fuel economy has become particularly important in recent years, and various heat recovery technologies are being developed. Of these, thermoelectric technology is gaining attention as a means of automobile heat recovery having a simple structure with no dynamic elements and ability to convert heat directly into valuable electrical energy⁽¹⁾.

However, while studies of automobile heat recovery have focused on the generated power^{(2),(3)}, or have taken into account only the generated power when evaluating fuel economy⁽⁴⁾, no studies so far have focused on realistic automobile fuel economy that accurately includes the negative effects of thermoelectric devices. Thus, at present the concrete steps needed to make thermoelectric technology a valuable means of enhancing automobile fuel economy have not yet been clarified.

Therefore, simulation technology focusing on fuel economy along with guidelines for determining optimal specifications were developed, and fuel economy effects

and development issues were clarified⁽⁵⁾.

This paper presents an overview of the simulations, and introduces issues for heat recovery using thermoelectric technology as well as concepts for making it a valuable technology.

2. Fuel Economy Simulations

Figure 1 shows a schematic diagram of the system used to perform the simulations. This thermoelectric power generation system uses the automobile exhaust gas as the heat source and automobile coolant as the cooling source. The effect on fuel economy assumes that fuel economy is enhanced by using the generated power to reduce the automobile generator load, which reduces the engine load. In addition, the effects of increased backpressure and weight due to system installation were also taken into account when calculating the automobile fuel economy effects. Table 1 shows the preconditions adopted for the simulation.

Figure 2 shows the simulation flow.

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Table 1 Preconditions adopted for simulation

Precondition factors		Adopted precondition
Target of exhaust condition to be optimized		Average mass flow and temperature in US combined driving cycle
Evaluated vehicle	Type and engine displacement	STREAM 2.0L
System configuration	Heating source	Exhaust gas
	Cooling source	Coolant (90°C:3L/min. constant)
	Efficiency of voltage converter	85% constant
Heat exchanger	Sectional area of exhaust path	Equivalent to sectional area of exhaust pipe
	Fin volume	10% relative to exhaust path
	Fin material	Exhaust: SUS Coolant: Copper
Thermoelectric unit	Sectional dimensions of element	5 mm × 5 mm
	Gap between elements	1 mm
	Electrode size and material	5 mm × 11 mm × 0.5 mm Copper
	Module efficiency	45% constant

- (1) Prior to evaluation, the automobile operating condition, to which the thermoelectric system is to be optimized, is defined.
- (2) Heat exchanger simulations were performed. The heat flux density per unit temperature difference and pressure loss generated by the heat exchanger are affected by the heat exchanger size and fin specifications. The effect of these specifications on the heat flux density was calculated using 3-dimensional CFD. The optimal heat exchanger specifications for fuel economy cannot be determined at this stage, so the characteristics were mapped without determining specifications.
- (3) To obtain output power effectively from the thermoelectric elements, the thermoelectric elements are connected in series to make a thermoelectric module, but this results in some loss. The loss to be taken into account when calculating the output power was clarified by actually assembling the thermoelectric elements into a module and measuring the output power.
- (4) The thermoelectric module output power was simulated. The element thickness dimension was optimized to maximize the output power for the heat conditions provided from the heat exchanger. The heat conditions

differ for each set of heat exchanger characteristics investigated in step (2), so the output power characteristics were mapped with the thickness dimension optimized for all specifications. The loss investigated in step (3) was also taken into account at this time.

- (5) To effectively utilize the power output from the thermoelectric module, electric power should be supplied at the voltage required by the car. Therefore, the DC-DC conversion loss was measured using an actual conversion circuit to clarify the loss to be taken into account in fuel economy calculations.
- (6) The fuel economy enhancement effects of supplying electric power to the car and the increase in fuel consumption due to backpressure were measured using an actual car to clarify the sensitivity of each factor to fuel economy.
- (7) The information obtained from the above investigations was reflected to the existing fuel economy simulation code so that all factors affecting fuel economy were taken into account. This enabled the optimum specifications

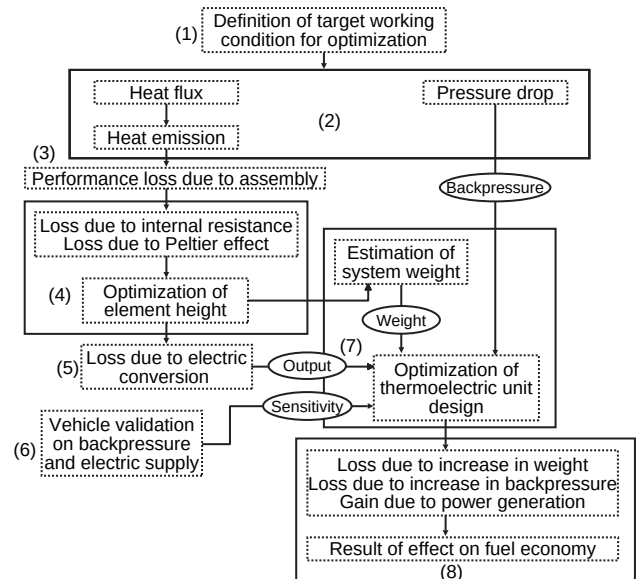


Fig. 2 Flow and factors considered in simulation

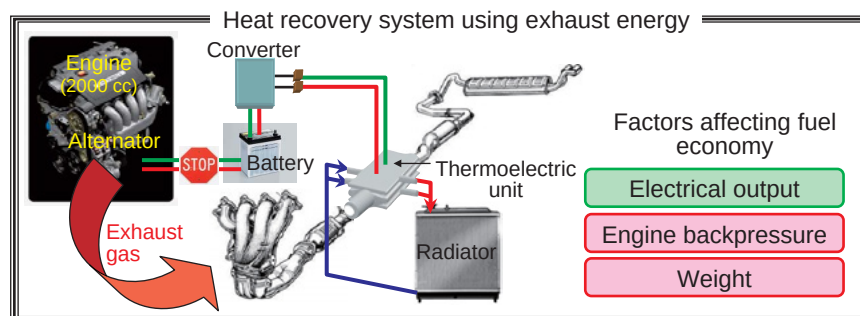


Fig. 1 General configuration of heat recovery system

Table 2 Effect of unrestrained specifications on factors affecting fuel economy

○: Has effect ×: No effect

Unrestrained specifications		Elements affecting fuel economy		
		Engine backpressure	Generated power	System weight
Heat exchanger	Fin pitch and thickness	○	○	×
Thermoelectric unit	Number of elements	○	○	○
	Element thickness	×	○	○

exhibiting the maximum fuel economy effects under the targeted operating condition to be determined.

- (8) The fuel economy effects for various driving cycles were calculated using the determined optimum specifications, and the effects of thermoelectric technology to enhance automobile fuel economy were clarified.

As mentioned previously, automobile fuel economy is calculated according to the three factors of power generated by the thermoelectric elements, exhaust pressure loss, and system weight. Table 2 summarizes the specifications that can be varied in the simulations, and their effects on each factor.

Each specification is affecting multiple factors determining fuel economy effect, and consequently, cannot be optimized one by one in any particular order. Therefore, it is necessary to map the effects on each factor without predetermining any specification. The constructed map is used to calculate the fuel economy effects for all combinations of specifications, and the optimum specifications are determined by finding the combination that provides the greatest fuel economy effects.

First, the heat exchanger, which affects the pressure loss factor, was mapped. The heat flux performance of the heat exchanger is determined by the exhaust pressure loss (fin thickness and pitch) and the number of elements

(dimensions of heat exchange area). Figure 3 shows a map of the heat exchanger performance simulation results using CFD. This shows that allowing an increase in exhaust pressure loss enhances heat flux performance, but this eventually reaches an equilibrium state. In addition, increasing the number of elements tends to lower the heat flux per unit area.

Next, thermoelectric performance, which affects the output power factor, was mapped. Output power performance is determined by the temperature difference and internal resistance occurring in the thermoelectric elements. The important point here is the element thickness. Increasing the element thickness increases the temperature difference of the thermoelectric elements, which produces greater electromotive force, but at the same time the internal resistance also increases, which is a factor reducing the output power that can be obtained from the elements. There is an optimum thickness for each heat exchanger specification, and Fig. 4 shows a map of output power performance with the element thickness set to the optimum value for each heat exchanger specification.

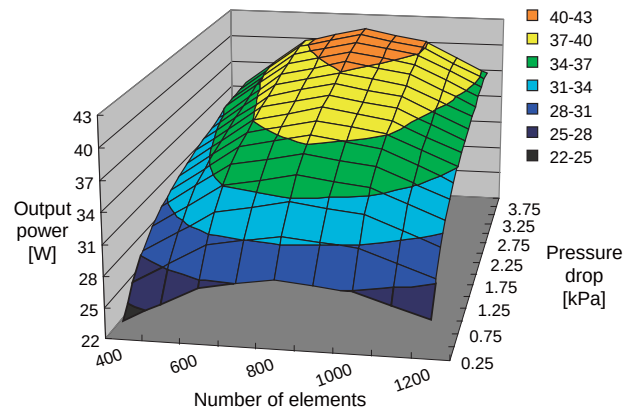


Fig. 4 Performance map of thermoelectric unit

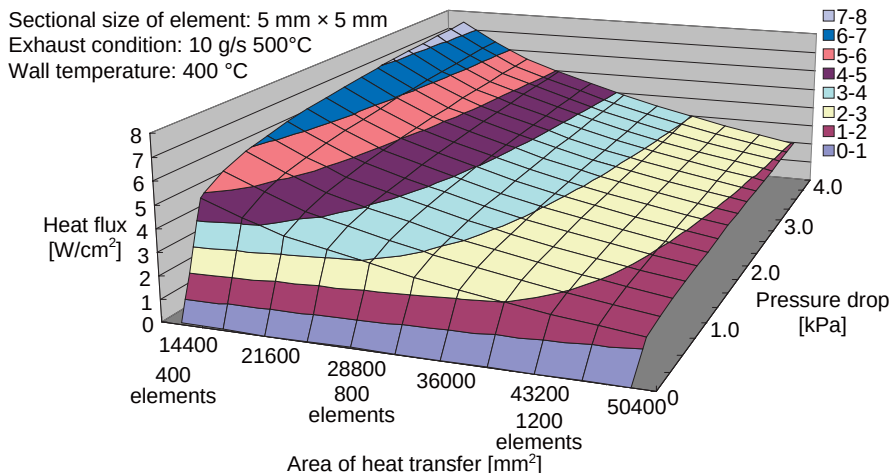


Fig. 3 Performance map of heat exchanger

There is also an optimum value for the number of thermoelectric elements. Increasing the number of thermoelectric elements has effects to increase the electromotive force. However, the heat flux supplied per unit area falls due to the heat exchanger characteristics, so the rate of increase in the electromotive force slows as the number of elements increases. On the other hand, the internal resistance continues to increase proportionally to the number of elements, so an optimal solution exists at the balance between the positive effect of a rise in electromotive force and the negative effect of increased internal resistance. In addition, from the viewpoint of pressure loss, fining off the fin tends to increase the output power. However, this rate of increase tends to slow as the pressure loss increases.

Finally, the system weight, which affects the weight factor, was mapped. The system weight is determined by the number and thickness of the elements, the weight of the heat exchanger needed for the number of elements, and the weight of the power conversion unit, piping and coolant, and other items. Figure 5 shows the system weight according to number and thickness of

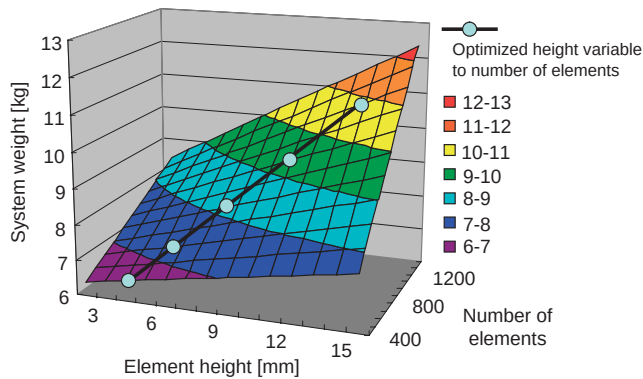


Fig. 5 Weight map of heat recovery system

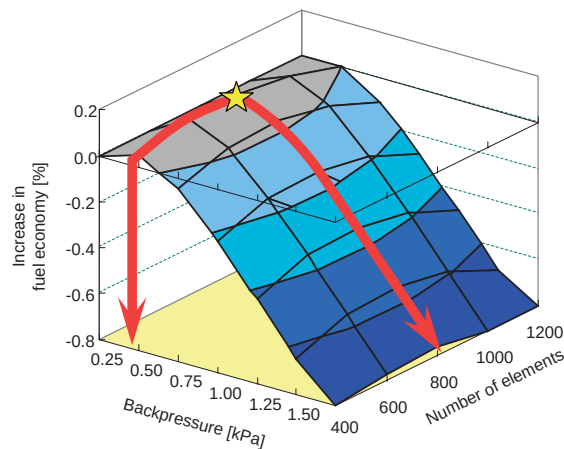


Fig. 6 Effect on fuel economy at target exhaust condition under various specifications

Table 3 Optimized specifications of thermoelectric unit

Hot side heat exchanger	Sectional size: 7 mm x 294 mm Fin specifications Fin thickness: 0.175 mm Fin pitch: 0.88 mm
Cold side heat exchanger	Sectional size: 2.5 mm x 294 mm x 2 paths Fin specifications Fin thickness: 0.03 mm Fin pitch: 0.2 mm
Element size	5 mm x 5 mm x 8.6 mm x 800 pieces
Unit weight	4.2 kg
System weight	8.3 kg

Table 4 Effect of thermoelectric generator on fuel economy

	Increase in fuel economy	Reduction of CO ₂ per km
	%	g/km
LA4	0.13	0.2
HWY	0.36	0.42
SC03	0.15	0.24
US06	0.08	0.14

thermoelectric elements. The system weight increases together with both the element thickness and the number of elements.

Mapping the heat exchanger performance, thermoelectric output power performance and system weight without predetermining any specification enabled the fuel economy effects of optional combinations of the three fuel economy factors of pressure loss, output power and weight to be verified. Figure 6 shows the results of calculating the fuel economy effects for various specification combinations under the average exhaust gas conditions in the U.S. combined cycle. These results show that there is an optimal value for pressure loss. This is because when the fin pitch and thickness is too large, heat cannot be recovered, so sufficient power cannot be generated. Conversely, when the fin pitch and thickness are too small, the backpressure rises, and the resulting drop in engine efficiency exceeds the effect of generated power. Likewise, there are also optimal specifications for the number of elements. Table 3 shows the optimized specifications. The system weight is 8.3 kg, which makes it a compact device suitable for installation in a car. Table 4 shows the results of calculating the fuel economy effects when a thermoelectric power generation system with the optimized specifications is applied to various driving cycles. This shows that while good installation capability in a car can be expected, heat recovery using current thermoelectric technology provides almost no fuel economy effects.

3. Loss Analysis based on Energy Balance

Figure 7 shows the energy balance in the LA4 driving cycle.

First, the conversion efficiency of the elements is low [Fig. 7 (6)]. Figure 8 shows the temperature characteristics of the elements used in this study, as well as the element temperatures used in the driving cycle. This shows that the elements are used in a temperature range lower than that which yields the maximum element performance. This is because as shown in Fig. 6, when the heat exchanger fin pitch and thickness is reduced to increase the element temperature, the thermoelectric unit power output increases, but the exhaust pressure loss rises by even more, with the result that fuel economy is not enhanced. Elements that exhibit sufficient performance between 100°C and 350°C are needed, but elements that can secure performance in

that temperature range do not currently exist. Therefore, the development of elements suited to this lower temperature range is the key to automobile heat recovery.

In addition, experiments conducted separately from this simulation showed that element damage occurring when joining the elements also accounts for a large part of the loss. Elements are joined together into a thermoelectric module by brazing. However, diffusion of the brazing materials onto the elements, vaporization of components during brazing, and other factors reduce element performance by approximately 45%, so preventing these is effective [Fig. 7 (7)]. Furthermore, measurements of exhaust system temperatures in an actual car showed that approximately 18% of the energy is lost due to heat radiation before reaching the thermoelectric unit, so countermeasures to help prevent this are also thought to be effective [Fig. 7 (1)].

4. Concepts for Further Increasing Fuel Economy Effects

The previous section presented locations to be modified from the viewpoint of energy balance, but fuel economy effects can also be enhanced by changing the way in which the thermoelectric system is used. When applying a thermoelectric system to an ordinary gasoline car as mentioned previously, three issues arise.

Figure 9 shows the exhaust temperature and its effect on thermoelectric power output for an ordinary gasoline car in the LA4 driving cycle and a series hybrid that assumes high-load constant speed operation. The 2-liter STREAM evaluated in this study requires average power output of approximately 10 kW for the LA4 driving cycle. The series hybrid was assumed to obtain the average output power required for driving by using a 0.65-liter displacement engine operated at constant speed while maintaining the point of maximum engine efficiency. In addition, the ordinary gasoline car used the average exhaust temperature measured by actually driving a 2-liter STREAM. The results showed that high-load constant-speed operation has a higher exhaust temperature and enabled efficient conversion of heat to electrical energy.

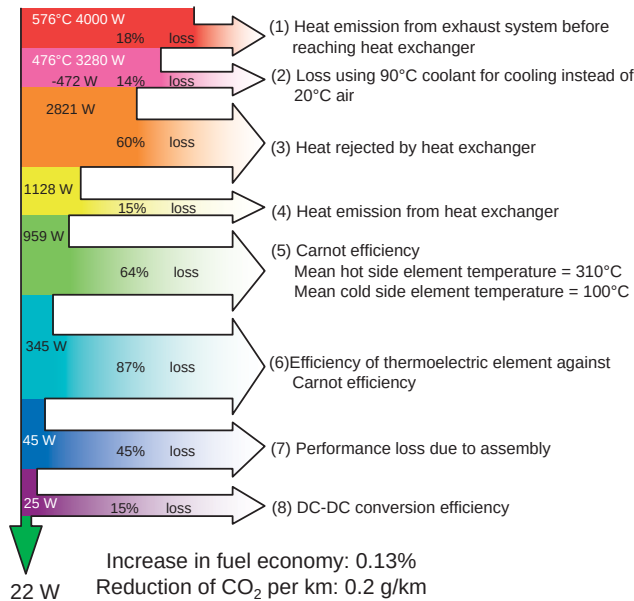


Fig. 7 Analysis of energy flow in LA4 driving cycle

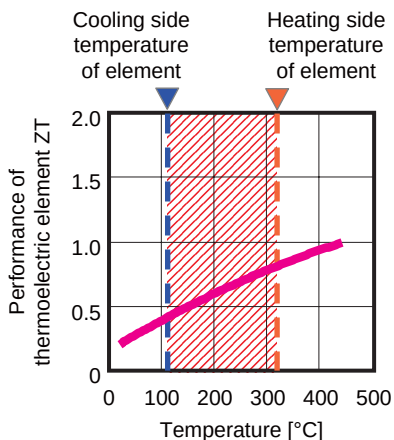


Fig. 8 Performance of thermoelectric element relative to temperature

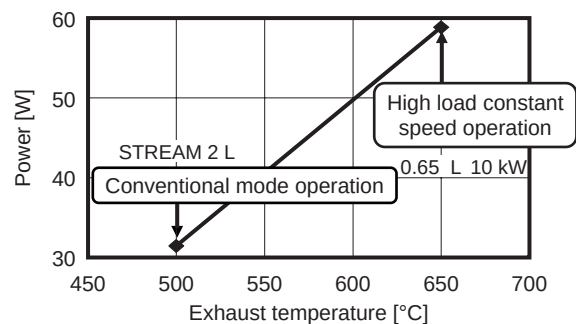


Fig. 9 Effect on output of thermoelectric unit due to difference in exhaust temperature

Figure 10 shows the effects of fluctuating exhaust gas conditions on fuel economy. This shows that the thermoelectric unit exhibits the maximum fuel economy effects under the optimized exhaust mass flow. The exhaust gas conditions of an ordinary gasoline car fluctuate during the driving cycle, so optimization was performed to match the most frequently occurring conditions. However, it is a challenge to constantly

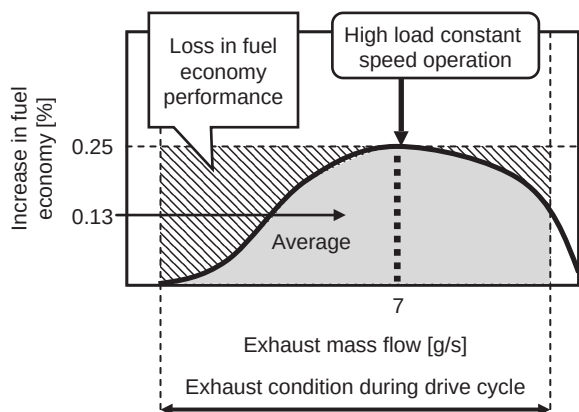


Fig. 10 Effect on fuel economy relative to exhaust mass flow

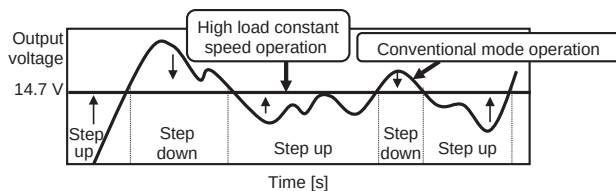


Fig. 11 Image of output voltage of thermoelectric unit during drive cycle

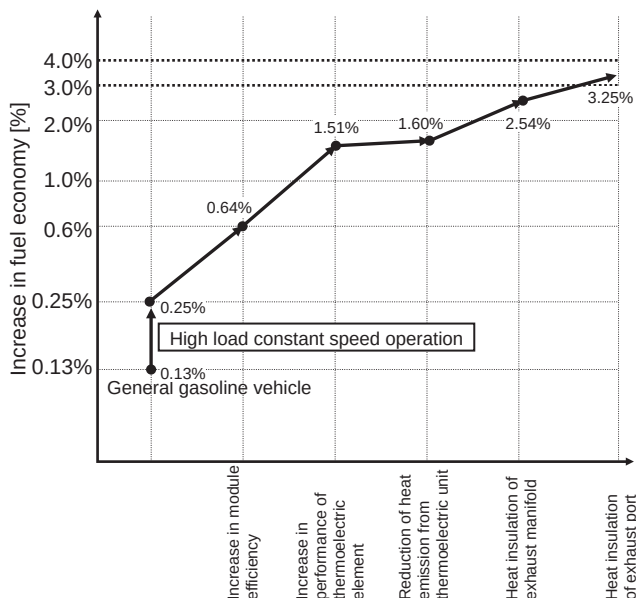


Fig. 12 Future potential of thermoelectric technology for fuel economy

maintain the optimized conditions, so the efficiency drops. In contrast, the exhaust conditions do not fluctuate during high-load constant-speed operation, which constantly enables to operate under the optimized conditions.

Figure 11 shows an image of thermoelectric output power during the driving cycle. The exhaust conditions of an ordinary gasoline car fluctuate during the driving cycle, so the output voltage from the thermoelectric unit also fluctuates accordingly. The voltage required by the car is constant, so when a voltage mismatch occurs, step-up or step-down voltage conversion is required, so power loss occurs during conversion. On the other hand, the exhaust conditions do not fluctuate during high-load constant-speed operation, so the approximately 15% conversion loss can be eliminated by presetting the thermoelectric power output to the voltage required by the car.

Figure 12 shows the enhancement in fuel economy effects when comprehensive measures are taken for locations to be enhanced from the viewpoint of energy balance, and the method of use. Simulations were performed using the conditions of high-load constant-speed operation such as in a series hybrid, a high exhaust temperature, optimized exhaust pressure loss, and constant output voltage. The results showed that approximately twice the fuel economy effects were obtained compared to when applied to an ordinary gasoline car. Furthermore, this provided the outlook that developing elements capable of securing ZT1 or more on average within the temperature range of 100°C to 350°C, establishing methods for reducing assembly loss to 15% or less, modifying the system usage method, and taking heat insulation measures could be combined to enhance fuel economy by approximately 3%.

5. Conclusion

Fuel economy simulation technology and guidelines were developed for an automobile heat recovery system that uses thermoelectric elements.

- (1) Effects and issues when using current thermoelectric technology were clarified.
- (2) Key technologies and enhancement methods were extracted, and optimal methods of use were determined. Estimates of increased driving cycle fuel economy when these measures are taken showed that enhancement of approximately 3% can be expected.

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Prediction of Transient Body Deformation during Handling Maneuvers

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ABSTRACT

A multi-body dynamics model that considers elastic deformation of the body was formulated in order to predict transient body deformation, a factor that affects handling. A comparative analysis with body deformation during handling maneuvers identified using a modal forced response method was conducted, and a good correlation was obtained between vehicle dynamic performance, transient body deformation, and the body modal contribution factor.

1. Introduction

It is well known that body characteristics affect the quality of the dynamics of a vehicle, such as handling performance, ride comfort, and noise and vibration.

In the area of handling performance, examples have been reported of prediction of body deformation during handling maneuvers employing models of body characteristics formulated using a variety of methods in combination with multi-body dynamics models^{(1),(2)}. Examples have also been reported in which the mechanical input to the suspension coupling points on the body framework has been identified from the component forces at the tire contact points and used as the basis for reproduction of body deformation in tests and simulations^{(3),(4)}. There is, however, a paucity of examples of detailed measurement of body deformation during handling maneuvers.

The research discussed in this paper used a modal forced response method to identify the forces acting on the suspension coupling points on the body framework, and rendered body deformation during handling maneuvers visible by inputting these forces into a modal model⁽⁵⁾. The simulation model was a combination of an elastic body model of the body formulated using the residual vector method, and a multi-body dynamics model⁽⁶⁾. This paper will discuss the results for body deformation obtained from the modeling method employed in the project in comparison with measurements of vehicle dynamic performance and body deformation during handling maneuvers.

2. Calculation of Transient Body Deformation during Handling Maneuvers

2.1. Modal Forced Response Method

A modal forced response method was employed as the method of identifying body deformation during handling maneuvers. Strain gauges were attached close to the suspension coupling points on the body framework, and data for body strain during handling maneuvers in the time domain, $\varepsilon(t)$, were measured. Next, the front and rear suspension parts and the powerplant parts were removed from the measurement vehicle to produce a trimmed body, and a strain gauge response matrix, $H(\omega)$, was measured for input to suspension coupling points with n degrees of freedom [Eq. (1)]. The inverse matrix of the force response matrix, $H(\omega)^{-1}$, was found and the inverse fast Fourier transform (FFT) shown in Eq. (2) was performed, enabling determination of the impulse matrix $h(t)$ for the force response of the suspension coupling points at each level of strain. Convolution of this impulse matrix and the measured body strain, $\varepsilon(t)$, enabled the force input to the suspension coupling points during handling maneuvers, $F(t)$, to be identified [Eq. (3)].

Next, accelerometers were attached to the framework, panels, and suspension coupling points of the trimmed body, and electromagnetic shaker was applied to several points on the body to enable the frequency response functions of different areas of the body to be determined. Modal analysis was then employed to obtain the modal shape of the trimmed body, Ψ_r , and the m_r , c_r , and k_r matrices for the system ($r=1,2,3,\dots,m$), and a second-order

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differential equation with the contribution factor of each body mode, $q(t)$, as a variable was formulated [Eqs. (4) and (5)]. The sum of the products of the modal shape and the contribution factors gave the body deformation during handling maneuvers [Eq. (6)].

$$H(\omega) = \varepsilon(\omega)/F(\omega) \quad (1)$$

$$h(t) = iFFT(H(\omega)^{-1}) \quad (2)$$

$$F(t) = h(t) \otimes \varepsilon(t) \quad (3)$$

$$m_r \ddot{q}_r(t) + c_r \dot{q}_r(t) + k_r q_r(t) = f_r(t) \quad (4)$$

$$f_r(t) = \sum \psi_{i,r}^T \cdot F_i(t) \quad (5)$$

$$X_i(t) = \sum \psi_{i,r} \cdot q_r(t) \quad (6)$$

$h(t)$: Impulse matrix for suspension coupling points

$H(\omega)$: Strain gauge response to input at suspension coupling points

$F(t)$: Input to suspension coupling points during handling maneuvers in an actual vehicle

$\varepsilon(t)$: Body strain during handling maneuvers in an actual vehicle

ψ_r : Modal shape ($r=1,2,3,\dots,m$)

$X_i(t)$: Displacement of suspension coupling points during handling maneuvers ($i=1,2,3,\dots,n$)

$q_r(t)$: Body modal contribution factor ($r=1,2,3,\dots,m$)

m_r : Equivalent mass of trimmed body modes ($r=1,2,3,\dots,m$)

c_r : Equivalent damping of trimmed body modes ($r=1,2,3,\dots,m$)

k_r : Equivalent stiffness of trimmed body modes ($r=1,2,3,\dots,m$)

m : Number of trimmed body modes

n : Degree of freedom of suspension coupling points

2.2. Study of Strain Gauge Attachment Points

Strain gauges were attached close to the suspension coupling points on the body side in order to enable identification of input to the suspension. Strain response tests using hammering excitation were conducted on the bench to enable the selection of sites on which sufficient strain would act during handling maneuvers. When a finite element model of the relevant body was available, strain response analyses were conducted to provide a guide for points of attachment of the strain gauges. Figure 1 shows the set-up for a hammering test to measure strain response, with strain gauges attached at several points close to the spring damper coupling points. In this case, response was highest from strain gauge numbers 4 and 6. Figure 2 shows the results of performing the same test using a finite element model. Response was highest in the simulation at the points at which the highest response had

been measured in the test. This is the means by which the attachment points for the strain gauges were determined.

2.3. Screening of Strain Response Matrix

Even when measurements were taken at the strain gauge attachment points that had been carefully selected using the method described in the preceding section, non-coherent results for strain response from multiple suspension coupling points were obtained. Figure 3 shows a strain response matrix with the number of input force locations on the horizontal axis and the number of strain gauge locations on the vertical axis. Figure 4 shows the results obtained when this response matrix was used to identify the input at the coupling points of the spring dampers for the left and right front wheels. Results for the left and right wheels should be identical, but

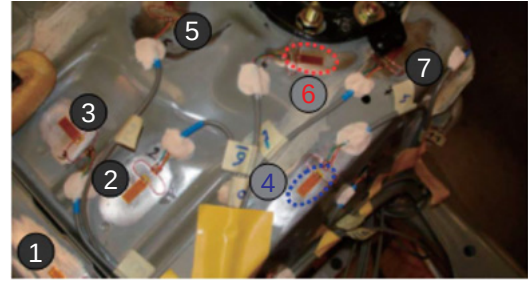


Fig. 1 Pretest for determination of strain gauge setting

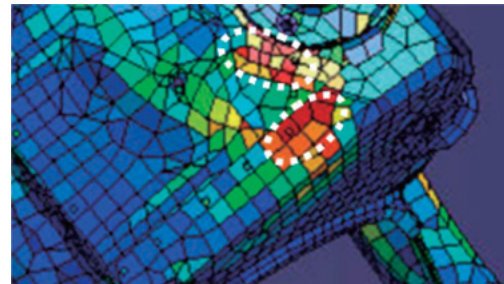


Fig. 2 Result of strain sensitivity simulation

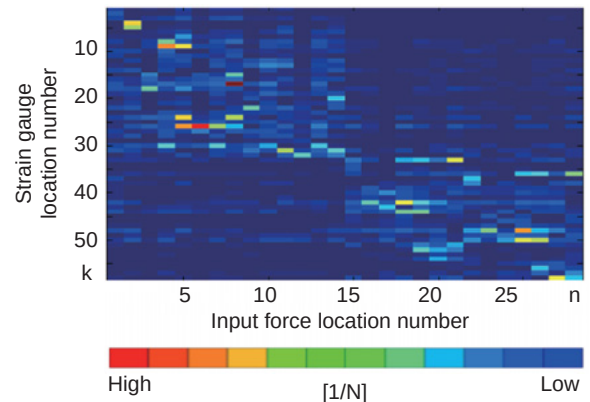


Fig. 3 Strain matrix before cleanup

differences of between two- and four-fold exist in these results.

Threshold values for coherence were therefore set, and any results falling below this threshold were judged as noise and the relevant strain response figures were deleted. Figure 5 shows the results obtained when the resulting matrix was used to identify input. The figures for input at the left and right wheels are almost identical, demonstrating that screening of the strain response matrix is an effective method of increasing the accuracy of identification of suspension input.

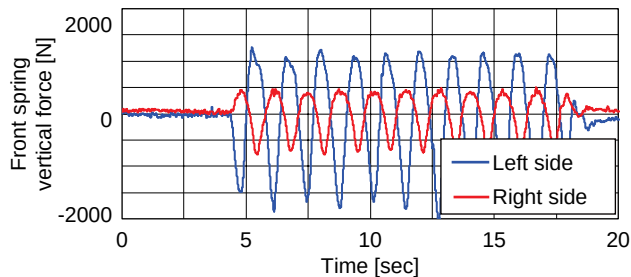


Fig. 4 Result of forced response around front spring damper connecting point before screening

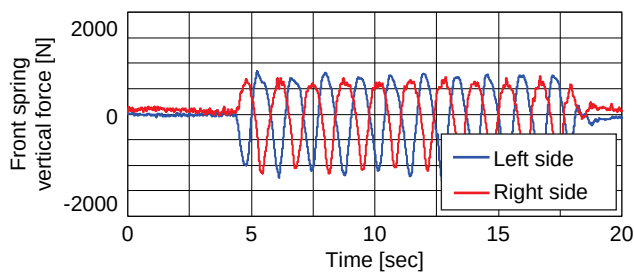


Fig. 5 Result of forced response around front spring damper connecting point after screening

3. Coupled Structural and Multi-body Dynamics Simulation

The project formulated a finite element model of the body system parts and a multi-body dynamics model of the chassis system parts. In order to enable prediction of body deformation during handling maneuvers, a reduced trimmed body model was incorporated in the multi-body dynamics model, and a coupled analysis was conducted.

3.1. Reduction of Body Model

The finite element trimmed body model, employing approximately 700 000 elements, was reduced using the residual vector method to a constrained mode up to 50 Hz and 155 degrees of freedom, including the degree of freedom of external points. This reduced simulation time, to also enable the model to be used in analyses of the

phenomenon of low-frequency noise and vibration. With regard to the total difference in mass between the real vehicle and the simulation model, the missing mass and inertia were incorporated into the trimmed body model and made to conform in a way that would not affect the elastic mode (Fig. 6). This reduction of the body model decreased simulation time to less than one-fifteenth of the original time.

3.2. Method of Formulation of Multi-body Dynamics Model of Chassis System

The front and rear suspension parts and powerplant parts were modeled using rigid elements which included items for coupling point geometry, positions of centers of gravity, mass, and inertia based on design data. The characteristics of the connections between suspension parts, powerplant parts, and body elements were updated with consideration of frequency-dependent and amplitude-dependent characteristics on the basis of a comparison with the results of measurements of the performance of springs, dampers, and rubber bushes in isolation and of an actual vehicle incorporating these components. The mechanical suspension characteristics (wheel rate, wheel center locus inclination brought about by longitudinal force, scuff, roll stiffness, roll steer, and side-force steer) and the frequency characteristic and vibration transmission rate of the powerplant, suspension, and body under forced excitation of the tires in the completed chassis model were

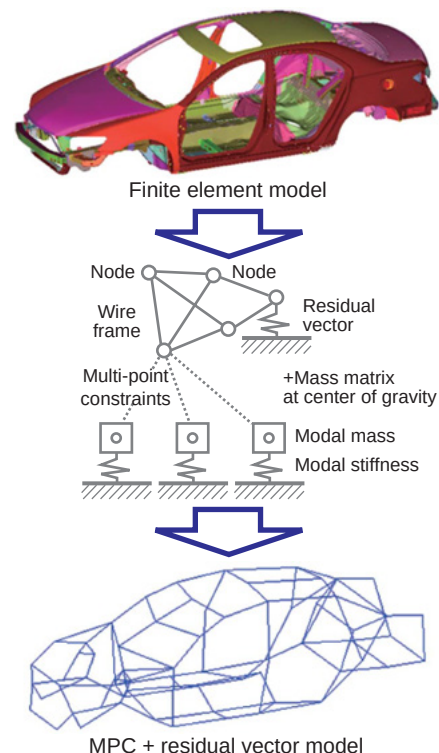


Fig. 6 Method of reduction of body model

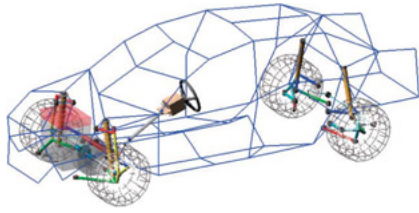


Fig. 7 Multi-body dynamics coupled with structural model

compared with measurement results and verified. Figure 7 shows the completed vehicle model formed by coupling the chassis and body models.

4. Results of Verification of Model

Test results and simulation results for body deformation during handling maneuvers were compared. The driving conditions for the actual vehicle measurements were: after a straight course on a flat road at a fixed vehicle speed of 60 km/h, slalom maneuvers (2.5 sec/cycle) with a steering input such that the peak lateral gravitational acceleration (lateral G) at the center of gravity of the vehicle was 0.4 G. The steering angle and drive force of the test vehicle, the driving conditions, and the measurements taken were input to the simulation.

4.1. Comparison of Dynamic Performance in Actual Vehicle and Simulation

Figure 8 shows a comparison of the results of the slalom maneuver test and the calculation of vehicle dynamic performance in the simulation. A comparison of the yaw rate around the vertical axis through the center of gravity, the lateral G, and the roll angle around the longitudinal axis through the center of gravity shows an error in the time domain of within 4%, indicating that the simulation is able to accurately reproduce the dynamic performance of an actual vehicle.

Figure 9 shows a comparison of results for changes in the lateral force on the suspension coupling points at the front of the front sub-frame from the vehicle test and the simulation. The test results and the input predicted by the simulation are largely identical.

4.2. Results for Body Deformation during Handling Maneuvers

Figure 10 shows the results of calculation of body deformation during handling maneuvers using input to the suspension coupling points calculated from handling data. Body deformation can be seen to change transiently in the time domain.

Figure 11 shows the results of an analysis of the contribution factor of the body modes when lateral G reaches its peak. The modes with the highest contribution factors were torsional mode, in which the entire cabin

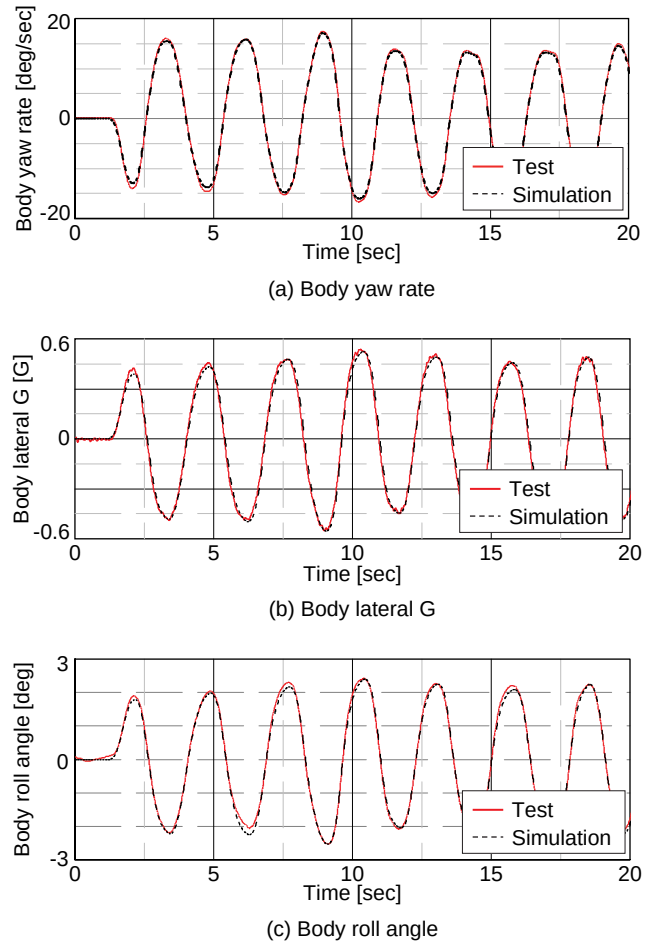


Fig. 8 Vehicle dynamics during slalom maneuver

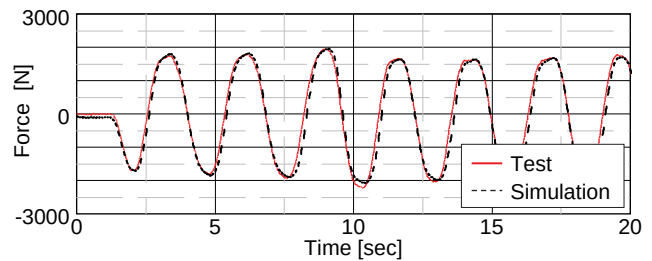


Fig. 9 Front sub-frame lateral force during slalom maneuver

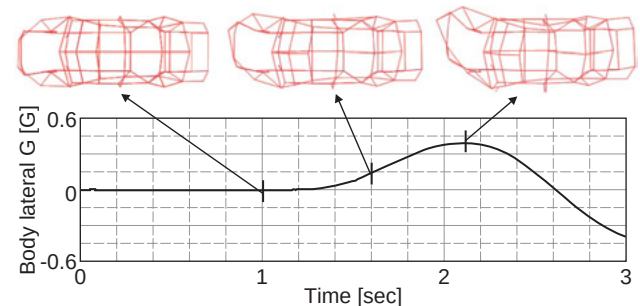


Fig. 10 Test results for body deformation

twists, and front lateral bending mode, in which the front of the frame bends laterally.

4.3. Simulation Results for Body Deformation

The steering angle and drive force from the vehicle test were used as the input conditions for the multi-body dynamics model incorporating the elastic body model, and body deformation was calculated. The results are shown in Fig. 12. A comparison of simulation results and test results for body deformation during the slalom maneuver in each time domain shows that there is a good correlation between results not only for peak values, but also during the transient period.

In addition, the simulation also showed that the torsional mode and the front lateral bending mode displayed higher contribution factors than other modes.

Figure 13 shows a comparison of test and simulation results for the contribution factors of the torsional and front lateral bending modes during handling maneuvers.

The contribution factors of both modes display a transition while changing in the time domain. The test and simulation results also correlate well. This indicates that the applied method was capable of analyzing the modal contributions that affect body deformation in test and simulation results by means of the time axes.

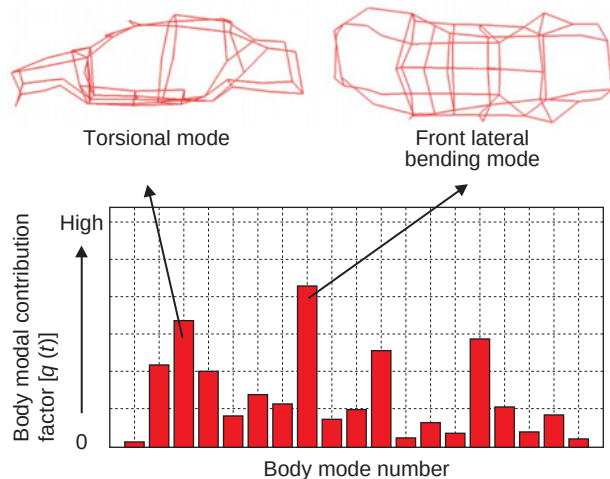


Fig. 11 Test results for body modal contribution

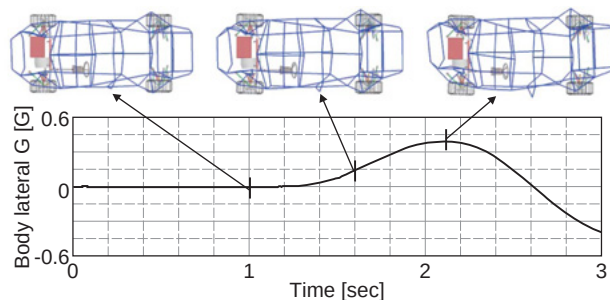
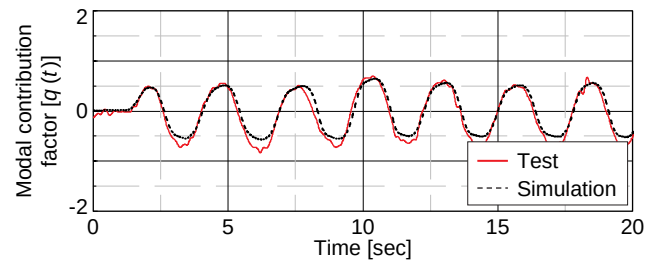
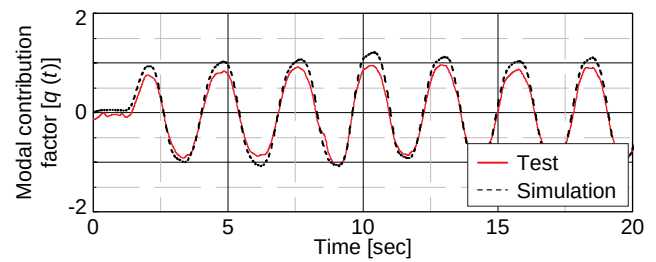


Fig. 12 Simulation results for body deformation



(a) Torsional mode



(b) Front lateral bending mode

Fig. 13 Two time domain body modal contributions

5. Conclusion

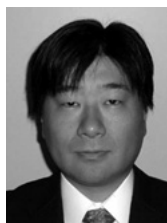
A modal forced response method was used to calculate the input at the suspension coupling points on a body framework, enabling visualization of body deformation during actual handling maneuvers, which had previously represented a challenge. The simulation model combined an elastic body model formulated using the residual vector method, and a multi-body dynamics model. This model was used in a comparison of the modal contribution factors in vehicle dynamic performance and body deformation during slalom maneuvers in test and simulation results, and a good correlation was obtained.

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Kohei UMEHARA

Vehicle Dynamics Simulation in Extreme Driving Conditions

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ABSTRACT

The increased weight produced by measuring instruments and the limited space available for such instruments make it a challenge to measure vehicle characteristics in extreme driving conditions such as circuit driving that take the vehicle to its performance limits. The ability to conduct bench simulations of vehicle behavior, that consider a variety of factors such as changes in the form of the vehicle and the forces acting on it, across a wide range of driving conditions, from standstill to extreme driving, would enable the measurement of physical characteristics which has been unlikely to be measured to date. Additionally, this would contribute to more precise analysis of vehicle characteristics during driving. Honda's Dynamic Vehicle Simulator (DVS) was developed as a multi-axis test system with the capacity to enable simulation of vehicle behavior from standstill to extreme driving on the bench. A method of efficiently reproducing this wide range of driving conditions on the bench using the DVS has been developed. This method has enabled vehicle characteristics in the extreme driving range, which has previously been challenging to study in vehicle tests, to be analyzed on the bench.

1. Introduction

Because actual driving tests for analyzing vehicle performance under extreme conditions are straining on drivers and may cause considerable wear in engines and tires, repeated tests are more challenging to conduct than with normal driving tests. In addition, many physical quantities cannot be measured in such tests because of the measuring equipment itself, the weight of which changes vehicle performance and the mounting of which is subject to various restrictions.

Consequently, the ability to simulate on the bench vehicle attitudes, forces, and various other conditions that occur during extreme driving would offer advantages such as eliminating the need for test drivers, reducing tire and engine wear, and, consequently, greater ease of repeated testing. In addition, quantities immeasurable in actual driving tests would be measurable, enabling much more detailed analysis. In short, such a capability would be highly significant.

However, reproducing vehicle behavior from that at standstill to behavior under extreme driving conditions on the bench necessitates a multi-axis, multiple-degree-of-

freedom test system with the control capabilities to simulate a broad range of vehicle and tire behavior. Control was challenging in such test systems because of frequent tire slips and tire lifts relative to the road surface during extreme driving. Thus the need existed for a control technique.

Honda's Dynamic Vehicle Simulator (DVS) is a multi-axis, multiple-degree-of-freedom test system developed with the goal of simulating, on the bench, a wide range of vehicle behavior, from standstill to extreme driving. The system is mainly composed of four wheel pans, which contact the tires, and a center table, which connects to the vehicle body. Various vehicle behaviors during actual driving are reproduced by simultaneously operating the center table and the four wheel pans, which simulate a road surface (Fig. 1). We have developed a technique called Body-Centered Mode Simulation for using DVS to reproduce actual driving conditions, up to vehicle performance limits, on the bench. This technique enables on-the-bench measurement and property analysis of even race-circuit driving and other extreme driving conditions involving intense steering maneuvers.

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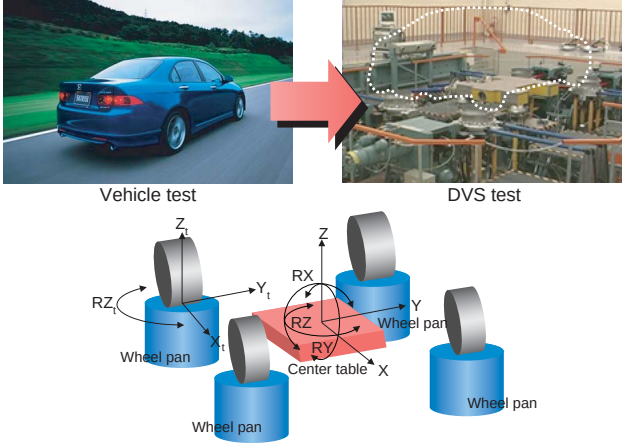


Fig. 1 Outline of DVS

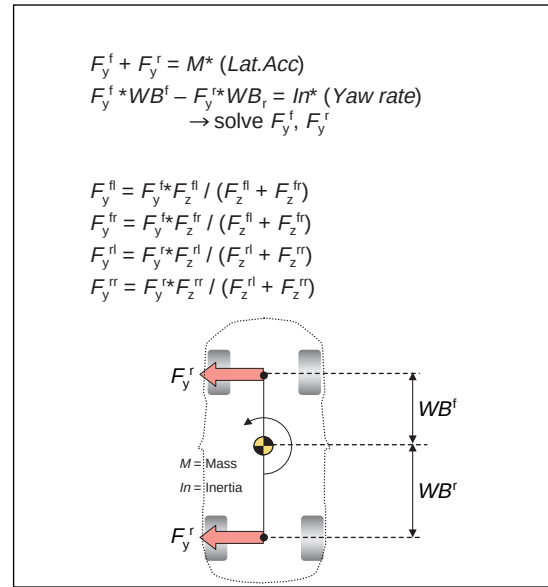
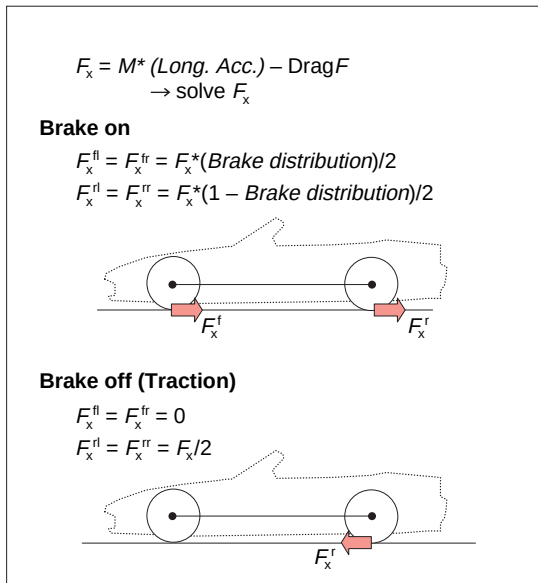
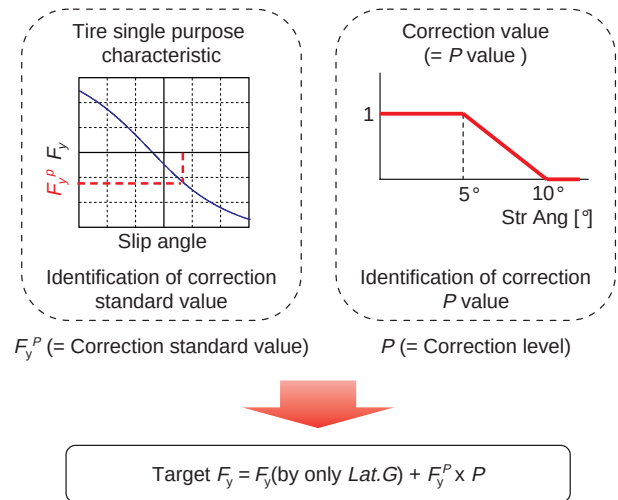
2. Road Simulation

Here, “road simulation” is broadly defined as encompassing simulation technologies for reproducing actual driving conditions on DVS. The fundamental concept of road simulation is to predefine control target quantities based on forces, displacement, and other variables occurring during actual driving and adjusting the DVS actuators to meet those targets in order to reproduce the various changes in condition that occur while actually driving.

Because measurable quantities are limited in actual driving tests at a vehicle’s performance limits, control targets should be defined based on measurable quantities. As this effort focused on the analysis of various compliance properties in suspension components, steering angle and force on the tire contact patch were chosen as

the control targets. Tire tread force was estimated from quantities measurable in actual driving tests.

Figures 2 and 3 illustrate the basic principles for estimating tire tread forces, longitudinal force F_x and lateral force F_y . The former is calculated from quantities such as longitudinal acceleration, air resistance, and brake distribution; the latter by correcting the value obtained from yaw angular rates, lateral acceleration, changes in wheel load, location of center of gravity, and other quantities, with the opposing forces that occur constantly during straight driving. Specifically, the corrected value was $F_y^P \times P$, where F_y^P is the opposing force during straight or near-straight driving, and P is a weighting factor for F_y^P according to steering angle. Adding this adjusted value yielded the final control target F_y (Fig. 4).


 Fig. 3 Identification of F_y generated in tire

 Fig. 2 Identification of F_x generated in tire

 Fig. 4 Method of correction of F_y

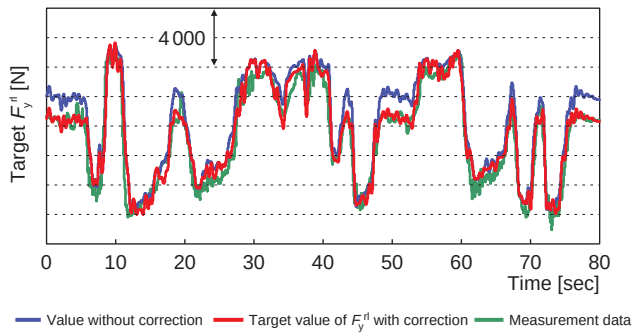


Fig. 5 Target data for F_y

Figure 5 is a graph comparing F_y values measured with a six-component transducer mounted to a tire under actual driving conditions and F_y calculated as described above, both with and without correction. This comparison shows that this correction method enables the calculation, with a high degree of accuracy, of F_y values that are consistent with those in actual driving.

3. Position Control and Load Control

Two methods for controlling vehicle and wheel movements with DVS are used, depending on the target quantity. One is position control, in which position and displacement information are controlled as the target quantities. The other is load control, in which force information is controlled as the target quantity. The advantage of position control is precise reproduction of quantitative displacement, whereas the disadvantage is that because the system is controlled so as to eliminate displacement drift, even when a slight drift away from the target quantity results in excessive force, vehicle damage can result. In contrast, load control involves accurately reproducing the forces that occur, eliminating the possibilities of vehicle damage due to excessive force, but loss of control can result when impractical force is defined as the target value, e.g., when slight lateral force is defined as the target value in a situation in which no contact load acts on tires. In road simulation that includes extreme driving conditions, a large force can occur locally,

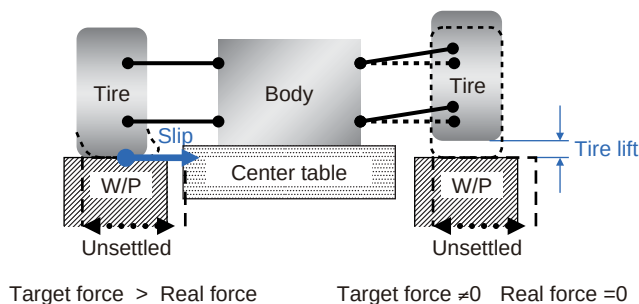


Fig. 6 “Slipping” and “floatage”

resulting in large displacement and in tire slip and tire lift relative to the contact surface as shown in Fig. 6. Consequently, relying exclusively on one control technique helps prevent accurate reproduction. An important element in road simulation is deciding which control technique to use to operate which part of the vehicle. Using both techniques for the appropriate parts enables the use of body-centered mode simulation (BCMS), described in the following section, to reproduce a wide range of driving conditions, including extreme driving ranges.

4. Body-Centered Mode Simulation (BCMS)

Depending on how changes in vehicle attitude are reproduced, road simulation can be categorized into several methods. Most broadly, there are two methods: body-fixed simulation, in which behavior of a moving vehicle is reproduced by fixing the vehicle body to the road surface and moving only the four tires; and body-moved simulation, in which the tires and vehicle body are moved simultaneously.

In body-fixed simulation, control targets are reproduced by using position control for the (immobile) vehicle body and load control for the wheels. However, despite this method’s advantage of requiring fewer actuators as only the wheel pans are moved, this method was not used in this study because of the many inherent error factors involved, such as shifting in the direction of gravity due to changes in the roll and pitch angles, and the tire–road contact angle differing from that of actual driving.

Body-moved simulation can be further divided into two methods: pin fix simulation^{(1),(2)}, in which a certain point on the vehicle body is fixed to a certain point in space and only rotational motion around the X, Y, and Z axes is reproduced; and a method in which both rotational and translational motion occur as the vehicle body is moved in all six degrees of freedom. In fact, BCMS is a type of the latter form of simulation (Fig. 7). In pin fix simulation, the center of gravity is fixed, so the vehicle body and road surface coordinate systems can be aligned with the position of the center of gravity. The advantage

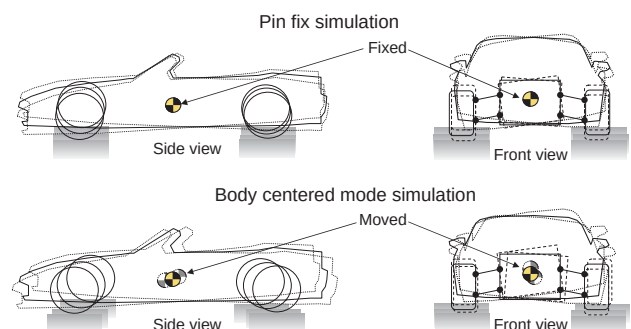


Fig. 7 Difference from pin fix simulation with BCMS

is the ease of measuring from the outside, making changes in vehicle body attitude easier to handle. However, because load control is used for the wheel pans, the occurrence of tire slip and tire lift (Fig. 6) in even a single wheel will immediately result in loss of control. Consequently, pin fix simulation is unsuited to the simulation of extreme driving conditions, in which tire slip and tire lift occur frequently.

BCMS is a method for moving the vehicle body in all six degrees of freedom. It is a road simulation method developed for on-the-bench simulation with a high degree of accuracy and robustness against tire slip and tire lift. Figure 8 shows the basic concept of the method. In BCMS, control targets are divided into high- and low-frequency components. The high-frequency component is reproduced by the wheel pans by means of load control, whereas the low-frequency component is controlled using load control for the center table and position control for the wheel pans. Position control used for the low-frequency component involves maintaining each wheel pan so that the center of rows and columns of each wheel pan pair stays aligned with a preset reference point. This makes it possible to determine the position of the vehicle body relative to the reference point at any time. With BCMS, even if slip and lift occurs in a wheel when simulating extreme driving conditions, position control of the wheel pan helps prevent any deviation from the control target. In short, BCMS is a road simulation system made possible by the multiple degrees of operational freedom that DVS provides for both the wheel pans and center table. Results validating the accuracy of BCMS are discussed below.

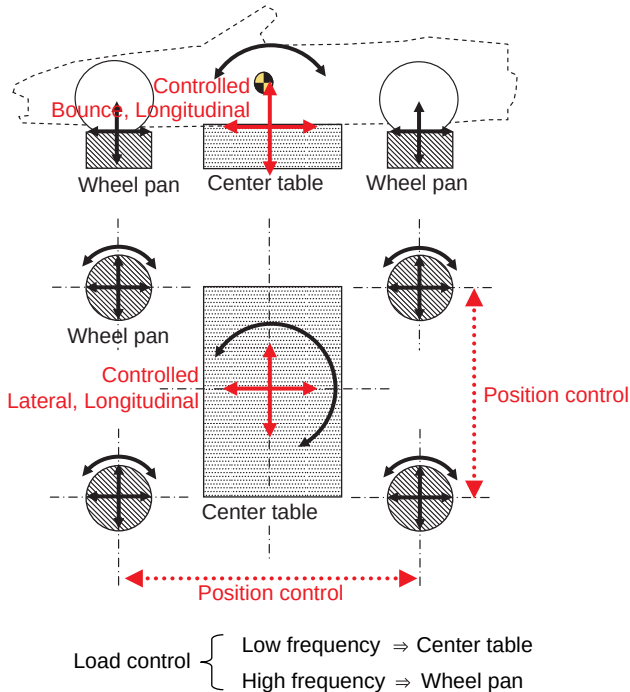


Fig. 8 Theory of BCMS

5. Validation of Simulation

Figure 9 is a graph comparing the control target (force acting on tire contact patches) with the force acting on tire contact patches in actual driving as reproduced under DVS-based BCMS. The satisfactory agreement between the two validates the ability of BCMS to accurately reproduce extreme driving conditions.

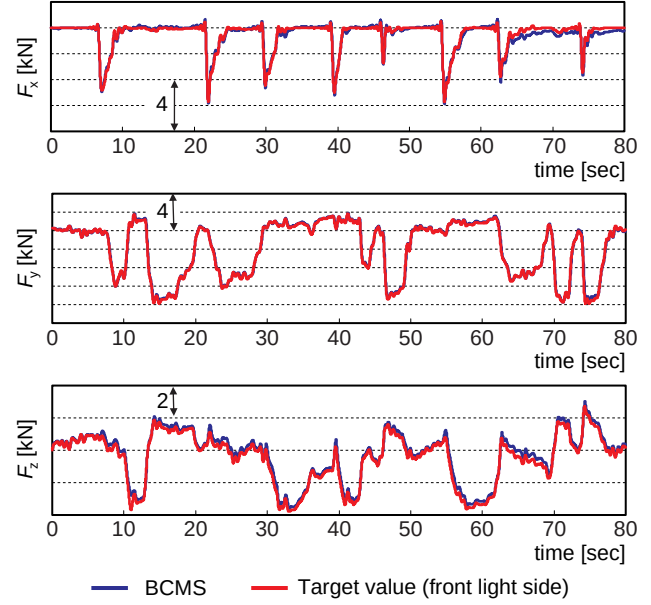


Fig. 9 Comparison between BCMS and measurement values

6. Example Analysis

The graphs in Fig. 10 illustrate the difference between measurements of changes in suspension alignment (i.e., toe changes) in actual driving as reproduced on the bench by BCMS, and toe change characteristics that occur when the forces are eliminated one by one in the following order: F_x , M_z , F_y . (Here, M_z represents alignment torque.) The top and middle graphs show toe change characteristics according to the tractive direction and alignment torque, respectively. The bottom graph shows toe change according to lateral force and indicates that various compliance characteristics relating to toe change can be determined on the basis of actual driving. Thus characteristic vehicle behavior in a certain location can be analyzed on the basis of compliance characteristics. It is also possible to analyze the effects of aerodynamic properties from changes in vehicle body attitude, for instance, and perform quantitative analysis of pitch and roll, which are challenging to measure in actual driving.

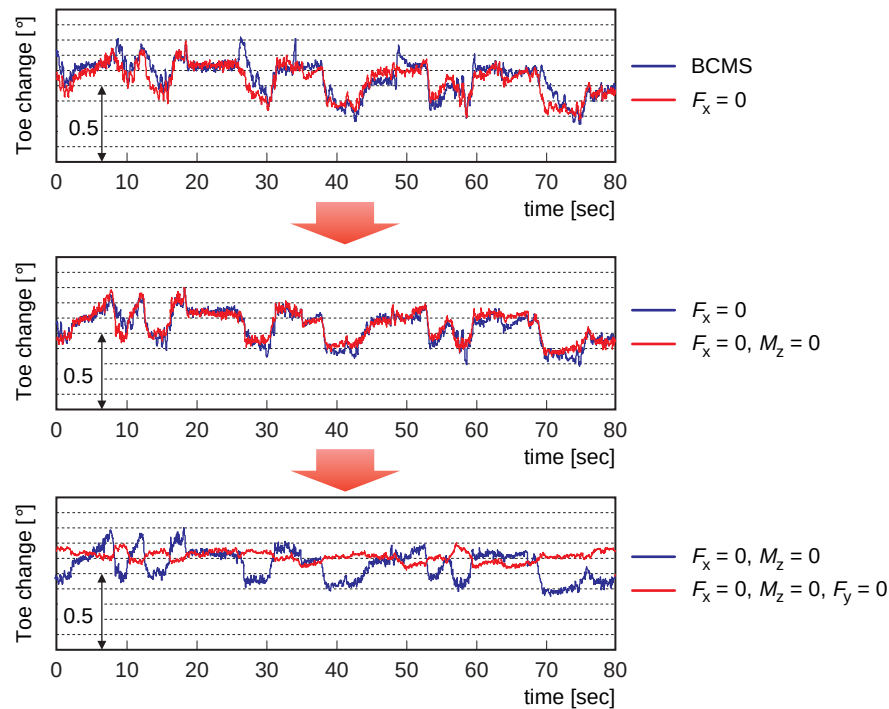


Fig. 10 Compliance characteristics of toe by F_x & M_z & F_y

7. Conclusion

This research aimed to use DVS to reproduce a wide range of driving conditions, from standstill to extreme driving, and thereby build the technology for the benchtop analysis of various vehicle properties during actual driving. The conclusions reached are as follows.

- (1) Appropriate use of both load control and position control is important, particularly when reproducing extreme driving conditions. When using BCMS, reproduction of driving (including extreme) conditions was made possible by having different control targets for the low- and high-frequency components and operating both the wheel pans and the center table according to each.
- (2) BCMS was shown to be capable of the benchtop reproduction of a wide range of driving conditions, from standstill to extreme driving at a vehicle's performance limits.
- (3) Road simulation using BCMS easily facilitates repeated testing, enables the measurement of otherwise challenging-to-measure quantities, and allows quantitative analysis of transient compliance characteristics on the basis of actual driving conditions.

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Driver-side i-SRS Airbag System with Continuously Staged Inflation

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ABSTRACT

It is desirable for airbags to provide optimal occupant protection performance for vehicle occupants, who come with a variety of physiques and riding postures, in a variety of collision circumstances, among other variables.

However, in order to enable the bag to be inflated more quickly and to maintain occupant protection performance over a longer period under various circumstances, current driver-side airbag systems necessitate the use of dual stage inflators, occupant position detection systems, and the like, to enable the complex control necessary for the provision of optimal occupant protection performance without increasing the risk of inflation injury upon airbag deployment.

A driver-side airbag with continuously staged inflation was therefore developed using spiral sewing technology that tears at specified pressures together with vent timing control. Featuring a simpler system than that of the existing technology, this airbag is able to provide more tailored occupant protection for a wider range of differing physiques and collision circumstances and appears to do so without increasing inflation injury risks.

1. Introduction

The first Japan-produced driver-side airbag systems were introduced in 1987, and since then our efforts have continued to address the unchanging issue of achieving a high-level balance between providing optimal occupant protection performance while minimizing deployment injury risks when airbags inflate. This effort has yielded a variety of technologies, including the world's first dual stage inflator and occupant position detection system.

Airbag development has taken into account a variety of different occupant physiques and riding postures, types of collision, and other such parameters. In order to cover this variety of circumstances, for example, for shorter drivers, who are typically positioned closer to the steering wheel, it would be ideal in some crashes if the airbag could provide restraint sooner. For occupants whose seats are positioned further from the steering wheel, it would be ideal in some crashes if the occupant protection performance could be sustained over a longer time.

However, in order to enable the airbag to be inflated more quickly and to maintain occupant protection

performance over a longer period, current driver-side airbag systems necessitate the use of dual stage inflators, occupant position detection system, and the like, to enable the complex control necessary for the provision of optimal occupant protection performance without increasing the risk of deployment injury.

The objective of the technology described in this paper is to provide both the capability to have faster inflation and longer occupant protection performance, using a simpler system than that of the existing technology, and to do so without increasing inflation injury risk. For that purpose, driver-side airbags with two new technologies were developed. These were a sewing technology that makes it possible to change volume continuously at specified pressures, and a vent timing control technology that is able to effectively utilize the gas that is generated by the inflator.

This new structure airbag for driver-side use will be introduced here. It is the i-SRS (Supplemental Restraint System) airbag system with the continuously staged inflation.

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2. Continuously Staged Inflation and Vent Timing Control System

2.1. Continuously Staged Inflation Technology

The driver-side airbag with this new structure is shown in Fig. 1. The driver-side airbag with existing technology is shown in Fig. 2.

The driver-side airbag with this new structure allowed two new technologies to be introduced to existing driver-side airbag technology.

The first of these, a continuously-staged inflation technology, was realized through the development of a technology for sewing in a spiral pattern that will tear continuously if the pressure in the airbag reaches or exceeds a specified level.

This performs three functions: It rapidly generates an airbag reaction force, limits the degree of airbag protrusion toward the occupant, and controls the airbag pressure so that it stays within a specified level while also continuously varying the airbag volume.

2.2. Vent Timing Control Technology

The second function is technology for vent timing control to keep from venting the airbag gas until a freely selected amount of time has passed.

Driver-side airbags with existing technology have vent holes that are always open, and gas exhausts through the vents even as the gas is being generated and in response to occupant loading. On the other hand, this driver-side airbag with the new structure performs these two functions: Since it does not vent the gas until the airbag

is nearly at full volume, it more efficiently uses the gas generated by the inflator, extending the time of sustained airbag protective performance, and it allows for use of a reduced output inflator to mitigate the impact force on the occupant.

Figure 3 shows the structure of the vent timing control technology.

A vent hole flap is installed between the panel on the passenger side and the panel on the steering wheel side that make up the airbag. This flap closes the vent valve. By stitching it together with the spiral seams that tear, venting action is achieved by both the internal airbag pressure and volume changes.

2.3. Deployment Process

The Japan New Car Assessment Program (JNCAP) provides a domestic standard for evaluating automobile safety performance in Japan. Figure 4 shows the deployment process and comparison of airbag internal pressure properties of the driver-side airbag with the new structure and that of a single stage driver-side airbag with existing technology. These two airbags received similar ratings for occupant protection performance on the JNCAP frontal collision test using an AM50% dummy (50 percentile adult male dummy). (The inflator is a domestic single-ignition specification product.)

At 17 ms after airbag ignition, the driver-side airbag with the new structure has generated a reaction force [Fig. 4(a)]. At this point, it is not venting gas. However, the driver-side airbag with the existing technology begins to vent gas at the same time the airbag begins to fill. A deployment reaction force is generated at an earlier time in this way in the case of the driver-side airbag with the new structure because the volume is smaller at the time of initial deployment. This effect also reduces the airbag stroke in the thickness direction, thereby reducing the likelihood of interaction with the occupants during inflation. The comparison of the new driver-side airbag and driver-side airbag with existing technology shown in Fig. 5 makes it apparent that the new driver-side airbag can reduce the degree of airbag protrusion toward the occupant.

At 27 ms, when the deployment has proceeded further,

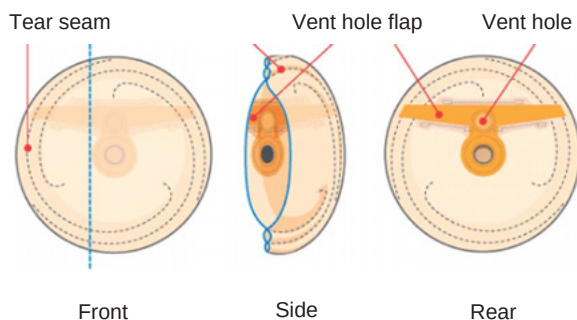


Fig. 1 New airbag structure

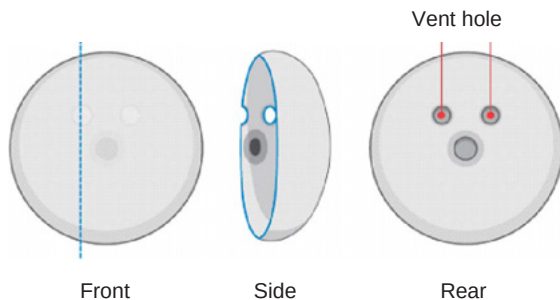


Fig. 2 Existing airbag structure

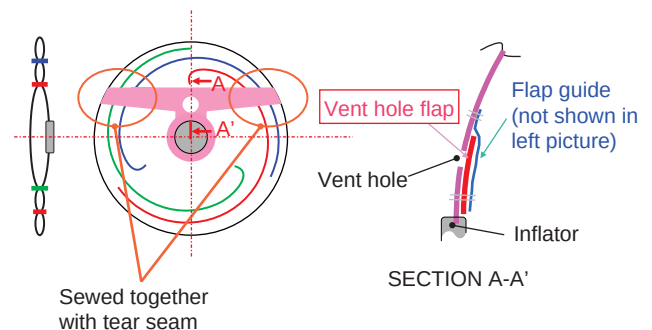


Fig. 3 Structure for control of venting

the airbag with existing technology generates a deployment reaction force [Fig. 4(b)]. When the internal pressure in the new airbag rises to the specified pressure, the spiral seam is torn continuously from inside the airbag, and inflation of the volumetric capacity continues with control applied so that internal pressure will not rise to or above the specified level.

When deployment has proceeded still further, at 40 ms, the internal pressure of the driver-side airbag with existing technology reaches its peak value [Fig. 4(c)]. On the other

hand, in the new driver-side airbag, the vent hole flap is freed and the airbag begins its gas venting operation.

Then, at 50 ms, the vent hole flap is pushed out of the vent valve by the pressure of the airbag, and gas venting takes place [Fig. 4(d)].

The time taken to generate the deployment reaction force with the new driver-side airbag is shown as T_N , while the time taken to generate the deployment reaction force with the driver-side airbag with existing technology is shown as T_E .

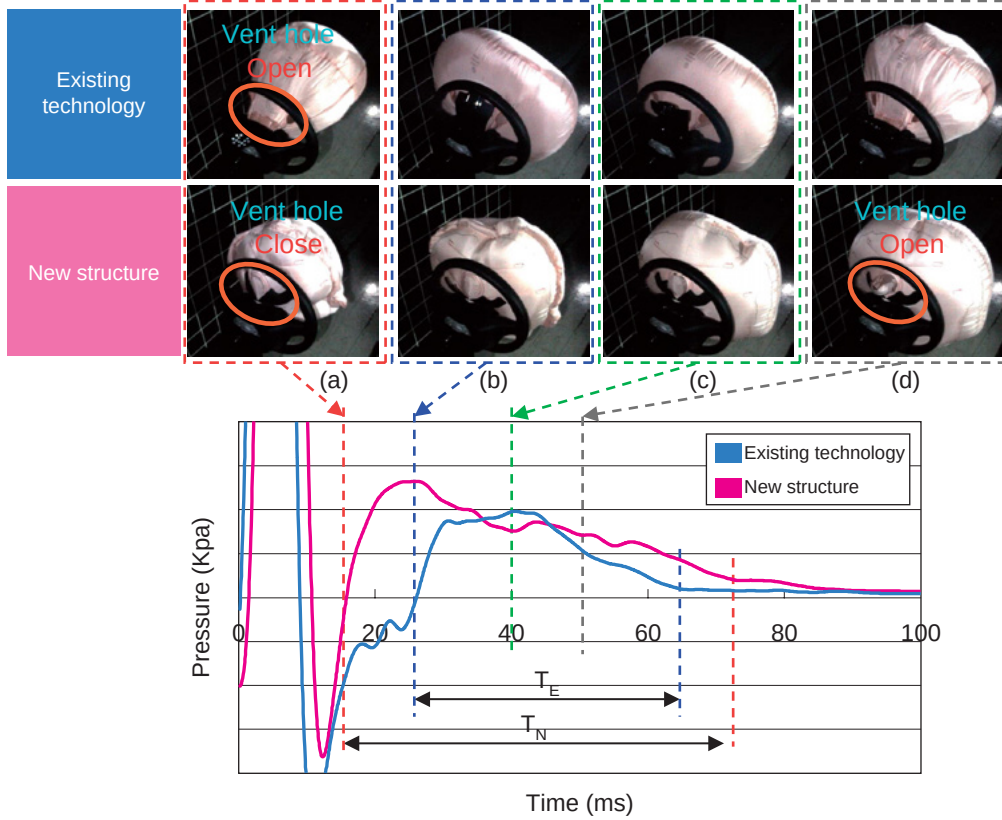


Fig. 4 Airbag pressure time histories: existing technology versus new structure with air bag deployment behaviors

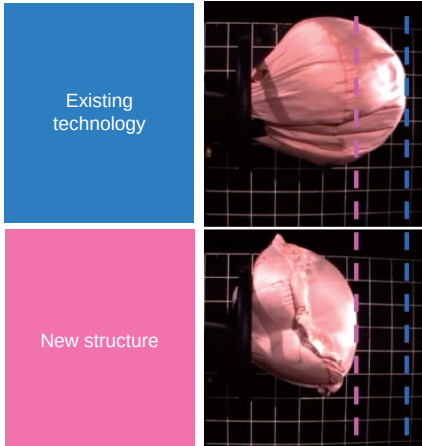


Fig. 5 Air bag shape at initial deployment stage

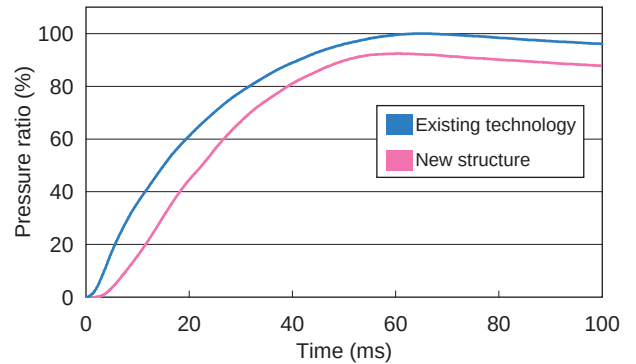


Fig. 6 Tank pressure-ratio time histories

The new driver-side airbag was able to generate a deployment reaction force (internal pressure ≥ 0 kPa) for a period about 1.5 times longer than that of the driver-side airbag with the existing technology.

The inflator output can also be reduced in order to efficiently utilize the gas generated by the inflator.

Figure 6 shows the ratio between the inflator pressure used in the driver-side airbag with the existing technology and the inflator tank pressure in the new driver-side airbag.

3. Performance Evaluation

3.1. Occupant Protection Performance

Figure 7 shows an injury ratio comparison in the JNCAP frontal barrier collision test for the new driver-side airbag and driver-side airbag with existing technology. (The inflator is a domestic single-ignition specification product.) The new driver-side airbag and driver-side airbag with existing technology that have

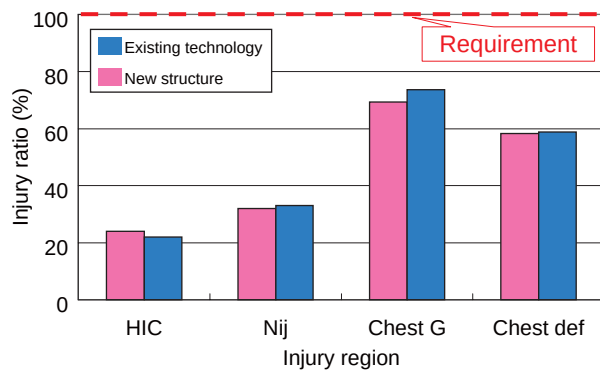


Fig. 7 Comparison of injury ratio of AM50% dummy in various injury measurement regions between existing technology and new structure

equivalent occupant protection performance on the JNCAP frontal barrier collision test were also subjected to the full-wrap frontal barrier collision testing at 55 km/h with the seat adjusted to the farthest forward point and an AF5% dummy (5 percentile adult female dummy) seated wearing a seatbelt. Figure 8 shows the airbag deployment behavior during the occupant protection time history.

This allows confirmation that at 20 ms the new driver-side airbag has taken on a shape that allows generation of airbag deployment reaction force more quickly than the driver-side airbag with existing technology.

Figure 9 shows the injury ratios relative to the driver-side airbag with existing technology for each injury measurement region in the results of this testing. (The inflator is a domestic single-ignition specification product.)

The injury levels were lower in all injury regions than with the single stage driver-side airbag with existing technology. Especially, in the neck region, the injury ratio was about 30% lower.

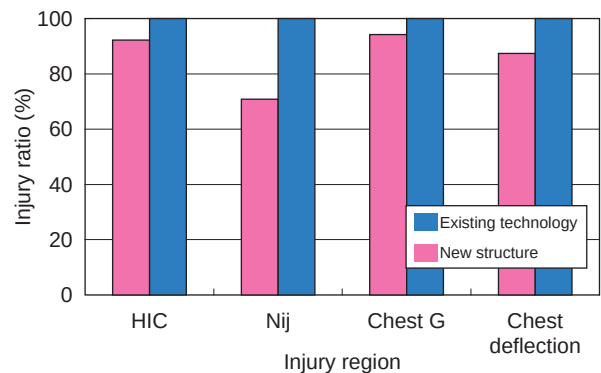


Fig. 9 Comparison of injury ratio of AF5% dummy in various injury measurement regions between existing technology and new structure

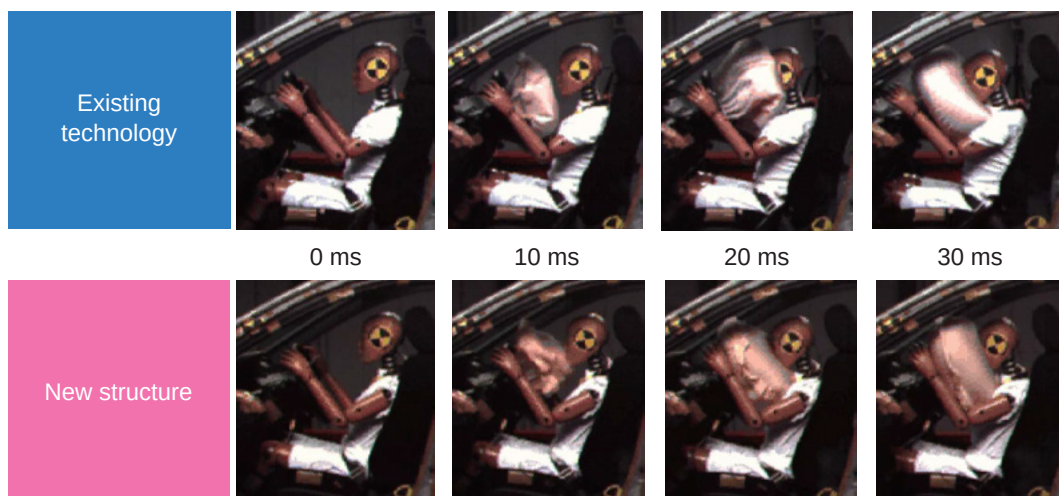


Fig. 8 Comparisons of behavior of air bag and AF5% dummy at frontmost seating position between existing technology and new structure



Fig. 10 AF 5 % dummy set for measuring impact force of air bag

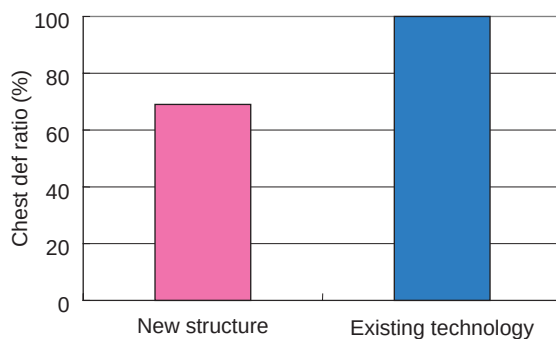


Fig. 11 Chest deflection ratio

4. Conclusion

The following two technologies were developed to enable a driver-side airbag to offer occupant protection performance in response to a wider range of occupant physiques and collision circumstances.

(1) Continuously staged inflation technology

(2) Vent timing control technology

These technologies have enabled a new driver-side airbag that can be deployed more rapidly and can provide occupant protection performance for a longer period of time, without increasing the deployment injury risk.

The aim from this point forward will be to continue to develop this technology, including phenomena that can occur in the real world while achieving a higher level balance between the further enhancement of airbag performance in occupant protection and impact force reduction.

3.2. Reduced Impact

Figure 8 shows that the new driver-side airbag at first fills to a smaller volume and then inflates in a radial pattern. It therefore allows limitation of the degree of airbag protrusion toward the occupant and reduction of the impact force on the occupant. This can be verified at the 20 ms point in Fig. 8.

One method of evaluating the impact force of the airbag is to conduct testing with an AF5% dummy positioned so its chest is in contact with the airbag module. Figure 10 shows a dummy in the position used for this evaluation method, and Fig. 11 compares the chest deflection ratio of the driver-side airbags with the new structure with that of the driver-side airbags with the existing technology.

The new driver-side airbag was able to reduce the inflator output by making more efficient use of the generated gas as shown in Fig. 6. This was able to reduce the impact force on the occupant.

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Plastic Window with View Control Function

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ABSTRACT

Plastic windows provided with a view control function that changes the level of transparency depending on the angle of view have been developed. In order to realize the view control function, special polymer films were selected which provide a clear view without ghost images and which possess a suitable relation between angle and opacity for each window. Taking the vehicle cabin environment into consideration, these special polymer films are sandwiched between hard-coated polycarbonate sheets, and the edges of the films are sealed with aluminum tape. In addition, a new film pressing process has been developed in order to help ensure stable quality. The use of the new windows in the next-generation fuel cell vehicle FCX Clarity has reconciled good rearward visibility for the driver with a practical trunk capacity, without affecting exterior design or vehicle standards.

1. Introduction

Attention is presently being focused on fuel cell vehicles as eco cars able to contribute to the resolution of environmental issues. The elements making up the powertrains of these vehicles, for example fuel cell stacks

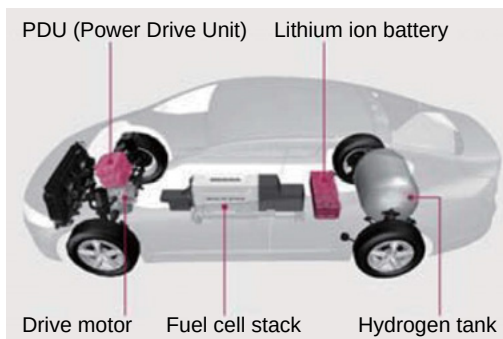


Fig. 1 FCX Clarity powertrain layout



Fig. 2 Rear view of FCX Clarity

and hydrogen tanks, are very different from those of conventional vehicles. Figure 1 shows the powertrain layout of the FCX Clarity, a next-generation fuel cell vehicle that went into production in June 2008. A reduction in size and optimum placement of the elements of the FCX Clarity powertrain have enabled the achievement of a high level of practicality while also realizing a sporty form with a low floor and low total height⁽¹⁾.

Figure 2 shows the rear form of the FCX Clarity. The hydrogen tank is positioned at the rear of the vehicle. The FCX Clarity is also fitted with an extra window in the upper section of the trunk lid, to increase rearward visibility for the driver. In order to realize a practical trunk capacity despite the restriction on trunk space due to the hydrogen tank, plastic windows with a view control function that changes the level of transparency depending on the angle of view (termed “view control windows” below) have been developed and used in combination with the glass extra window.

This paper will discuss the technological details of the developed view control windows.

2. Body Design around the Trunk

Figure 3 shows the FCX Clarity’s trunk space. With the positioning of the hydrogen tank behind the rear seat, the realization of a practical trunk capacity was the critical factor in the design of the body around the trunk. Increasing the overhang or the vehicle width at the rear

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Fig. 3 Trunk room of FCX Clarity

were considered as measures to secure trunk capacity, but the restrictions imposed by exterior design and vehicle standards prevented these measures from being implemented. The development project therefore examined the possibility of increasing the height of the trunk lid as a means of increasing the height of the trunk space. However, increasing the height of the trunk lid would reduce the vertical width of the rear window, thus reducing the driver's rearward field of vision. In order to increase trunk capacity without reducing the rearward field of vision, transparent plastic windows were positioned in the rear tray garnish and trunk lid lining (interior parts)(Fig. 4). (These windows will be referred to as the "rear tray window" and the "trunk lid window" below.) The use of these two plastic windows helped to ensure rearward visibility by enabling the driver to use extra windows in the body in addition to the rear window.

3. Visibility Design around the Trunk

The configuration shown in Fig. 4 provided good rearward visibility, but presented a new issue: when the vehicle was parked, people outside could look into the

trunk space from the side and the rear. It was desirable to control visibility from outside the vehicle in the interests of ensuring that the trunk space remained private. View control windows using films that changed in transparency depending on the angle of view (termed "view control films" below) were therefore developed. View control windows were employed for the two plastic windows in the rear of the FCX Clarity.

Figure 5 shows a plane view diagram explaining the relationship between the view control windows and the driver's field of vision. One aim established for the rear tray window and the trunk lid window was to help ensure visibility for the driver in the shaded areas, the rearview mirror visual area and the direct visual area. At the same time, it was desirable to restrict the visibility of the trunk space through the rear door windows to people standing at the sides of the vehicle. Taking an object positioned in the middle of the trunk space as an example, the areas in which visibility should be restricted would correspond to the two areas marked out by the broken lines in Fig. 5. The view control window used for the rear tray window was therefore one that provided a high level of transparency at the angle of the driver's line of sight, but a low level of transparency at the angle of the line of sight through the rear door windows.

Figure 6 shows a side view diagram explaining the relationship between the view control windows and the driver's field of vision. From the side view also, the aim was that the rear tray window and the trunk lid window would help ensure visibility for the driver in the shaded areas, the rearview mirror visual area and the direct visual area. At the same time, it was desirable here to restrict the visibility of the trunk space through the extra window for people standing behind the vehicle. Taking an object placed in the middle of the trunk space as an example, the area in which visibility should be restricted would correspond to the area marked out by the broken lines in

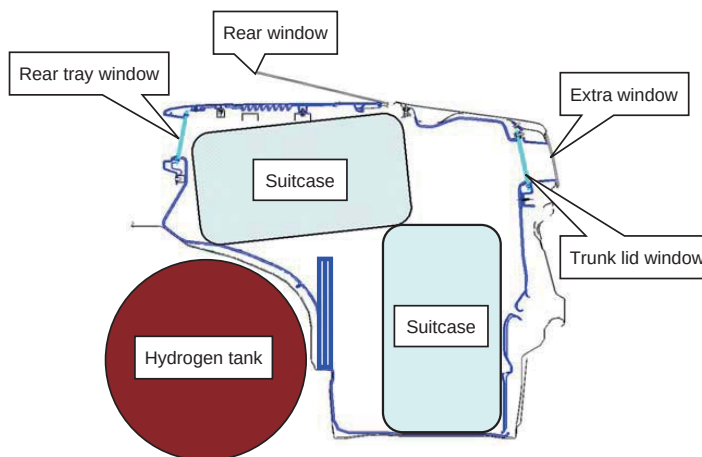
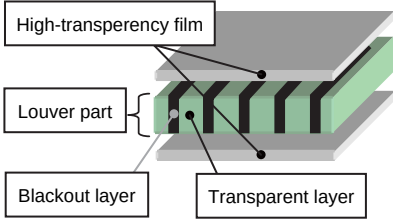
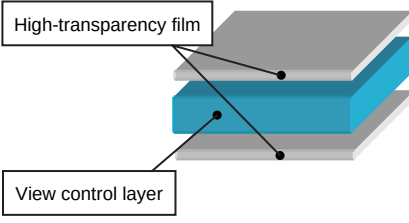


Fig. 4 Structure around trunk of FCX Clarity

Table 1 Setting angle and transparency of view control windows

Setting area	Setting angle		Setting transparency (haze ratio)
	Rear tray window	Trunk lid window	
Transparent area	From -10 to 10 deg.	From -10 to -30 deg.	20% Max.
Opaque area	From 30 to 50 deg., from -30 to -50 deg.	From 5 to 50 deg.	60% Min.

Table 2 Structures of view control films

	Louver structure film	Special polymer film
Structure		
Control factor	Light transmission	Haze ratio

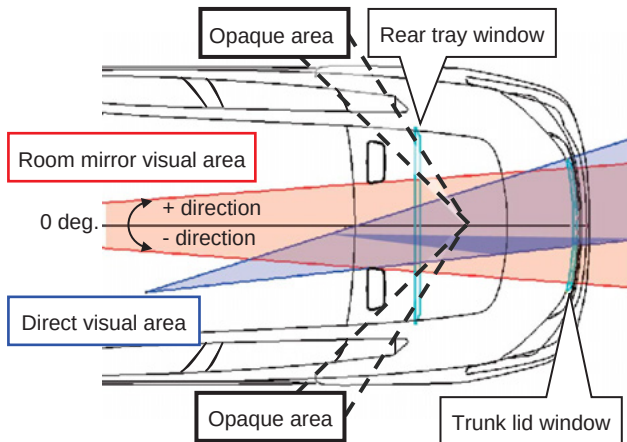


Fig. 5 Plane view of visual areas around rear tray window (for left-hand drive car)

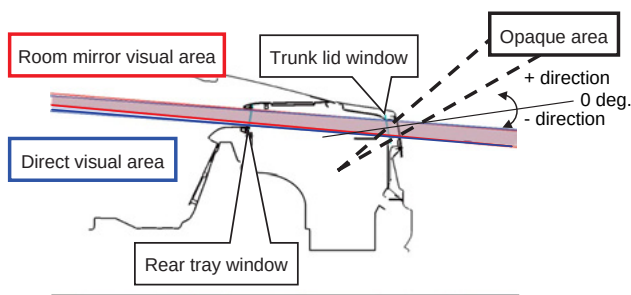


Fig. 6 Side view of visual areas around trunk lid window

Fig. 6. The view control window used for the trunk lid window was therefore one that provided a high level of transparency at the angle of the driver's line of sight, but a low level of transparency at the angle of the line of sight through the upper section of the extra window.

Table 1 shows the relationship between the angle of the view control windows and their transparency, as determined by verification based on the layout and measurements in an actual vehicle.

4. Selection of View Control Films

View control films can be roughly divided into two types based on their method of light control. Table 2 shows the structures of these two types of view control film.

Louver-structure films are made up of a louver section that functions to control light, and high-transparency films that protect the louver section. Blackout layers and transparent layers alternate in the louver section. The aperture ratio of the louver section changes depending on the angle of incidence of light, and the total light transmission of the film therefore changes. If the film is looked through at an angle at which its total light transmission is low, the view is dark and difficult to see. The mechanism described above enables the transparency of louver-structure films to change with the viewing angle⁽²⁾.

Special polymer films are made up of a view control layer that functions to control light, and high-transparency films that protect the view control layer. The view control layer is formed from alternating layers with differing indexes of refraction. This regular high-order structure

changes the level of scattering of light (the haze ratio) depending on the angle of incidence of the light. When the film is looked through at an angle at which its haze ratio is high, the view is cloudy and difficult to see. By this means, the transparency of special polymer films changes depending on the angle of view⁽³⁾.

Louver-structure films employ silicon rubber, a material with good optical properties, for the louver section, and these films therefore also offer the advantage of displaying good environmental resistance. However, the films also present a disadvantage in that interference between light entering at different apertures produces ghost images in the field of vision through the film. By contrast, special polymer films offer a clear field of vision through the film. Taking the ease of checking the view at the rear for the driver into consideration, special polymer films providing a clear field of vision were selected for use in the view control windows. Figure 7 shows the relationship between the angle of incidence of light and the haze ratio for the special polymer films used in the view control windows.

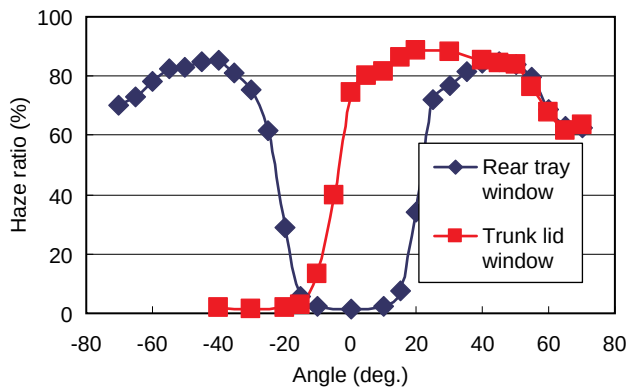


Fig. 7 Relation between angle and haze ratio for view control films

5. Configuration of View Control Windows

It was necessary to address two issues in employing special polymer films in a vehicle cabin environment.

The first of these was the fact that the films are prone to scratching. View control windows designed to enhance rear visibility for the driver would be required to display a high level of scratch resistance, but sample tests showed that the films were easily scratched.

The second issue was volatile substances. Sample tests that reproduced conditions in the cabin of a vehicle left out in the summer sun indicated the validity of concerns that volatile substances produced by the special polymer films would adhere to the surfaces of the view control windows and the inner surfaces of the glass windows, forming oil films and clouding the windows.

The view control window configuration shown in Fig. 8 was employed to address these two issues. The special polymer films to which an adhesive treatment has been applied are sandwiched between polycarbonate sheets, and the external surfaces of the sheets are coated with a polysiloxane hard coat with high abrasion resistance. In addition, the ends of the sheets are sealed with aluminum tape, which provides a good gas barrier. This configuration enabled the use of special polymer films in a vehicle cabin. Black paint has been applied around the external edges of the polycarbonate sheets, giving them a black ceramic appearance.

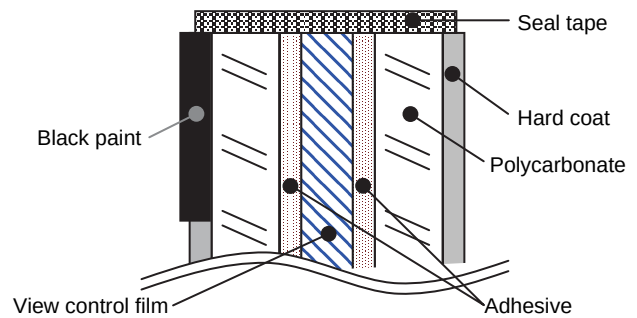


Fig. 8 Configuration of view control window

6. Production Process

Attention was also focused on the production process for the view control windows, in order to help ensure stable quality.

It was considered that if special polymer films were applied to untreated polycarbonate sheets, the water in the polycarbonate would volatilize in the heat, affecting visibility. The polycarbonate sheets are therefore heated and dried prior to application of the special polymer films.

In addition, given the comparatively large surface area of the parts, the view control films are pressed onto the polycarbonate under reduced pressure using a specially developed tool in order to keep air from becoming trapped under the films.

The development of this new pressing process for the view control films has helped to ensure stable initial and long-term quality in the view control windows.

7. Conclusion

Newly developed view control windows have been employed as the trunk lid windows and rear tray windows in the next-generation FCX Clarity fuel cell vehicle.

- (1) The use of special polymer films that display a low haze ratio at the angle of the driver's line of sight but a high haze ratio at the line of sight from the exterior of the vehicle has enabled a clear rearward field of vision to be

reconciled with the privacy of the trunk space.

- (2) View control windows able to be used in a vehicle cabin environment have been developed with optimal design of structures and materials.
- (3) Efforts to optimize the production process for the view control windows have helped to ensure stable quality.

The use of the view control windows has reconciled good rearward visibility for the driver with the realization of a practical trunk capacity, without affecting the exterior design of the vehicle or vehicle standards.

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Technology for Rapid Manufacture of Prototype Molds for Instrument Panels

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ABSTRACT

A method has been developed enabling rapid manufacture of prototype molds for instrument panels used in test vehicles in the automotive development process.

The new prototype molds are produced using polypropylene injection molding, as used for mass-produced parts, enabling manufacture in a shorter period. The master model transcription method is used, obviating the necessity for heavy machining or electrical discharge machining. Carbon fibers have been used in the material for the new resin molds (known as “carbon molds”) resulting in outstanding strength and durability.

The new method was employed to manufacture prototype instrument panels for the new model INSIGHT, which were used in crash tests. The use of the new method has enabled prototype molds to be produced at the same cost as conventional ZAS molds, but with a 20% reduction in production time.

1. Introduction

Crash safety is an important automotive performance parameter. Crash safety laws and regulations become increasingly stringent year-by-year, and automakers are responding by increasing the safety of their vehicles. The instrument panel plays a role in occupant protection in a crash, and it is therefore necessary to create prototype

instrument panels of the same level as mass-produced instrument panels to be used in crash tests during new vehicle developments.

To enable the instrument panels to be tested using mass-production materials during the vehicle development period, molds are produced more quickly and at lower cost than mass-production molds, and used to manufacture prototype instrument panels by injection molding.

Conventionally, simple molds for prototype use, of the type shown in Fig. 1, have been manufactured using zinc alloys (these will be referred to as “ZAS molds” below), and the molds have been used to produce the number of prototype instrument panels required for crash tests.

2. Reduction of Period for Creation of Prototype Mold

The reduction of the period required to create a mold for the body of the instrument panel, which is lengthy in comparison with other resin parts, represented an issue in enabling response to today’s demand for reductions in the period for new vehicle development.

A development project for a new prototype mold (Fig. 2) was therefore undertaken in order to reduce the time for production of the mold against the conventionally-used ZAS molds.

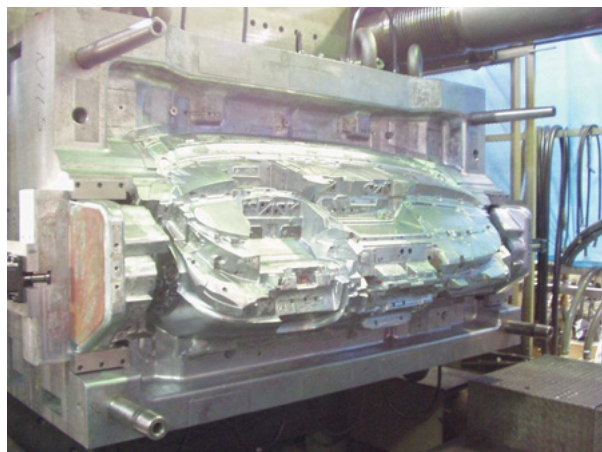


Fig. 1 ZAS mold

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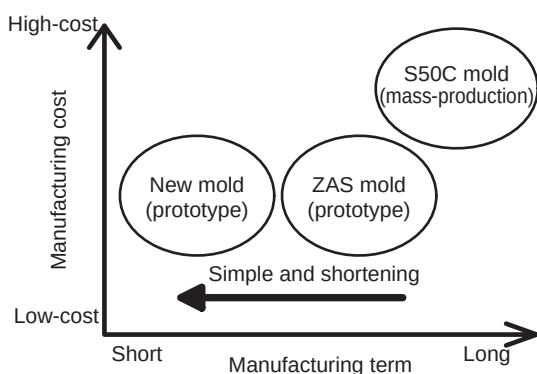


Fig. 2 Development concept for prototype mold

3. Development of New Prototype Mold

The creation of a form requires working of material. Whether carving or modeling in clay, a new form is created by adding or subtracting material. Mass-produced parts are manufactured through transcription from a mold, but it is necessary to add or subtract materials to create the form of the original mold. This project examined the mold manufacturing method and selected appropriate materials to enable the time required for this working of materials to be reduced, resulting in the development of a technology for rapid manufacture of prototype molds.

3.1. Selection of Manufacturing Method

The injection-molding molds used in mass-production are manufactured by NC machining of S50C and other steels. Only several hundred units will be produced from prototype molds, and they therefore do not need to display the durability of mass-production molds. Zinc alloy is currently used for prototype molds because it enables a rough form to be cast more easily than steel, and the speed of NC machining and other forms of processing is faster than it is for steel. The manufacturing method for the molds is well matched to its purpose in creating molds for prototypes, enabling injection molding of resins as in mass-production, but without the need for the level of durability achieved using steel.

In order to enable molds to be manufactured more rapidly than these conventional ZAS molds, the present project selected a manufacturing method enabling simple creation of a form.

It was determined that the mold would first be produced using a transcription method enabling the form to be transferred. Traditionally, a wooden pattern – a method in use since ancient times – has been used, but more recently, the material has been changed from wood to resin to produce what is known as a “master model.” The process of adding and subtracting material to create a form is easier using resin than metals. It was decided that the rough form of the instrument panel would be

produced using a master model.

The next procedure would be rapid prototyping, as exemplified by stereolithography. The detailed forms of the instrument panel would be produced using stereolithography, and these would be incorporated in the master model.

The mold form shown in Fig. 3 was created using these two methods.

The transcription method can also be used to transfer surface designs. Texturing of the mold is therefore possible simply by using a texture sheet or the like on the master model and transcribing. This reduces the time required for texturing from the four weeks required for conventional ZAS molds to only one week.

3.2. Selection of Mold Materials

Plaster or silicon rubber are generally employed as materials for molds used to transcribe forms. However, in the molds used for the injection molding of polypropylene to mass-produce instrument panels, high pressures are applied to high-temperature molten resin. In addition, the transcription process would require several days, and these materials therefore did not offer an advantage in terms of reducing manufacturing time against the ZAS molds.

The following conditions were therefore considered in the selection of materials:

- (1) Mold manufacturing process
 - Able to manufacture molds using existing equipment
 - Completion of transcription process within two days
- (2) Mold performance
 - Able to withstand molding pressures of 30 MPa
 - No damage resulting from contact with molding resin at 200°C
 - Heat conduction to enable cooling of molded resin

Based on these conditions, a thermosetting resin was selected as the mold material. This would mean that a resin would be used to form a resin; however, the polypropylene used in the mass-production of instrument



Fig. 3 Master model

panels is a thermoplastic resin. If a thermosetting resin displays heat resistance and does not melt at the melting temperature of a thermoplastic resin, it can be used as a mold material. Such molds, generally termed “resin molds,” are formed from epoxy resins mixed with aluminum powder, and are in use as a method of injection molding prototypes. However, the majority of these prototypes are cellular phones or objects of a similar size, and there are cases in which the mold is unable to resist the molding pressure and breaks when a large part such as an instrument panel is being formed.

The following points were therefore established as development aims:

- (1) Mold strength: Able to mold instrument panel
- (2) Durability: Sufficient durability to manufacture several hundred prototypes
- (3) Properties of molded part: Equivalent to part manufactured in ZAS mold
- (4) Accuracy: Equivalent wall thicknesses and external dimensions to mass-produced part

3.3. Method of Strengthening Mold Materials

The mold materials were strengthened to enable the development of a resin mold that was sufficiently durable to produce instrument panels.

The standard method of strengthening thermosetting resins is to use fibers to create a compound material known as a fiber reinforced plastic (FRP). In the present project, the conditions for the selection of materials, as discussed above, were also taken into consideration in the selection of the fibers to be used. It was decided to employ carbon fibers, and to create the mold using a carbon fiber reinforced plastic (CFRP).

The reason for this choice was that in addition to being generally known to possess a high degree of specific strength and a high specific modulus of elasticity, carbon also displays a low coefficient of thermal expansion, high heat resistance, chemical stability, and is self-lubricating. The selection focused in particular on carbon's high coefficient of thermal conductivity, which would increase the low coefficient of thermal conductivity of the mold material. It was considered that these properties of carbon would enable the development targets to be reached.

The molds employed in injection molding serve the function of absorbing the heat of and hardening molten resin. For this reason, the temperature of the molds increases during casting. A decline in the strength of the mold due to temperature increase, rendering it unable to resist pressure during casting, is thought to be one factor in breakages of large molds when employing conventional resin molds. It was thought that the use of carbon to increase the coefficient of thermal conductivity of the mold material would enable it to rapidly absorb and dissipate heat, thus controlling temperature increase and assisting in preventing a decline in strength.

A test mold was manufactured using carbon fibers and

epoxy resin in order to verify this concept. Molds were produced using cloth fibers and mild fibers, and their performance in injection molding was compared.

The cloth fibers were laminated by means of hand lay up. Because this is a manual method, transcription required four days. In addition, the cloth fibers were unable to trace the detailed forms of the instrument panel. As the mold cross-section in Fig. 4 shows, multiple voids occurred in the mold. The mold was unable to resist the pressure of injection molding, and cave-ins occurred on its surface, as shown in Fig. 5.

In the case of the mild fibers, the fibers and the resin were laminated using a simple spray-up. Figure 6 shows

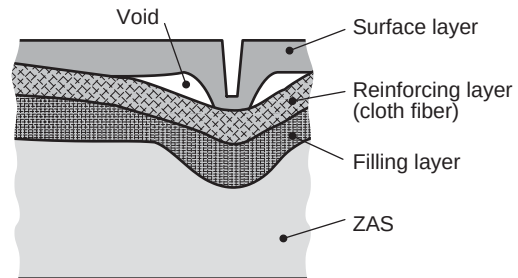


Fig. 4 Void due to lamination defect

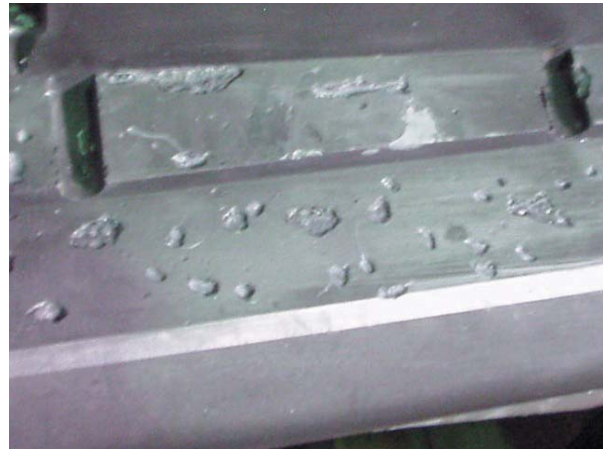


Fig. 5 Cave-in due to void

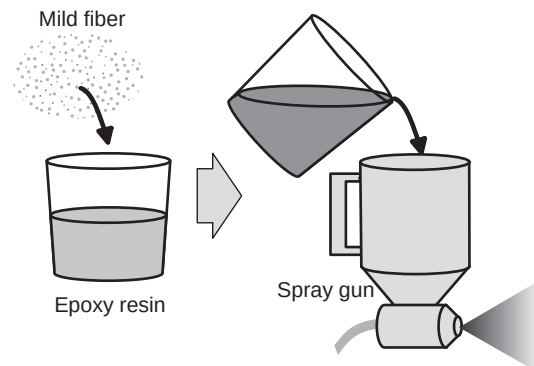


Fig. 6 Simple spray-up of CFRP

Table 1 Comparison of materials

	Unit	Carbon epoxy	Aluminum epoxy	ZAS
Tensile strength	MPa	63.5	52.0	244.0
Tensile elongation	%	10.3	3	4
Rockwell hardness	—	93.1 HRM	35.3 HRM	63.0 HRG

a schematic of this simple method. Mild carbon fibers of 1 mm or less in length were mixed with epoxy resin, and applied from a spray gun. The carbon fibers were able to trace the detailed forms of the instrument panel, and lamination was possible with no voids. In addition, the transcription process required only two days. For these reasons, spray-up lamination of mild fibers was selected as the method used to produce the mold.

Next, test pieces were formed using a variety of spray guns and mild carbon fibers and subjected to tensile strength tests in order to determine whether a mold laminated with mild carbon fibers alone would be sufficiently strong to resist injection molding (Fig. 7).

As Table 1 shows, the carbon epoxy material performed better than the conventional aluminum epoxy resin mold material in tensile strength tests. In addition, it displayed greater elongation than aluminum epoxy or ZAS. The fact that cloth fibers could not be used reduced the rigidity of the material, but the flexibility imparted to the mold by the elongation characteristic of the material would make it less prone to breakage. It was considered that this would increase the resistance of the mold to damage or cracking under injection molding pressures.

The development concept for the new mold was to be sufficiently flexible to resist injection molding pressures. Given that the method was considered to offer sufficient potential for the achievement of development targets, the simple spray-up method was adopted to produce the molds.

This simple spray-up method of lamination using a mixture of mild carbon fibers and epoxy resin was employed to produce the test mold shown in Fig. 8, which incorporated the complex forms of the instrument panel's bosses and ribs.

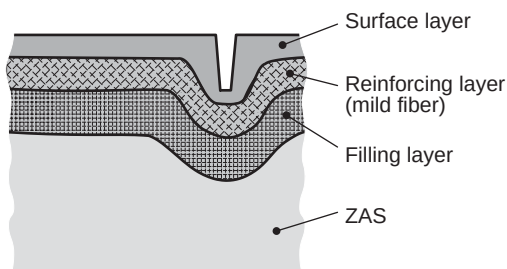


Fig. 7 Voidless lamination using spray

The lengths of the bosses and ribs in this test molding were at the upper limit for lengths in instrument panel design. Successful molding of these elements of the instrument panel form by the test mold would indicate the applicability of the new method to any instrument panel.

In order to determine whether the mold was able to resist molding pressures, an injection molding test was conducted using polypropylene, as used in the mass-production of instrument panels.

Molding of the same type as conducted in ZAS molds was conducted for the molding test. As Fig. 9 shows, an internal pressure of 37 MPa was measured, but the mold did not break. It was therefore judged that the target, a level of strength enabling molding of an instrument panel, had been achieved.

In conventional resin molds, metal inserts are embedded in the detailed forms in order to help prevent breakage of the mold. As Fig. 10 shows, inserts formed by machining aluminum or other metals are embedded in vulnerable sections where the resin mold would be prone to breakage in order to strengthen it. However, embedding



Fig. 8 Test mold

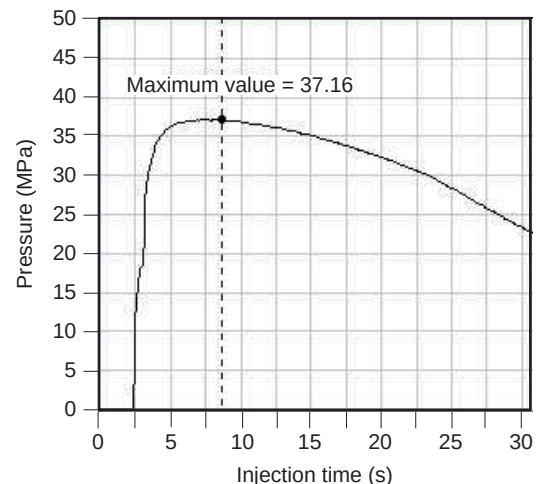


Fig. 9 Internal pressure of mold

inserts in the mold can also cause cracks, and these cracks can become the points of origin of breakage of the mold.

If the flexibility of the material used in the developed mold (termed a “carbon mold” below) could be exploited to create a mold configuration matching the elements of the form of the instrument panel discussed above, injection molding could be carried out without any requirement for inserts. This insertless molding is another feature of the developed method, and the consequent reduction in the use of machining has also contributed to reducing the time for manufacture of the molds.

3.4. Properties and Accuracy of Molded Parts

The test mold was designed to enable molding of test pieces for tensile and other tests. Test pieces were also molded in a ZAS mold. Comparison of the tensile strength and elongation of the test pieces showed that the properties of the parts molded in the carbon and the ZAS molds were almost identical.

The accuracy of the molded part is affected by the accuracy of the transcription of the master model. The wall thickness and external dimensions of the parts molded in the test mold were within design tolerances. It was demonstrated that the developed mold, while being flexible and able to be produced using a simple transcription process, was able to resist injection molding pressures, and the molded parts fell within the required range of accuracy. These results showed that the project had successfully developed a carbon mold able to mold the bosses and ribs of an instrument panel.

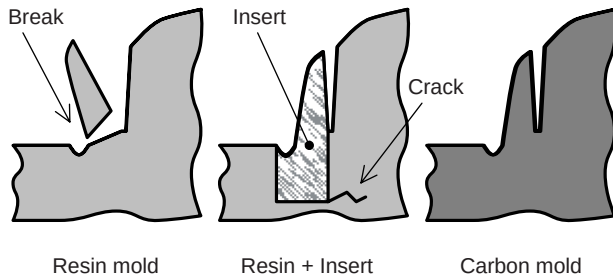


Fig. 10 Insertless molding of vulnerable sites

4. Method of Manufacture of Carbon Mold

As the cross-section in Fig. 11 shows, the carbon mold used in the new manufacturing method is made up of a CFRP layer that forms the molded part, and a ZAS section that reinforces the main mold, i.e., the section of a ZAS mold that forms the molded part has been replaced with CFRP. As Fig. 7 shows, this CFRP layer is composed of three layers: a surface layer, a reinforcing layer, and a filling layer.

In addition to the main mold that forms the instrument

panel, the slide core and the small mold used in the undercut sections are manufactured using a mixture of mild carbon fibers and epoxy resin.

4.1. Main Mold

The master model, which represents the basis of the form of the main mold, is given the form of the desired product by NC machining of a general purpose tooling resin.

The ZAS core is formed in the same way as a conventional ZAS mold, by casting in a sand mold using a disappearing model.

As indicated above, the CFRP layer has a three-layer structure. The surface and reinforcing layers are laminated in the master model. The surface layer is laminated by means of a spray-up of a mixture of epoxy resin and carbon powder. Next, the reinforcing layer is laminated by a spray-up of a mixture of epoxy resin and mild carbon fibers. As shown in Fig. 12, the master model in which these two layers have been laminated is covered by a ZAS core. The ZAS core is manufactured by casting a rough form which incorporates the section that produces the molded part and a 15 mm cavity. The ZAS core is not machined. The filling layer, composed of a mixture of mild carbon fibers and epoxy resin, is injected into the cavity.

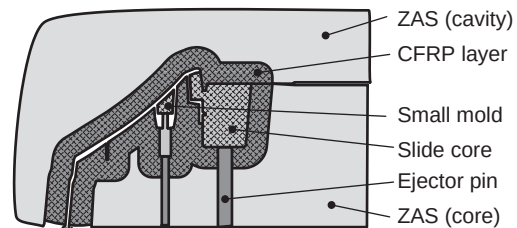


Fig. 11 Section of assembly mold



Fig. 12 Combination of master model and ZAS core

4.2. Slide Core and Small Mold

To produce the slide core and small mold, models are created using stereolithography (Fig. 13), and the material is poured into these models (Fig. 14). As in the case of the filling layer of the main mold, the material used is a mixture of mild carbon fibers and epoxy resin.

When the material has hardened, the casting is demolded from the stereolithographic model and the small mold is removed. There is no requirement for machining or electrical discharge machining.

After the completed slide core and small mold have been coated with a demolding agent, they are placed in the master model of the main mold, and a pocket shape



Fig. 13 Model for rapid prototyping



Fig. 14 Casting of core

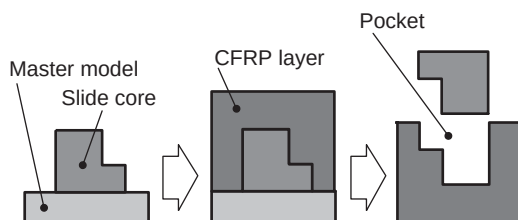


Fig. 15 Non-machined pocket

in which the slide core will be fitted is transcribed to the main mold by lamination of the CFRP layer (Fig. 15). The fact that there is no requirement for machining or lapping of the pocket shape reduces the time required to manufacture the mold.

5. Example of Application of Carbon Mold

The carbon mold prototype manufacturing method was employed during the development process for the 2009 year model INSIGHT (Fig. 16). The use of the new mold reduced mold manufacturing time by 20% against conventional ZAS molds. The bodies of the instrument panels were molded using equivalent injection molding pressures to those used in ZAS molds, and the panels were used in a variety of tests, including crash tests.

The use of the method in the INSIGHT development process also served as a durability test. Two hundred instrument panels were produced in different batches, but no breakage of the mold was observed, and the method was able to supply the prototype parts required for the new vehicle development process.

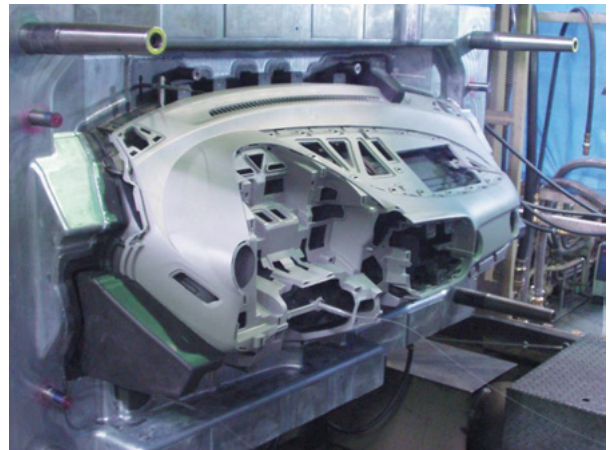


Fig. 16 Carbon mold for INSIGHT prototype

6. Conclusion

A carbon mold has been created specifically for the molding of instrument panels, which are large parts with complex forms. The cost of manufacturing the molds is the same as that for conventional ZAS molds, but 20% less time is required for manufacture, enabling the new method to supply prototypes in a shorter period. If the parts to be produced are small, even if their forms are complex, a carbon mold can be manufactured by transcription from a rapid prototyping model alone, without the need to create a master model by NC machining.

Another advantage presented by the carbon mold is the ease with which the mold can be altered and additionally

worked, a feature that is unique to resin molds. Adding to or subtracting from a ZAS mold necessitates welding and heavy machining, while a carbon mold can be worked as easily as using putty to add and a chisel to subtract. The mold can even be altered without removal from the molding machine.

7. Afterword

The project for the development of a prototype manufacturing technology discussed in this paper provided an opportunity for reflection on the importance of production engineering development, and for consideration of what precisely is evaluated using prototype parts, what the performance requirements of the prototype parts are, and what factors make a prototype manufacturing tool easy to use. The development of prototype manufacturing technologies will continue, to enable the process of new vehicle development to be accelerated.

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Yasuhiro TOGUCHI

In-line Recycling Technology for AZ91D Magnesium Alloy

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ABSTRACT

An in-line recycling technology and equipment for recycling scraps generated in the process of die casting AZ91D magnesium alloy parts have been developed. The new technology enables the scraps to be recycled at the same quality as primary alloy and the molten metal to be continuously supplied to the die casting process.

Material and melting costs have been reduced by approximately 20% compared to the use of conventional recycled ingots. The technology has been applied in the manufacture of magnesium head covers and intake manifolds for V6 engines from 2009 year models onwards.

1. Introduction

The achievement of automotive weight savings in order to increase fuel efficiency is an important issue today, in view of global environmental issues and other factors. In Europe and the U.S. in particular, there is an increasing trend towards the use of magnesium alloys as a means of achieving these weight savings. Honda has also, to date, commenced mass production of engine head covers, steering wheels, and V6 engine intake manifolds using a general purpose magnesium alloy, and oil pans and manual transmission cases using a heat-resistant magnesium alloy.

However, magnesium alloys display a high level of activity, and attempting to help ensure burn, oxidation resistance and corrosion resistance increases costs against aluminum alloy parts, a factor that limits the application of magnesium alloys in numerous cases. The reduction of costs is therefore an important issue in enabling increased use of these materials.

In the case of aluminum alloy parts, die casters are able to directly recycle the scraps such as runners, biscuits, warm-up shots, and casting rejects that are produced during casting. However, while some

manufacturers are able to do so in the case of magnesium alloy scraps, the vast majority send the scraps out to specialist recycling companies. The resultant costs for transporting scraps and recycled ingots, recycling, and ingot-forming is one factor that increases the cost of magnesium alloy parts against those of aluminum alloy parts.

2. Development Goals

The aim of the project discussed in this paper was to reduce the manufacturing costs of magnesium alloy parts by enabling in-house recycling of AZ91D magnesium alloy scraps by die casters (Fig. 1) and instituting an in-line recycling process, in order to increase the application of lightweight magnesium alloys. The following specific goals were established:

- (1) Development of a technology enabling scraps to be recycled, including runners and biscuits, to the same quality as primary alloys
- (2) The development of in-line recycling equipment able to continuously supply recycled molten metal to the casting process

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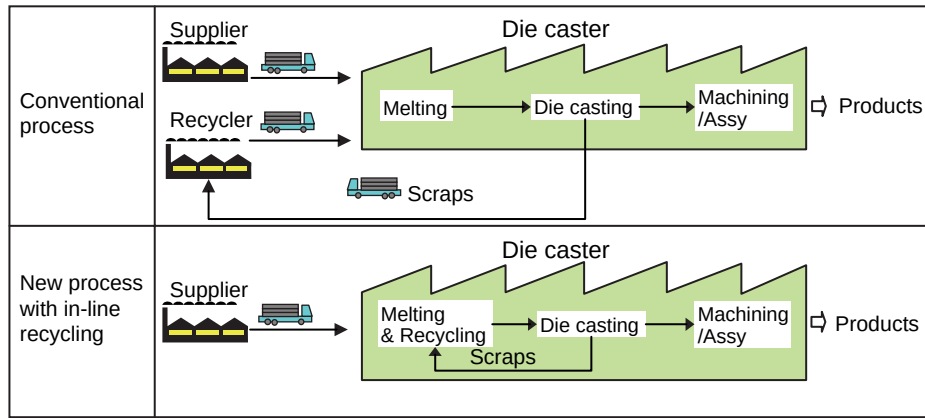


Fig. 1 Comparison of manufacturing process for AZ91D magnesium alloy parts

Table 1 Chemical components of AZ91D and effect of melting

		Chemical component (wt%)						
		Al	Zn	Mn	Si	Cu	Fe	Ni
AZ91D specification (ASTM B93)	Alloy	8.5 -9.5	0.45 -0.9	0.17 -0.40	0.05 Max	0.025 Max	0.004 Max	0.001 max
	Product	8.3 -9.7	0.35 -0.10	0.15 Min	0.10 Max	0.03 Max	0.005 Max	0.002 max
Scrap	Before melting	8.8	0.80	0.19	0.03	0.003	0.0049	0.0005
	After melting	8.8	0.80	0.18	0.03	0.003	0.0055	0.0005
Primary alloys	Before melting	9.1	0.82	0.23	0.03	0.003	0.0010	0.0005
	After melting	9.0	0.81	0.22	0.03	0.003	0.0015	0.0007

3. Technological Issues

As Table 1 shows, the specifications regarding alloy composition and the quantities of Fe, Ni, and Cu in the finished product are strict for AZ91D in order to help ensure corrosion resistance⁽¹⁾. To enable the nature of the changes occurring in the components of AZ91D during the melting and casting processes to be determined, scraps from a diecast product and a primary alloy were dissolved and cast into 200 mm-long plate-shaped test pieces measuring 55 x 20 mm. Following cooling, the microstructures of these test pieces were compared, enabling the agenda for scrap material recycling to be determined. The melting temperature and the holding time until casting for the test pieces were average figures drawn from melting and casting conditions.

Table 1 shows the composition of the materials before and after melting. For both the scraps and primary alloy, no change is observed in Ni and Cu content, but Fe content increases in both cases. The Fe content of the scraps before melting is 49 ppm, close to the upper limit in product standards. Following melting, Fe content increases to 55 ppm, exceeding the maximum established in product standards. The solubility limit of the Fe

	After remelting of primary alloys	After remelting of scraps
Fe (ppm)	15	55
Organization		
Composition analysis (EPMA)		
Corrosion resistance (after 24 hr salt spray test)		

Fig. 2 Comparison of organization and corrosion resistance after remelting of AZ91D scraps and primary alloys

increased from less than 1 ppm to more than 30 ppm at 650°C⁽²⁾. Given this, the increase in the Fe content can be attributed to the fact that the Fe from the crucible is eluted into the molten metal in the melting and holding processes.

The test pieces were cut through the middle and abraded to enable study of their microstructures and corrosion resistance. The results are shown in Fig. 2. When depositions between which no differences could be observed using optical microscopy were subjected to electron probe micro-analysis (EPMA), they were determined to be Al_6Mn in the primary alloy, while they were $\text{Al}_8(\text{Mn}, \text{Fe})_5$ in the scraps, in which Fe content had increased. A decline in corrosion resistance was determined. $\text{Al}_8(\text{Mn}, \text{Fe})_5$ has a higher potential difference with the magnesium mother phase than Al_6Mn , and it was conjectured that the deposition of this intermetallic compound due to the increase in Fe content had caused corrosion resistance to decline⁽³⁾.

In addition, the vacuum fusion extraction absolute pressure reading method was used to study the gas content of the test pieces, and they were also cut through the middle to enable evaluation of the ratio of their surface area occupied by inclusions. The results showed that gas content and inclusions had both increased in the scrap material. These included gases trapped during casting and surface oxide films, and it was therefore considered that casting quality and product strength might decline if the material was recast without their removal.

Based on the tests discussed above, the following agenda was set for the recycling of AZ91D magnesium alloy scraps:

- Reduction of Fe content
- Removal of gases and inclusions

In order to enable these objectives to be met, the project decided on the development of in-line recycling equipment, which would enable continuous supply of recycled molten metal to the casting process at the same quality as primary alloy, and without any change to casting conditions such as cycle time.

4. Development of Recycling Technology

4.1. Reduction of Fe Content

Figure 3 shows the behavior of Al-Mn-Fe intermetallic compounds in a molten Mg-9%Al alloy, as reported by Holta, et al⁽⁴⁾. L indicates the liquid phase, and $\text{L} + \text{Al}_8(\text{Mn}, \text{Fe})_5$ indicates that the intermetallic compound $\text{Al}_8(\text{Mn}, \text{Fe})_5$ is deposited in the liquid phase. The range of deposition of $\text{Al}_8(\text{Mn}, \text{Fe})_5$ expands with increasing Fe content in the molten metal. This correlates with the test results discussed in Chapter 3, that numerous deposits of $\text{Al}_8(\text{Mn}, \text{Fe})_5$ were observed in the test piece in which Fe content had increased. Even if the Fe content is constant, an increase in the Mn content or a reduction of the temperature of the molten metal results in the

deposition of $\text{Al}_8(\text{Mn}, \text{Fe})_5$ or $\text{Al}_6(\text{Mn}, \text{Fe})$. This indicates that control of the Mn content and the temperature of the molten metal could be used to promote the deposition and settling of Al-Mn-Fe intermetallic compounds artificially, thus enabling the Fe content of the alloy to be reduced. Obtaining a Mn content of 0.18% or more when the molten metal temperature is 660°C and of 0.22% or more when the molten metal temperature is 670°C would enable the deposition and settling of the intermetallic compound $\text{Al}_8(\text{Mn}, \text{Fe})_5$, as well as the consequent reduction of the Fe content of the alloy when the Fe content exceeded 40 ppm, the upper limit for alloy standards.

The addition of Al-Mn, as used when primary alloys are cast, is available as a method of obtaining high Mn content. However, given that a rapid increase in Mn content was necessary in the in-line recycling method, it was decided that the Mn content would be increased by adding a primary alloy containing an appropriate quantity of Mn at a fixed ratio.

In order to control the elution of Fe from the crucible and obtain the necessary Mn content, it was desirable to

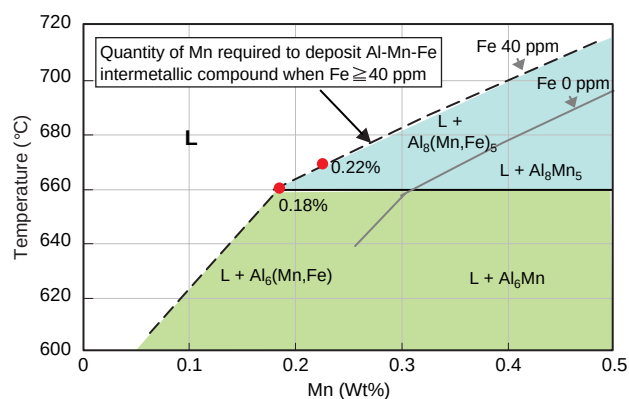


Fig. 3 Composition of Mg-9%Al-Fe-Mn alloy

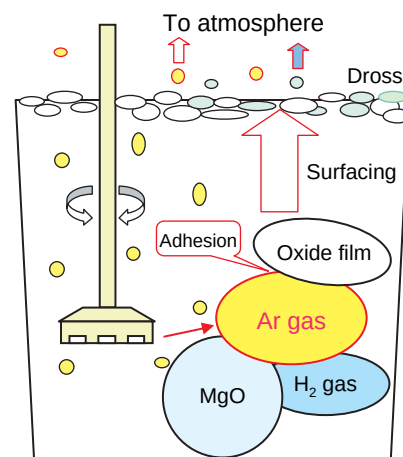


Fig. 4 Concept of reduction of gas/oxide in smelting process

reduce the temperature of the molten metal. However, a temperature of 660°C or more was needed to enabling the alloy to be melted without leaving any residue of the intermetallic compounds (Al_6Mn and $\text{Al}_6(\text{Mn}, \text{Fe})$) formed by the Mn.

It was decided that promotion of the deposition and settling of the intermetallic compound of Mn, $\text{Al}_8(\text{Mn}, \text{Fe})_5$, by means of controlling the Mn content and the temperature of the molten metal, would be employed as a method of reducing the quantity of Fe in the alloy.

4.2. Reduction and Removal of Gases and Inclusions

The addition of flux to the alloy is one method of removing gases and inclusions from AZ91D alloy scraps, but a considerable amount of time is required for settling following the addition of the flux, making this method unsuitable for in-line recycling. The method shown in Fig. 4⁽⁵⁾, which does not involve the use of flux, was therefore selected. A metal treatment unit with two-way rotation is used, enabling separation and flotation of gases, inclusions, and oxide films in the molten metal by means of argon gas bubbling. The unit turns argon gas into fine bubbles, and a shaft and disk for dispersion of the argon gas bubbles rotate in the opposite direction every few seconds. This controls the drawing in of dross on the surface of the molten metal and the stirring up of sludge that has settled on the bottom of the crucible, and distributes argon gas uniformly throughout the molten metal. This results in a short settling time following treatment, making this method suitable for in-line recycling.

4.3. Development of Equipment for In-line Recycling Use

In order to realize in-line recycling, it was necessary to reduce the Fe content of the alloy and remove the gases and inclusions quickly and continuously, without changing casting conditions such as cycle time. In order to enable this, an in-line recycling furnace for melting, smelting, and settling the alloy was developed by dividing the crucible into three sections. Control of the temperature of the molten metal in the first section has been enabled by optimization of the temperature and the positioning of the

Table 2 Mn and Fe content in AZ91D after in-line recycling

Material		Mn (%)	Fe (ppm)
Before recycling	Primary alloy	0.234	10
	Scrap	0.204	36
After recycling	50% scrap/primary alloy	0.217	20

burner. The scraps, to which primary alloy has been added in order to adjust their Mn content, are introduced to the first section, where they are melted in order to promote deposition and settling of $\text{Al}_8(\text{Mn}, \text{Fe})_5$ and reduce their Fe content. The metal treatment unit with two-way rotation is positioned in the second section. The speed of rotation of the disk, the period for counter-rotation, and the flow rate of the argon gas have been optimized, enabling separation and flotation of the gases and inclusions in the molten metal by means of uniform dispersion of argon gas. The sludge that has been stirred up in the process of treatment of the molten metal is then allowed to settle in the third section, after which the recycled molten metal is supplied to the casting process.

This three-section recycling furnace is connected to the melting and dosing furnace contiguous to the die-casting machine by a siphon tube, enabling the realization of in-line recycling (Fig. 5).

4.4. Recycled Molten Metal and Product Quality

In order to help prevent foreign matter or extraneous material from adhering to or being mixed with the scraps for recycling, only runners, biscuits, warm-up shots, and parts rejected during the casting process are used, and the mixing ratio is determined by the quantity of scraps produced and the quantity of Mn in primary alloy required to reduce the Fe content of the scraps.

Table 2 and Fig. 6 show the results of an evaluation of the quality of the recycled molten metal using a 50% mix of scraps from the casting of a head cover. The recycling processing has reduced the Fe content, and the quantities of gases and inclusions have also been reduced to a level equivalent to or below those of primary alloy. Figure 7 shows the external appearance of the part cast by supplying this recycled molten metal to the melting and dosing furnace contiguous to the die-casting machine. The external quality of the part cast using the recycled alloy is equivalent to that of a part cast using primary alloy. Figure 8 shows the results of a strength test of a test piece cut from the part. The average strength of the test piece is the same as that of a primary alloy test piece, but the range of $\pm 3\sigma$ variation is approximately 26% lower in the case of the recycled alloy, indicating that the stability of its quality is equivalent to or greater than that of primary alloy.

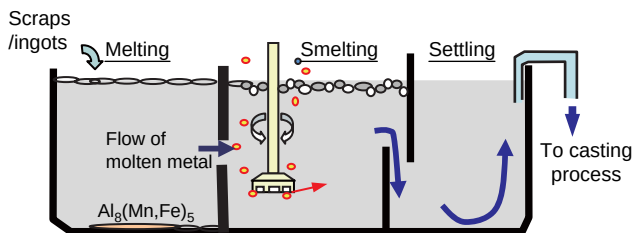


Fig. 5 Process of manufacture of AZ91D magnesium alloy parts with in-line recycling furnace divided into three rooms

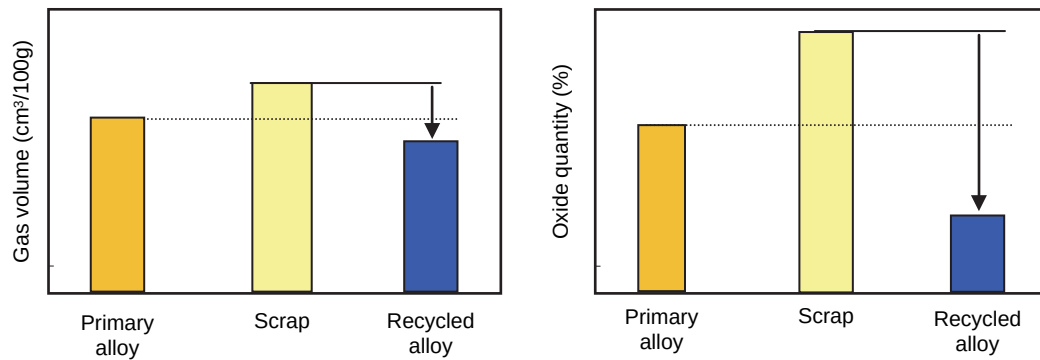


Fig. 6 Comparison of gas volume/oxide quantity after AZ91D in-line recycling

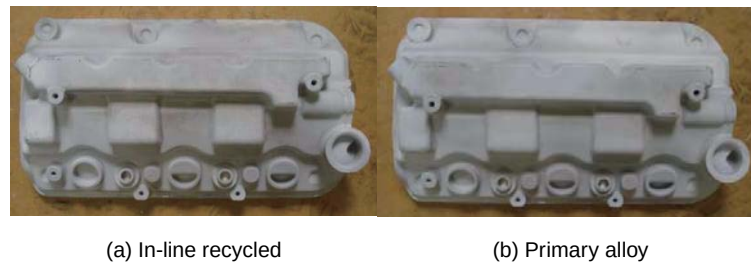


Fig. 7 Comparison of appearance of AZ91D magnesium front head cover for V6 engine

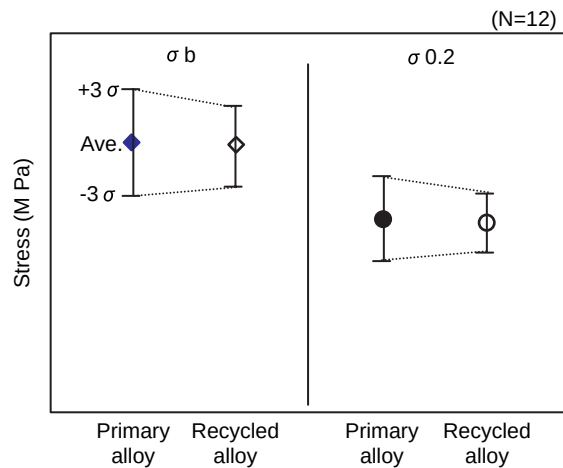


Fig. 8 Comparison of intensity of stress in test pieces taken from AZ91D magnesium front head covers

5. Conclusion

A technology for recycling AZ91D magnesium alloy scraps and an in-line recycling furnace based on this technology have been developed. The new method produces recycled alloy of an equivalent quality to primary alloy, but the cost of producing and melting the material is approximately 20% lower than the cost when using conventional recycled ingots. In addition, doing

away with the requirement for forming the recycled molten metal into ingots, re-melting and transporting the material, has reduced the CO₂ released during production by approximately 36%. The new technology has been applied in the production of V6 engine head covers and intake manifolds from 2009 year models onwards.

The details of the new technology are as follows:

- (1) Reduction of the Fe content of recycled magnesium alloy through control of Mn content and the temperature of the molten metal, and the removal of gases and inclusions through the use of a metal treatment unit with two-way rotation, have enabled AZ91D magnesium alloy scraps to be recycled at the same quality as primary alloy.
- (2) The division of the crucible into three sections and the optimization of the temperature and position of the burner and the processing conditions for the molten metal have enabled the development of an in-line recycling technology able to rapidly and continuously supply recycled molten metal to the casting process, with no modification of casting conditions.

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Precision Measurement Method of Circumferential Length and Uncertainty for Steel Ring in CVT-pushing Belt

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ABSTRACT

The accuracy of the circumferential length of the metal rings used in CVT-pushing belts need to be controlled on the micrometer level to help ensure the durability of the belts. The principle used in measuring the circumferential length of the metal rings is the measurement of infinitesimal differences in length between a master ring for circumferential length and the ring being examined. A highly accurate measurement method and a method of evaluating the uncertainty of these measurements are therefore necessary for the master ring for circumferential length.

In the measurement method discussed in this paper, the master ring for circumferential length is positioned between two rollers, the length between the centers of the rollers and the radii of the sections of the rollers around which the ring winds are measured, and the circumferential length of the ring is quantified. A high level of accuracy has been realized in the two sets of measurements through the use of a high-accuracy three-dimensional coordinate measuring machine (CMM). In addition, the uncertainty of the measurements of the length between the centers of the rollers and the radii of the rollers is quantified using gauge block and gauge ring measurements.

Because gauge blocks and gauge rings are instruments of a standard length with a specified level of dimensional uncertainty, the measured results for the master rings for circumferential length based on this measurement method are traceable with a high degree of accuracy.

1. Introduction

CVT-pushing belts are made up of layers of multiple metal rings. To help ensure belt durability, it is necessary to precisely control the circumferential length of the rings. The principle used in the measurement of the circumferential length of the metal rings is the measurement of infinitesimal differences in length between a master ring for circumferential length (MRC) and the ring being examined.

The accuracy of the circumferential length of individual rings is on the micrometer level. This level of accuracy depends significantly on the accuracy of the MRC. However, the accuracy of measurement of the MRC has not to date been sufficiently discussed. This is because issues itemized below arise in the measurement, during which the MRC is placed between two rollers, the length between the centers of the rollers and the radii of the

rollers at the sections around which the ring winds are measured, and the results are taken to represent the circumferential length of the MRC.

- (1) The achievement of increased accuracy in the measurement of the length between roller centers
- (2) Complexity of evaluation of uncertainty in measurements

The method of precision measurement of MRC to be introduced in this paper employs a high-accuracy three-dimensional coordinate measuring machine (CMM) in order to measure the length between the centers of the rollers and the radii of the rollers at the sections around which the ring winds. A practical method of evaluating the uncertainty of CMM measurements involving comparative measurements using calibrated workpieces is also proposed in ISO/TS 15530-3⁽¹⁾.

Following ISO/TS 15530-3, by means of this method of evaluating uncertainty, the uncertainty of measurements of the length between the centers of the rollers and the

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radii of the rollers at the sections around which the ring winds can be quantified, respectively, from gauge block and gauge ring measurements. Gauge block and gauge ring measurements display a low level of uncertainty, and help to ensure traceability of length at a high level of accuracy for MRC measurements.

With today's globalization of production systems, the importance of technologies enabling efficient quality control in the distribution of parts is increasing. The integration of methods of evaluating reliability and methods of evaluating uncertainty, in particular methods based on ISO standards, is beginning to spread widely.

This paper will discuss a method of evaluating uncertainty, and will present an evaluation of the uncertainty of MRC measurements as an example of the application of the method.

2. Principle of Measurement of Master Ring for Circumferential Length and Uncertainty

2.1. Method of Quantification of Uncertainty and Method of Part Inspection

Uncertainty expresses the range of variation within which the true value of a measurement result exists. Standard deviation, σ , is used as the statistic quantitative expression for the degree of uncertainty. For example, if the uncertainty of a measurement result "a" is 2σ , then there is a high level of confidence - a probability of 95.4% - that the true value exists in the range defined by $a \pm 2\sigma$. The procedure for quantifying uncertainty can be summed up simply as follows.

- (1) The multiple factors in the uncertainty relating to measurement subject $Y(x_1, x_2 \dots x_n)$ are enumerated.
- (2) A mathematical model of measurement subject Y is formulated using the variables $x_1, x_2 \dots x_n$.

$$Y = f(x_1, x_2 \dots x_n)$$

- (3) The uncertainty of each factor x , $u(x)$, is quantified individually, and if there is no correlation between the factors, the combined standard uncertainty of Y , $u(Y)$, is expressed as follows:

$$u(Y) = \sqrt{\left(\frac{\partial f}{\partial x_1}\right)^2 u^2(x_1) + \dots + \left(\frac{\partial f}{\partial x_n}\right)^2 u^2(x_n)}$$

The standard for judging the conformance of the part, including measurement uncertainty, is provided by JIS B0641 (Geometrical Product Specifications (GPS) – Inspection by measurement of workpieces and measuring equipment – Part 1: Decision rules for proving conformance or nonconformance with specifications)⁽²⁾.

As Fig. 1 shows, the conformance of the part in

relation to the specification zone 1 is judged within the scope that is not excluded by measurement uncertainty (U). Because of this, when measurement uncertainty is high, the conformance zone 3 is small. When the conformance of the same part is judged in different production facilities, it is necessary to consider the traceability of the evaluation of uncertainty.

2.2. Measurement of the Master Ring for Circumferential Length

Figure 2 shows the components of a CVT-pushing belt. The belts are made up of multiple layered metal rings and elements. The MRC is arbitrarily selected from the metal rings.

Figure 3(a) shows an overview of the MRC measurement device. The MRC, with a circumferential length of approximately 650 mm, is wound around rollers 1 and 2, which have diameters of approximately 110 mm. A 20 kg weight is attached to the slider, and, because it is a mechanism that moves translationally in the Y direction, the slider, which is positioned at roller 2, exerts tension on the MRC.

The degree of rotation of roller 1 is measured using a rotary encoder. This device is positioned on the plate of the CMM when the length between the centers of the rollers is measured. In this paper, the CMM measurement accuracy, U , is $U = 0.4 + L_E/1000 \mu\text{m}$, where L_E is the millimeter-level evaluated length.

When the MRC is positioned between rollers 1 and 2, and the rollers rotate with the tension exerted by the

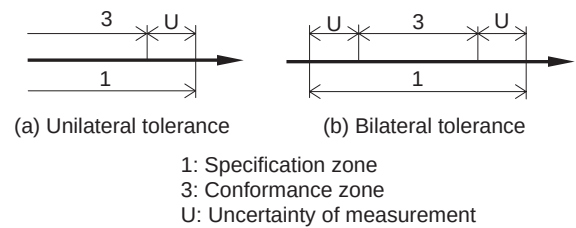


Fig. 1 Product inspection considering uncertainty of measurement

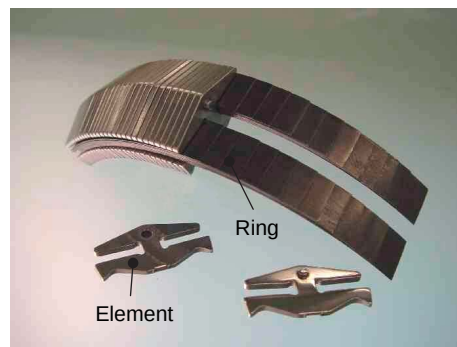


Fig. 2 Components of CVT-pushing belt

weight, due to the centering effect of the surface of the inner circumference of the MRC and the arcs of the cylindrical surface of the rollers, the apex of the arc of the inner circumference of the MRC, S_1 , and the apex of the arc of roller 1, H_1 , match, as shown in Fig. 3(b). In the same way, S_2 for the inner circumference of the MRC and the apex of the arc of roller 2, H_2 , also match.

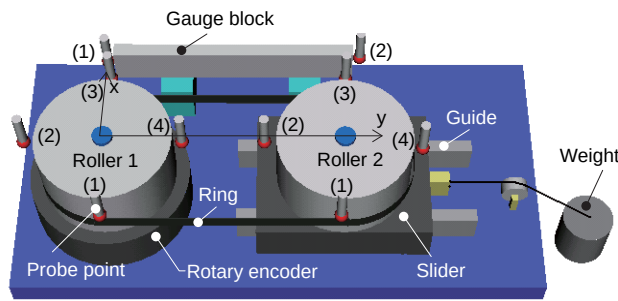
The height of the rollers is adjusted in order to reduce the difference between the positions of the apices of their arcs, Z_1 and Z_2 , to 0.1 mm or less. By this means, the cosine error for the length between the centers of the rollers is reduced to 0.03 μm , enabling it to be ignored.

Measurement of the coordinates of the centers of rollers 1 and 2 at this time enables the length between the centers of the rollers, E , to be calculated. If the measured figures for the radii of the apices of the arcs around which the MRC is wound are termed R_1 and R_2 for rollers 1 and 2 respectively, the circumferential length of the MRC, L , can be expressed as Eq.(1). According to the principle of propagation of uncertainty^{(3),(4)}, the uncertainty of L , $U(L)$, can be expressed as Eq.(2), where there is no correlation between E , R_1 , and R_2 , and k is the coefficient of inclusion.

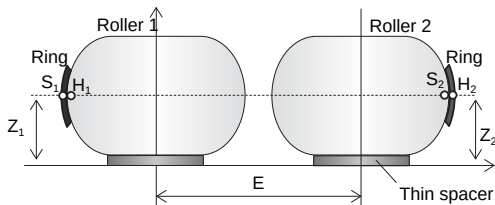
$$L = 2E + \pi (R_1 + R_2) \quad (1)$$

$$U(L) = k \times \sqrt{4U^2(E) + \pi^2 (U^2(R_1) + U^2(R_2))} \quad (2)$$

The coordinates of the centers of rollers 1 and 2 are calculated from measurements taken at four measurement points equi-positioned on the cylindrical surface of each



(a) Probe points position for measurement of length between two rollers using CMM



(b) Adjustment of roller's height for reducing cosine error

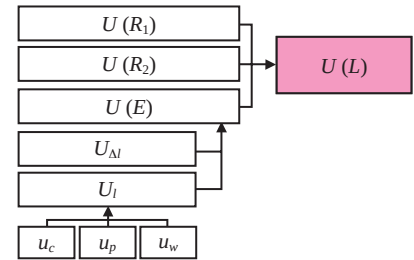
Fig. 3 Schematic diagram of instrument for CVT ring circumferential length measurement

roller [Fig. 3(a)]. In order to compensate for the effect of the eccentricity of rollers 1 and 2 on the length between the centers of the rollers, E , the rollers are synchronized and E is measured for multiple 15 deg rotations of the rollers.

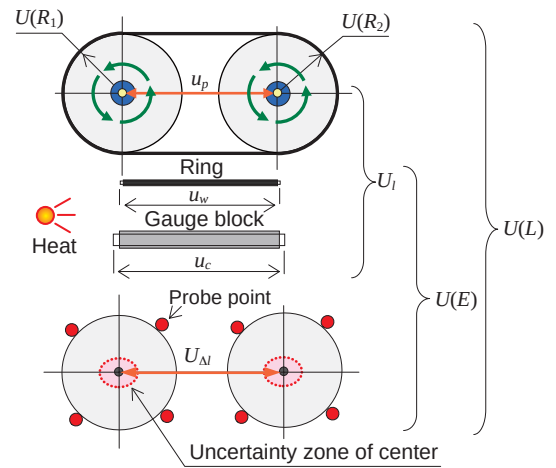
The data obtained displays a systematic fluctuation due to eccentricity that is dependent on the angle of rotation of the rollers. The length between the centers of the rollers can be numerically corrected. For the present measurements, the length between the centers of the rollers was measured after every 15 deg rotation for 24 times.

In addition, when the length between the centers of the rollers is measured, the length of a 150 mm gauge block, equivalent to the length between the centers of the rollers, is measured in order to compensate for the effect of thermal expansion on the scale in the CMM. The position of the end of one side of the gauge block is aligned with the center of roller 1, and the gauge block is positioned parallel to the line connecting roller centers.

The gauge block length measurements enable the uncertainty of the length measured by the CMM to be



(a) Combination of uncertainties for ring circumferential length measurement



(b) Classification of uncertainty sources

Fig. 4 Classification of uncertainty sources and combination for uncertainty of ring circumferential length measurement

known and the uncertainty of the measurement of the length between the centers of rollers to be evaluated.

The purpose of this measurement method is to quantify the uncertainty of the circumferential length, L , expressed by Eq. (1). As shown in Fig. 4(a), there are three broad factors generating uncertainty in this measurement method: the uncertainty of the radius of roller 1, $U(R_1)$, the uncertainty of the radius of roller 2, $U(R_2)$, and the uncertainty of the length between the centers of the rollers, $U(E)$. $U(L)$ from Eq. (2) is a synthesis of these factors.

Figure 4(b) shows a classification of the factors generating uncertainty in $U(L)$. u_c is the uncertainty of the calibrated value from the gauge block and the compensation for thermal expansion, u_p is the uncertainty of the length between the centers of the rollers originating in change of the contact faces between the rollers and the ring due to the rotation of the rollers, and u_w is the uncertainty of compensation for thermal expansion of the metal rings. U_l is the combined standard uncertainty synthesized from u_c , u_p , and u_w .

$U_{\Delta l}$ is the uncertainty of the length between the centers of the rollers originating in the uncertainty of the roller center coordinates, which are determined solely by the position and number of the measurement points used in the CMM circular measurements, and the accuracy of the shapes of the subjects of the measurements.

3. Results of Measurement of Master Ring for Circumferential Length and Evaluation of Uncertainty

Figure 5 shows the results of measurements of the length between the centers of the rollers and the results following compensation for the eccentricity of the rollers. The median value of the measurements prior to compensation and following compensation for 1st-order eccentricity error is 158.2306 mm in both cases, but the standard deviation declines from 2.5 μm prior to compensation to 0.4 μm following compensation.

The same MRC was repositioned in the measurement

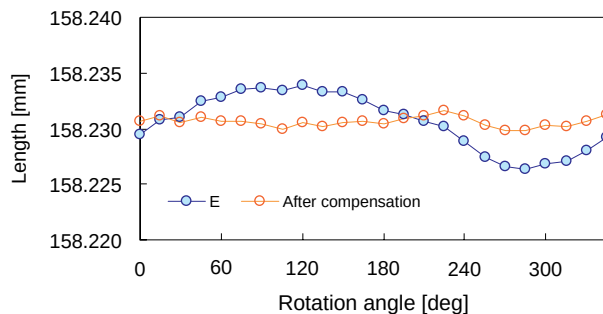


Fig. 5 Measurement of length between two rollers and compensation of perpendicular eccentricity of rollers

device and re-measured after 24 hours. The difference between the median values of the first and second sets of data was 0.1 μm , indicating that the measurement method achieves a sufficiently high level of reproducibility.

The evaluation of the uncertainty of the MRC measurements employed a comparative measurement method with the calibrated values for the gauge block and gauge ring as reference values, in accordance with ISO/TS 15530-3.

Figure 6 shows an overview of ISO/TS 15530-3. The uncertainty of the measurements, U , is calculated from repeated measurements of a calibrated workpiece (CW) of the same shape and dimensions as the subject of the measurements.

u_c is the uncertainty synthetically evaluated from the uncertainty of the calibrated values for the CW and the compensation for thermal expansion. u_p is the uncertainty of the CW measurements after 20 or more repetitions. u_w is the uncertainty synthetically evaluated from the uncertainty of the compensation for thermal expansion and the uncertainty in alignment of the subject of measurement. The uncertainty, at this time, U , is calculated from the sum of squares of u_c , u_p , and u_w , which can be evaluated independently.

Table 1 shows the factors generating uncertainty in MRC measurements and their uncertainty. The table also shows the calculated uncertainty of the measurement of the length between the centers of the rollers, $U(E)$, of the calculation of the coordinates of the centers of the rollers from roller measurements, $U_{\Delta l}$, and of the measurement of the radii of the rollers, $U(R)$. The uncertainty of both $U(E)$ and $U(R)$ was approximately 0.5 μm .

The uncertainty of the coordinates of the centers of the rollers determined solely by the position and number of measurement points for circular measurements affects $U_{\Delta l}$. For example, if measurement points are established uniformly following a circular form, the uncertainty of the coordinates of the centers tends to diminish as the number of measurement points increases. In the present measurement method, the time and accuracy of

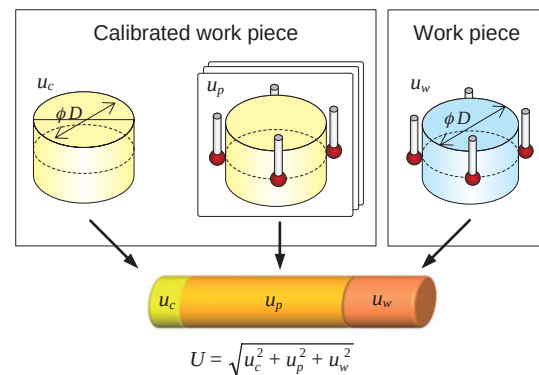


Fig. 6 Uncertainty estimation method based on ISO/TS 15530-3

Table 1 Uncertainty budget for circumferential length of ring measurement

Source	Symbol	Nominal value	Standard uncertainty	Distribution
Gauge block				
Length of gauge block	g^0	150 mm	50 nm	Normal
Linear coefficient of expansion	α_G	$10.8 \times 10^{-6}/K$	$\pm 0.5 \times 10^{-6}/K$	Normal
Temperature of gauge block	t_G	-0.627 K	0.1 K	Rectangular
CVT metal ring				
Length between two rollers	E	158 mm	—	—
Linear coefficient of expansion	α_R	$11 \times 10^{-6}/K$	$\pm 0.8 \times 10^{-6}/K$	Normal
Temperature of ring	t_R	-0.682 K	0.06 K	Rectangular
u_p [μm]			0.40	
u_w [μm]			0.14	
u_c [μm]			0.16	
$U(E)$ [μm]			0.45	
$U(R)$ [μm]			$U(R_1) = 0.46, U(R_2) = 0.60$	
U_l [μm]			0.37	
U_M [μm]			0.26	
$U(L)$ [μm] ($k=1$)			2.6	

measurements were optimized, and four measurement points were employed. Because of this, U_M was approximately 0.3 μm .

The temperature gauge used to compensate for thermal expansion in the gauge block, gauge ring, and MRC was calibrated in advance at an uncertainty of 0.0025 K. The uncertainty of the MRC measurements, $U(L)$, when k is 1 was 2.6 μm .

4. Conclusion

The measurement method discussed in this paper is a highly rational method, which can be used in place of direct measurement of the MRC, involving combined measurement of linear and circular forms that can be machined and measured with a high degree of precision.

In the area of judgment of product conformance, the necessity for quantification of the uncertainty of measurements is increasing, as exemplified by JIS B0641, and the importance of specifying processes of calculating uncertainty can also therefore be considered to be increasing.

High-accuracy measurements and evaluation of the

uncertainty of these measurements are necessary for numerous auto parts. The establishment of principles of measurement that consider the evaluation of uncertainty is demanded for highly important parts to which existing measurement methods cannot be applied.

This study of the precision measurement of MRC and the evaluation of the uncertainty of these methods produced the following results:

- (1) A combination of linear and circular shapes, representing the simple geometric form of the MRC, was measured using a high-precision CMM. The uncertainty of the measurements was 2.6 μm . The difference between first and second sets of measurements was 0.2 μm , indicating good reproducibility.
- (2) The employment of a method of evaluation conforming to the standard for evaluation of the uncertainty of CMM measurements, ISO/TS 15530-3, enabled quantification of the uncertainty of MRC measurements allowing traceability of length.
- (3) The provision of MRC with specified measurement uncertainty can be expected to contribute to quality management in mass production facilities and boost traceability between places of business.

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Approach to Application of Executable Specifications in Development of Automatic Transmission Control Software

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ABSTRACT

Model-based development is being introduced to the development of control software for automatic transmissions in order to increase control reliability and reduce development times. The introduction of model-based development necessitates an enhancement in the readability of executable specifications formulated using MATLAB, i.e., specifications for simulatable models, and the reduction of the time for formulation of these specifications. An original style guide was developed as a supplement to the general description guidelines provided by the MAAB and J-MAAB style guides, and the like, on the basis of a method eschewing connecting lines and division of the model based mainly on Stateflow, and post-processing was applied to the expression of the model when documents were formulated. These methods increased the readability of the specifications. In addition, a block library for automatic transmission control, an automatic modeling tool conducting routine processing, and a tool that automatically sets existing variable information were developed in order to support modeling conforming to the new style guide. These tools have reduced the time for modeling to less than one-twentieth of the time for manual modeling. This has enabled executable specifications to be employed in the development of automatic transmission control software.

1. Introduction

The importance of automotive electronic control technologies is increasing year-by-year, and the scale and complexity of control software continues to grow. Demands on automakers to increase the reliability of control, reduce development times, and lower costs are also increasing. Against this background, the introduction of model-based development (MBD) is today proceeding rapidly as a means of increasing the efficiency of automotive software development^{(1),(2)}.

When MBD is employed, executable specifications, i.e., simulatable control models, are formulated using MATLAB at the design stage, the upstream phase of the development process. These control models are combined with plant models to enable virtual control tests. C codes for implementing can also be automatically generated.

MATLAB offers a high degree of freedom in description, and enables a diverse range of types of modeling to be conducted, even when the same control logic is described. This can cause readability to decline,

and the treatment of MATLAB models as control specifications to be used in the development of mass-produced software has represented a challenge, including for suppliers. In response to this issue, MATLAB users' bodies in automobile industry, the MathWorks Automotive Advisory Board (MAAB) and the Japan MATLAB Automotive Advisory Board (J-MAAB), have formulated MATLAB guidelines and defined the fundamental principles for modeling^{(3),(4)}. However, these guidelines have proven to be insufficient to the description of automatic transmission control, which involves a large amount of switching between different shift stages depending on driving conditions and the driving environment, meaning that numerous condition branches are generated and a great deal of resultant switching between tables and maps is necessary. Original rigorous guidelines were therefore formulated to help ensure readability, but it was discovered that while these guidelines ("the style guide" below) would increase readability, they would also result in an increase in modeling time.

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2. Development Aims

The following two development aims were established in order to enable MATLAB models to be treated as control specifications for use in the development of mass-produced software:

- (1) Achievement of increased readability for MATLAB models
 - (2) Reduction of modeling time for MATLAB models
- To enable these aims to be realized, the following would also be developed simultaneously:
- (a) A style guide enabling the formulation of high-readability models
 - (b) Support tools to enable the reduction of modeling time

3. Development of Style Guide Enabling the Formulation of High-readability Models

In the development of the style guide, four methods were considered to increase the readability of the models:

- (1) A modeling method based mainly on Stateflow
- (2) A method eschewing connecting lines for exchange of data
- (3) A method eschewing division of the model when searches are conducted for tables and maps
- (4) A post-processing method for the expression of the model when documents are generated

These four methods will be discussed in detail below.

3.1. Modeling Method Based Mainly on Stateflow

Broadly speaking, MATLAB contains two control design tools, Simulink and Stateflow. Simulink's forte is the description of data flows that specify the flow of transformation of input data, while Stateflow's is the description of control flows that specify the order, conditions, and timing of executing those data flows. Examples are presented in Figs. 1 and 2, respectively. The use of both tools in response to control is important in terms of high-readability modeling, but it is claimed that 85% or more of the flows in automotive control are control flows⁽⁵⁾. An analysis of existing mass-production control specifications also showed that the majority of flows were control flows even in control systems for automatic transmissions, and demonstrated that readability declines when the modeling method is based primarily on Simulink. Given this, the project discussed here set out to base the modeling method for automatic transmission control systems primarily on Stateflow.

3.2. Method Eschewing Connecting Lines for Exchange of Data

One of the cumbersome features of modeling control specifications using Simulink and Stateflow, and one that results in a decline in readability, is the use of connecting lines for the exchange of data. The structure of the software may necessitate data reference points (bounded

by red in Fig. 3) that span multiple levels, and when this is the case, it is necessary to use connecting lines for data exchange between all levels. This increases the scale and the number of levels of the model, and the increase in the variables renders the connecting lines more complex and may cause readability to decline.

In order to address this issue, attention was focused on a variable management method for Stateflow variables, and principles for the management of the variables described on the Stateflow charts ("the charts" below) were specified in the style guide. Normally, the variables described on the charts are all managed at either the machine level or the chart level (Fig. 4). The values of the variables managed at the machine level can be referred

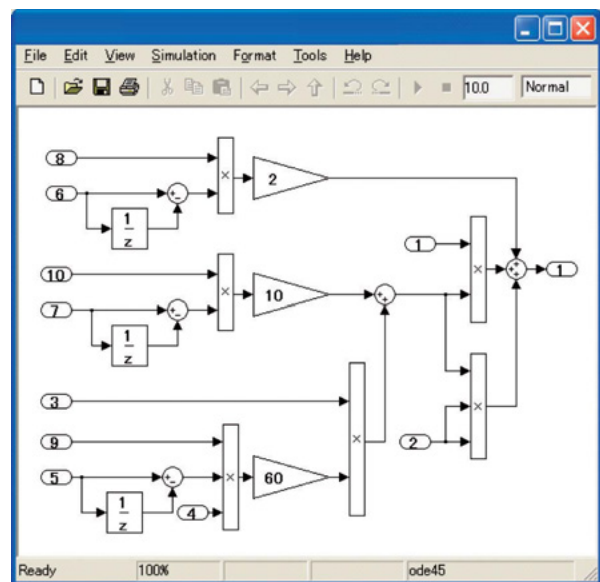


Fig. 1 Sample of Simulink model

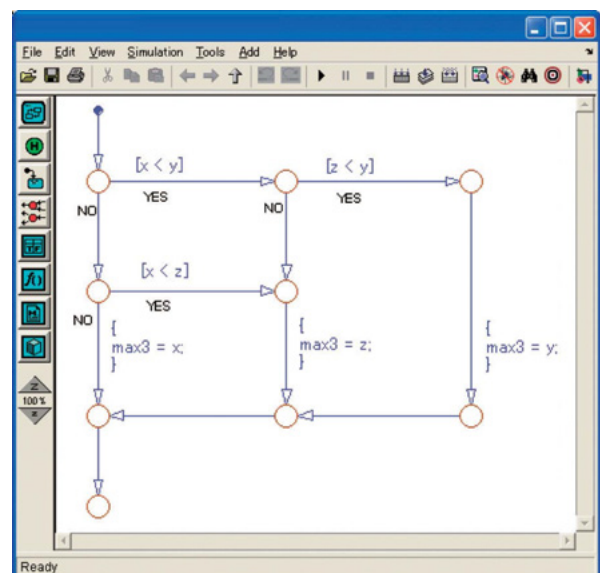


Fig. 2 Sample of Stateflow model

to or revised from any of the charts in the model. By contrast, the values of the variables managed at the chart level can only be referred to or revised from that chart. Exploiting this characteristic, the new principles specify management of variables shared between multiple charts at the machine level, and management of variables used only on a single chart at the chart level. This helps ensure that even when the same variable is used on multiple charts, there is no necessity to exchange data between charts, and therefore no necessity for connecting lines.

This has enabled the realization of high-readability model configurations with few connecting lines. Figure 5 shows the control model produced by application of the variable management method described above to the model shown in Fig. 3.

3.3. Method Eschewing Division of Model when Searches Are Conducted for Tables and Maps

In some control logics, as illustrated by the speed change characteristic logic for an automatic transmission shown in Fig. 6, specific parameters are described in tables and maps, and control is applied using the results of searches for these tables and maps. When modeling this control, the table and map searches cannot be directly described on the charts, and the Lookup Table (LUT) and Lookup Table (2-D) (LUT2D) block shown in Fig. 7 have therefore been used. However, as Fig. 8 shows, this raises the issue of the division of the model during the process of the table or map search, and the consequent decline in the readability of the model.

It was therefore decided to introduce a modeling

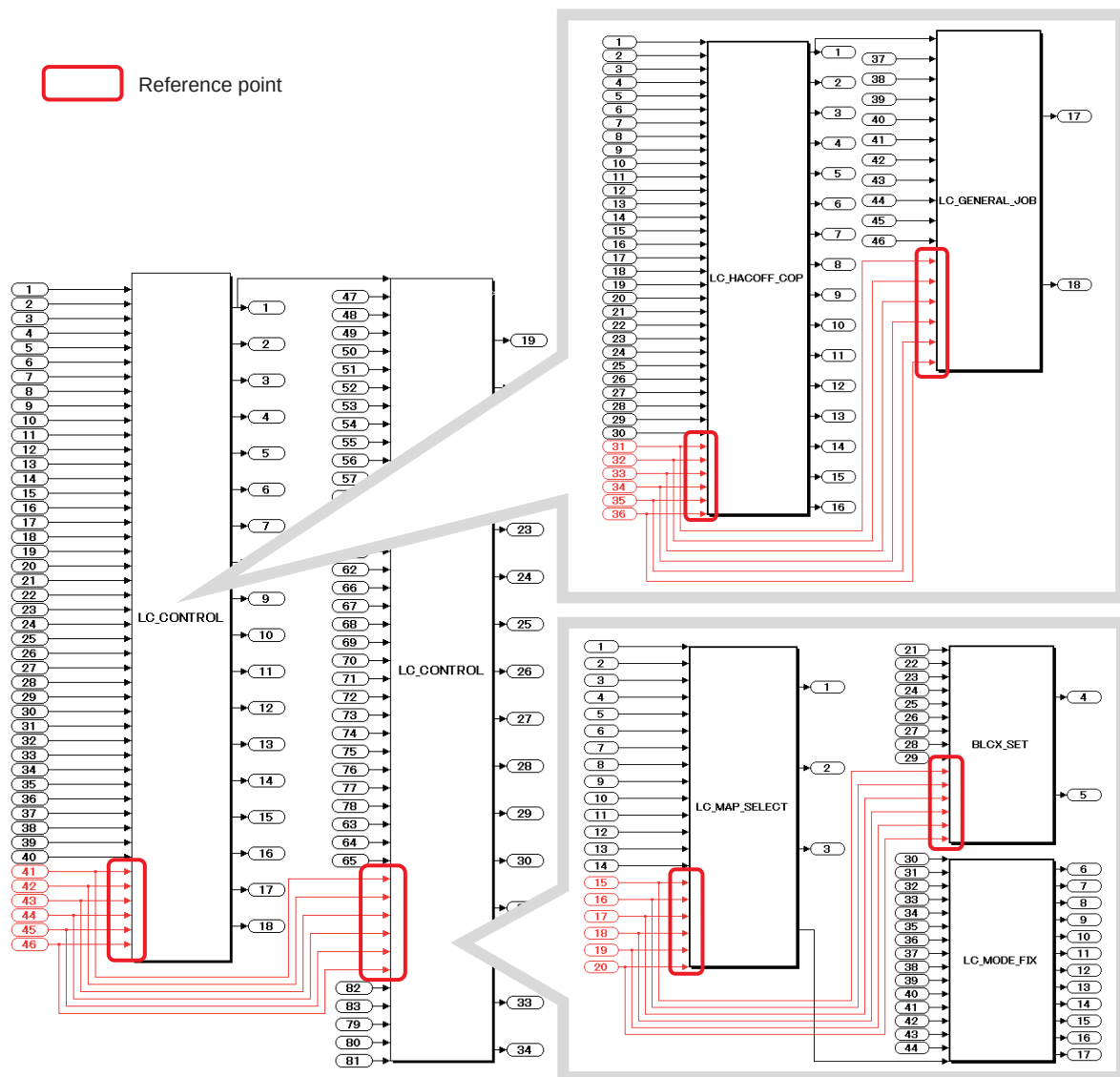


Fig. 3 Complicated model with many connecting lines

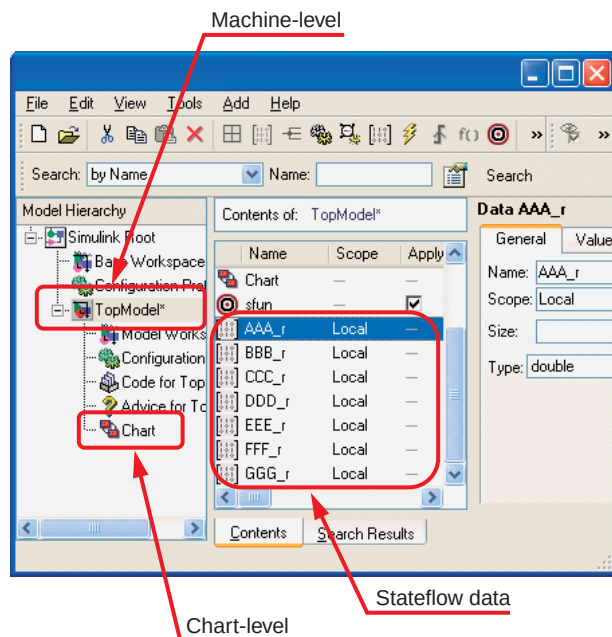


Fig. 4 Machine-level and chart-level

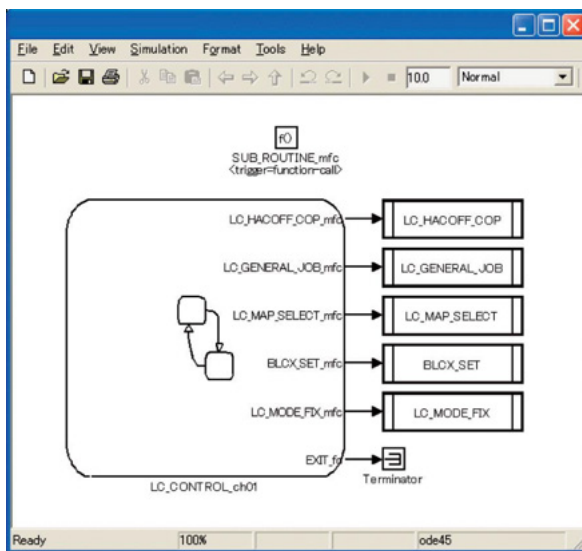


Fig. 5 Simple model with few connecting lines based on machine-level

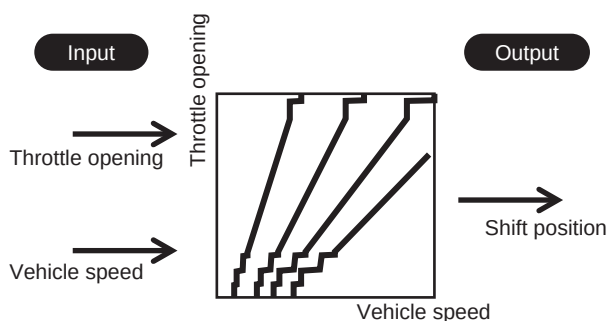


Fig. 6 Speed change characteristic logic of automatic transmission

method using loops of event signals and return values, as shown in Fig. 9. In the proposed method, the table search is conducted by outputting an event signal (Event) that invokes the LUT block in the area in which the table search is desired, and at the same time providing a search parameter, (x); the search results are again returned to the chart as a return value, (y). This enables modeling using table and map searches without division of the model.

3.4. Post-processing Method for Expression of the Model when Documents are Generated

Control specifications for use in the development of mass-produced software are not used only by designers, but are shared among a wide range of individuals involved in development, including testers, bench and vehicle personnel, and suppliers. This has made it necessary to render models into documents that can be viewed in widely used applications such as Microsoft Office Word.



Fig. 7 Lookup Table and Lookup Table (2-D)

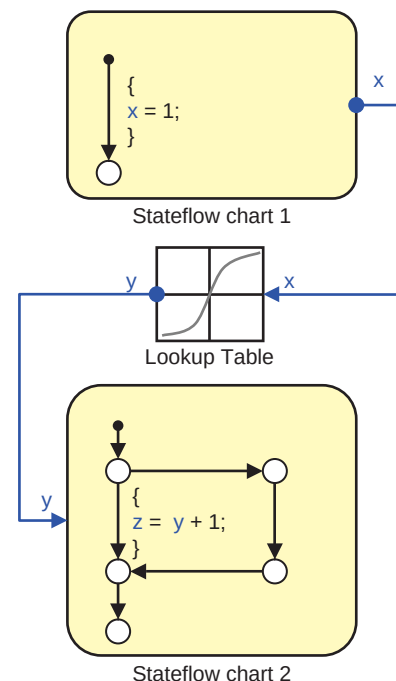


Fig. 8 Model divided into two charts by Lookup Table block

Table 1 Notation rule of variables on document

	RAM	CALIB	WORKRAM
Color	Blue	Red	Blue
Prefix	—	#	—
Capital/ Small	Capital	Capital	Small

Table 2 Naming rule of variables on stateflow chart

	RAM	CALIB	WORKRAM
Suffix	_r	—	—
Capital/ Small	Capital	Capital	Small

Rules for notation, shown in Table 1, were therefore formulated to enable simple visual discrimination of the three types of variables (RAM, CALIB, and WORKRAM) used in control specifications when these documents are created. In addition, points at which conditions branch are notated as diamond shapes. In order to enable documents conforming to these rules of notation to be automatically generated from the model, rules for naming the variables described on the chart were preliminarily specified in the style guide (Table 2). Following this, a post-processing tool was developed to conform the notation of the model to the rules of notation shown in Table 1. This tool was formed by linking MATLAB and the application used in the documents.

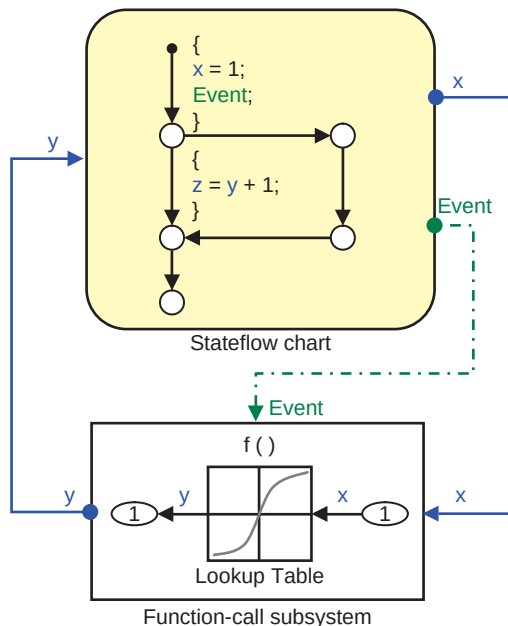


Fig. 9 Modeling method: Searching table data without division

First, MATLAB was programmed to classify the types of variables, specify the points at which conditions branch, and copy the images in the model. The classification of the variables followed the naming rules specified in the style guide (Table 2). The points at which conditions branched were specified from the arrangement of junctions (the circular objects in Fig. 10) and transitions (the arrow-shaped objects in Fig. 10) on the charts. In Fig. 10, if the condition $(X_r < Y)$ above the transition arrow is manifested, processing will proceed in the direction of the arrow $z=1$. If the condition is not manifested, processing will proceed in the direction of the arrow $z=0$. i.e., at a point at which a condition branches, two transitions extend from one junction. The points at which conditions branched were specified by searching for this feature in relation to all the junctions on the chart and analyzing the

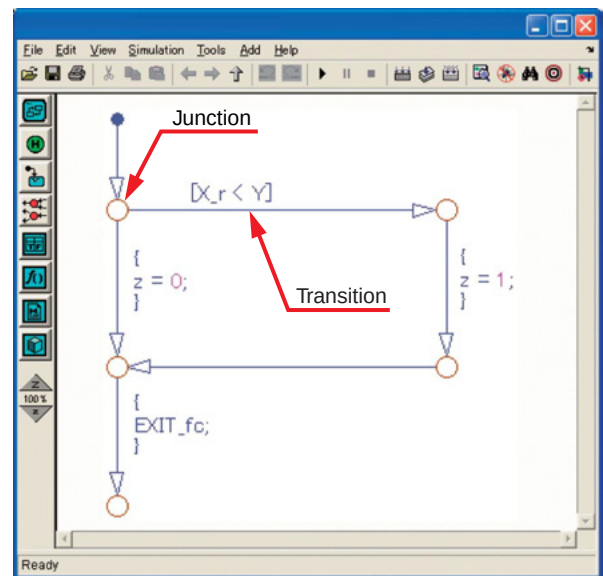


Fig. 10 Junction and transition

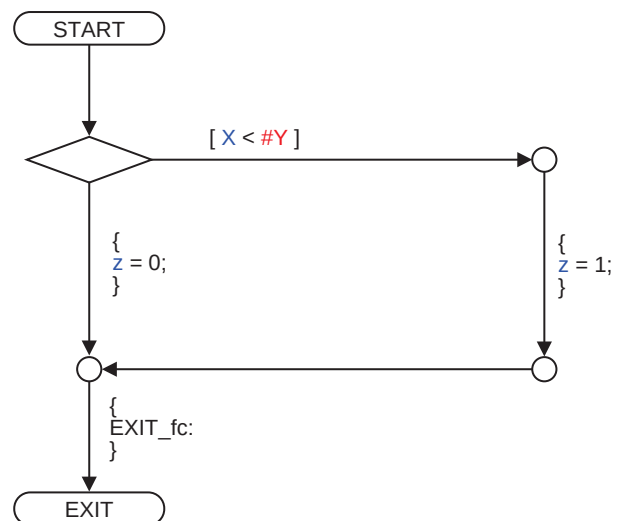


Fig. 11 Document generated from model in Fig. 10

results. A meta format, i.e., a data format in which multiple types of data such as images and text are included, was selected for the copying of the model images, enabling MATLAB functions to be employed and the text data to be retained.

Next, the application used for the documents was booted, and programmed to enable pasting of images from the model and processing of notation. An Active X function supported by MATLAB was employed to enable the document application to be booted from MATLAB. The notation processing – the use of different colors for variables and the substitution of diamond shapes for condition branch points – employed automatic functions of the document application, and was conducted from MATLAB. Figure 11 shows a document automatically generated from the model shown in Fig. 10.

The automatic document generation tool described above, which linked MATLAB and the application employed for the document, enabled the achievement of increased readability in the specifications.

4. Development of Tools to Support Reduction of Modeling Time

Chapter 3 discussed four methods proposed in the development of the style guide in order to increase the readability of models. This chapter will discuss the following three modeling support tools that were developed in order to reduce the time needed for modeling

executable specifications conforming to the style guide:

- (1) A block library for automatic transmission control
- (2) An automatic modeling tool for routine processing
- (3) A tool for the automatic setting of existing variable data

4.1. Block Library for Automatic Transmission Control

As Fig. 12 shows, MATLAB's standard block library contains a diverse range of blocks for use in control design. From these, the present project selected the blocks necessary for the modeling of automatic transmission control in accordance with the style guide, and developed a unique, customized block library (Fig. 13). The blocks in this library were customized to automatically display the data contained in the blocks on masks. Figure 14 shows an example of this. When the axis data name is input to the graphical user interface (GUI), the data contained in the table search block is automatically displayed on a mask.

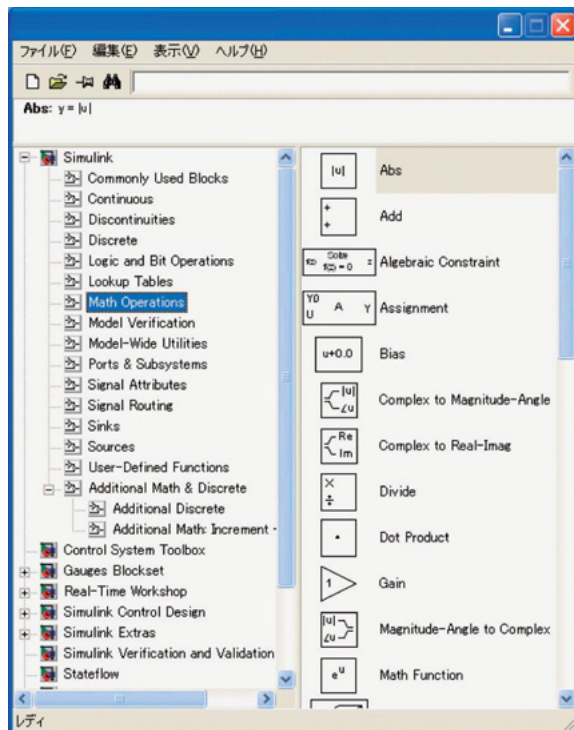


Fig. 12 Simulink library

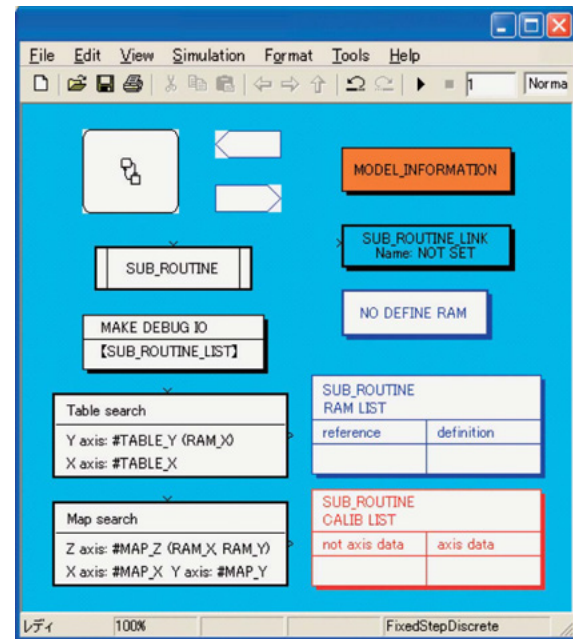


Fig. 13 Automatic transmission modeling library

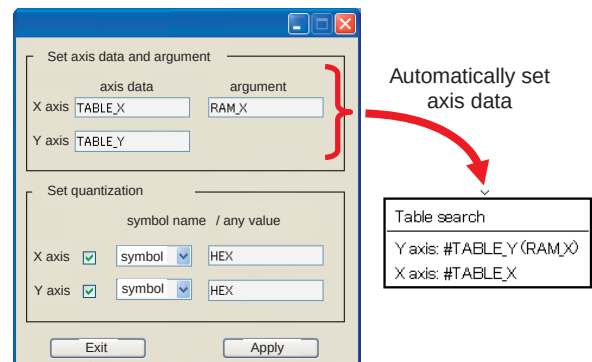


Fig. 14 GUI and customized table block

This function was realized using GUIDE, the MATLAB graphical user interface development environment, to develop a GUI for input of the axis data name and an M-File program for the automatic display of input data on a mask.

The development of the block library for automatic transmission control use increased the readability of the model and reduced the time for modeling.

4.2. Automatic Modeling Tool for Routine Processing

As indicated in Chapter 3, control logics employing table searches and map searches may, depending on control conditions, need to switch between multiple tables and maps. When this is the case, a routinized model of the type shown in Fig. 15, formed from switch case blocks, merge blocks, and the customized table and map blocks discussed in Section 4.1. is used. However, the greater the amount of switching between tables and maps, the more the number of elementary modeling tasks increases, and this also increases modeling error.

An automatic modeling tool was therefore developed in order to enable this type of routine modeling to be conducted automatically. This tool is made up of a GUI for data input by designers, and an automatic modeling program.

First, for the design of the GUI, the switching patterns

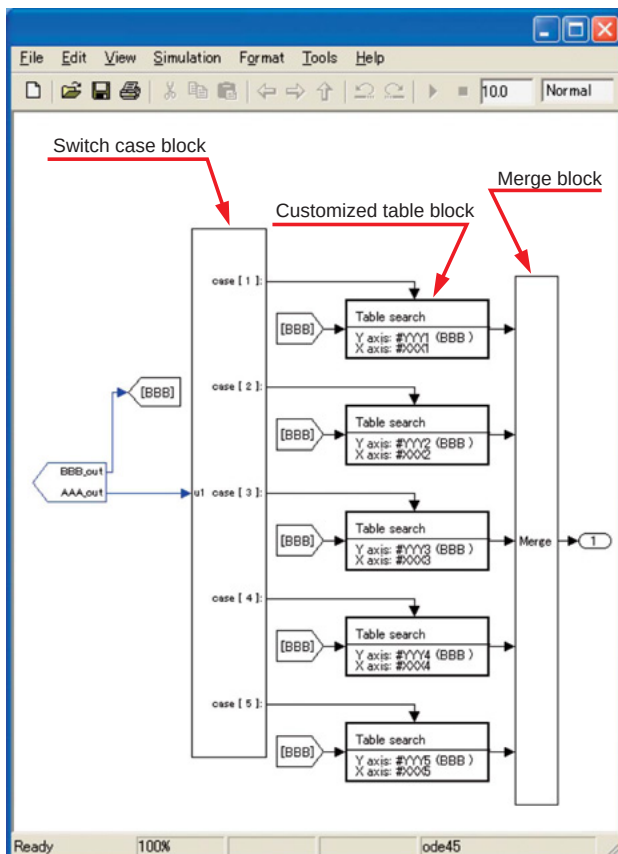


Fig. 15 Table switching model

in existing mass-produced automatic transmission control specifications were analyzed. The results of this analysis showed five representative switching patterns. These are, in addition to table switching and map switching, CALIB data switching, RAM data switching, and map switching under multiple conditions. In addition, the results also indicated that the number of times switching is conducted and the switching conditions vary in response to the type of control applied, necessitating a high degree of freedom in design. Therefore, as Fig. 16 shows, the GUI was designed to enable designers to freely select from the five representative patterns, and to easily set the number of times switching is conducted as well as switching conditions.

Next, a program enabling automatic modeling using Simulink or Stateflow based on the data selected and input using the GUI was developed. This program automatically executes the following sequence of processes:

- (1) The blocks, which are necessary for automatic modeling of the switching pattern selected using the GUI, are

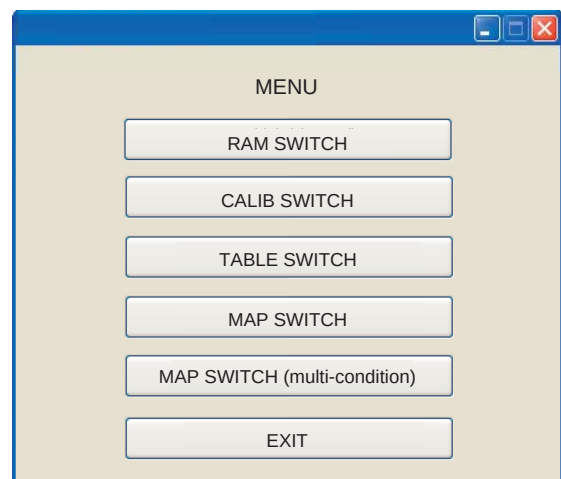


Fig. 16 GUI of auto-modeling tool

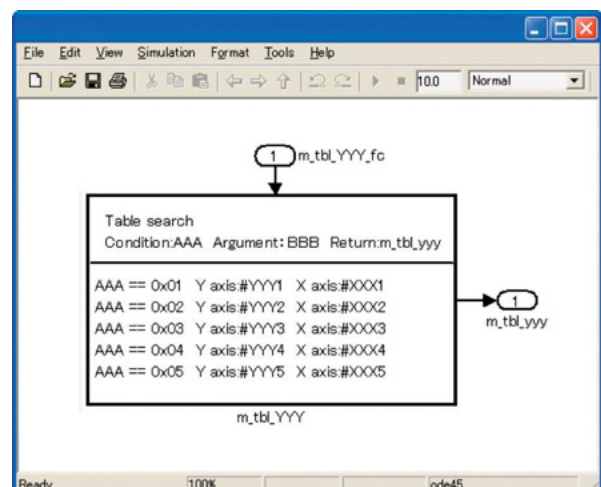


Fig. 17 Result of auto-modeling

obtained from the block library discussed in Section 4.1., and placed in a function-call subsystem.

- (2) The data input using the GUI are reflected in the blocks.
- (3) The individual blocks are connected.
- (4) The switching logic is notated on a mask in the function-call subsystem.

Figure 17 shows a result obtained from automatic modeling using this tool.

The use of the automatic modeling tool discussed above, made up of a GUI and an automatic modeling program, enabled modeling time to be reduced.

4.3. Tool for Automatic Setting of Existing Variable Data

For all of the variables treated in control specifications for use in the development of mass-produced software, it is necessary to set data scale (LSB) and data type information, which specifies the accuracy of the variables. This is also the case when MATLAB models are treated as mass-production control specifications. In the case of large-scale control models, which contain a vast amount of variables, a large amount of time is required to input data for each variable.

However, the existing variables treated in mass-produced software are managed in databases, and this makes this data easy to reuse.

A GUI was therefore developed that would link to databases, automatically obtain existing variable data, input it in bundles, and display the results of setting the data in the model as a list. In addition, a specialized block was developed that would enable the variable data to be retained in the MATLAB model.

To realize the ability to link with databases, i.e., the ability to automatically obtain existing variable data and input the data as a bundle, the system was preliminarily

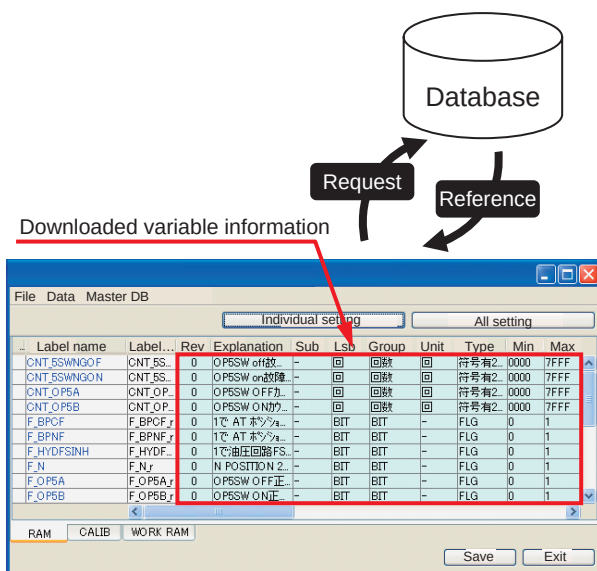


Fig. 18 Link system between database and GUI managing variable information

programmed to enable the model to be automatically analyzed in accordance with the naming rules (Table 2) specified in the style guide, and the variables, for which it was necessary to be set in the model, to be automatically identified by their variable names, when the GUI was booted. The system was then programmed to enable it to refer to variable data that is on the database and associated with the variable names using the database language SQL (Fig. 18).

To enable the variable data that had been input in a bundle to be retained in the MATLAB model, the system was programmed to enable the variable data to be stored in a special block properties column. The use of MIME, also used in E-mail and other applications, as the data format for the storage of the data enabled matrix data, formed from multiple types of variable data, to be stored in a single block (Fig. 19).

The tool for the automatic setting of existing variable data described above reduced modeling time.

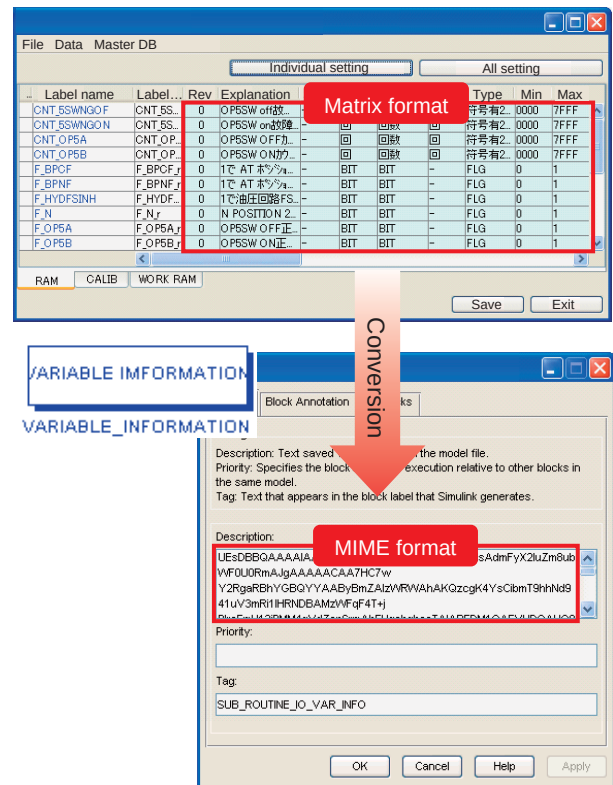


Fig. 19 Conversion of variable information format

5. Example of Actual Application

Figure 20 shows executable specifications for automatic transmission control software that were formulated using the developed style guide and modeling support tools. The introduction of the new tools enabled a MATLAB model, which is able to be treated as control

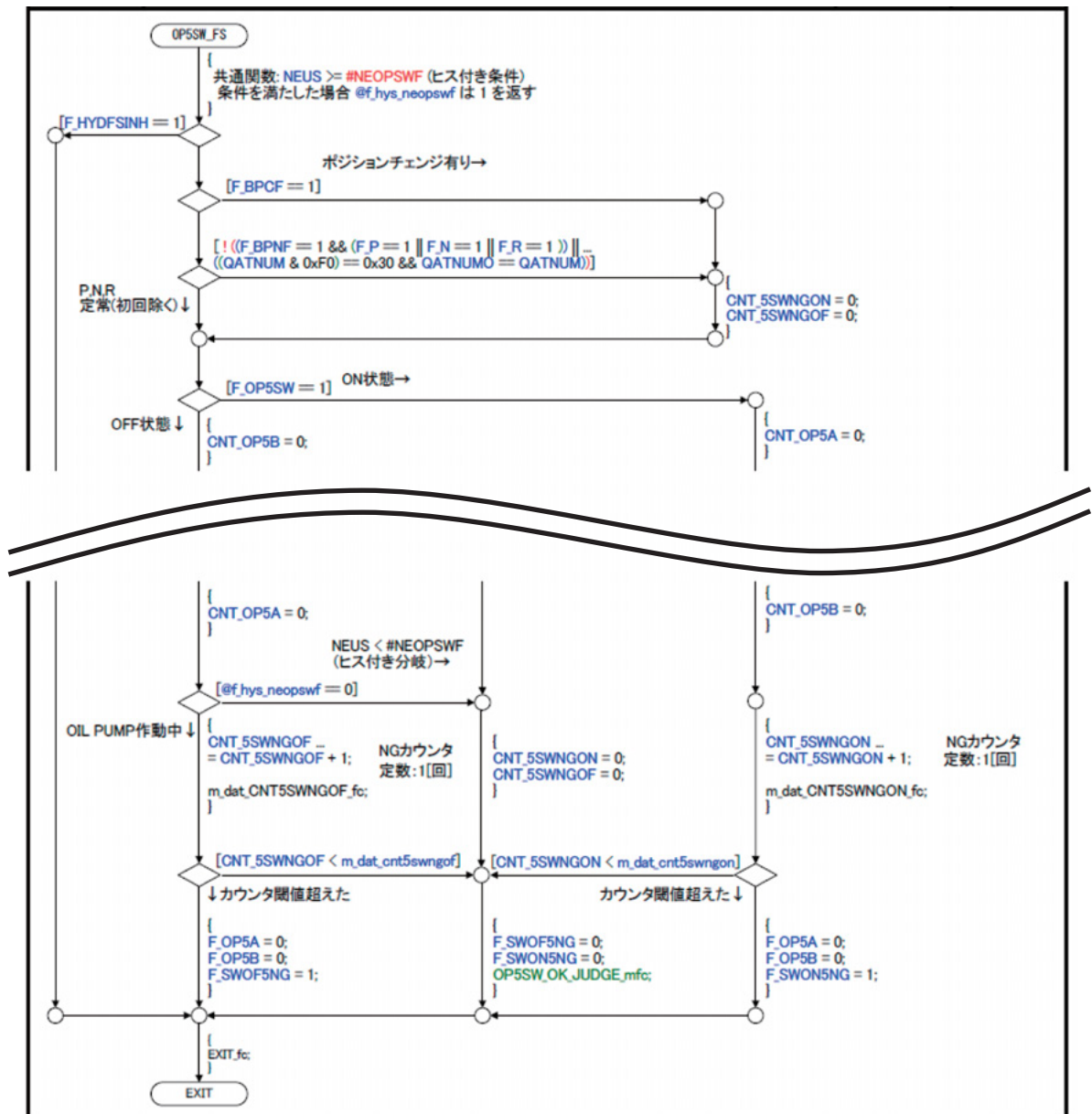


Fig. 20 Example of application

specifications for the development of mass-produced software, to be formulated in less than one-twentieth of the time previously needed.

6. Conclusion

- (1) The development of a style guide based mainly on Stateflow that eschewed connecting lines and did not necessitate division of the model, and the development of a post-processing tool for notation of the model when documents are generated, has increased the readability of control specifications for automatic transmissions.

- (2) The development of a block library for automatic transmission control, an automatic modeling tool for routine processing, and a tool for the automatic setting of existing variable data has reduced the time needed for modeling in conformance with the abovementioned style guide to less than one-twentieth of the time previously needed.

The developed style guide and tools are therefore able to be employed in the formulation of executable specifications for use in the development of control software for automatic transmissions.

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Using CAD, CAE, and CAM to Enhance Automotive Body Assembly Design, Analysis, and Fabrication

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ABSTRACT

Standards, processes, and software were developed to automate the process of creating the Body In White (BIW) fasteners, such as, spot welds and MIG welds. Enhancements were made to the previous process and software where the CAD data for fasteners was mostly geometric representations. The new method provides data that has complete embedded information, including actual connection properties, for the parts being welded. The key benefits include the ability to check geometry and design intent in 3D, quickly create and revise connections in finite element simulation models, and import data into weld offline teaching software to accelerate robot welding.

1. Introduction

In the late 80's to early 90's, automotive design engineers communicated weld information with symbols and annotations on drawings (Fig. 1). For spot welds, the symbols showed the location and quantity of parts connected while the annotations described the weld coordinates and the part numbers being connected. Such drawings were verified by visually contrasting the illustrations and annotations and comparing with the design intent. Once all errors were corrected, the drawing was issued and distributed. These drawings were used to create weld connections in Computer-Aided Engineering (CAE) models and welding templates for assembling prototype vehicles. In both cases, extensive labor and

time were necessary to read each drawing and either manually create a weld location in a CAE model or physically measure and mark a location on a weld template.

Once we moved to welds in 3D, the process was enhanced since weld locations could be extracted into CAE software. The source of communication was based on drawings. The 2D drawing contained the weld information for both the CAE world and Computer-Aided Manufacturing (CAM) environments. As CAD systems evolved (early 2000), we could embed knowledge in 3D. This provided us with the base for significant enhancements.

2. Developing the Body Fasteners Workbench

As shown in Fig. 2, we divided the flow of BIW assembly into four phases. In phase one, the design engineer provides the necessary inputs. In phase two, the program determines the parts that are being connected, gathers information about these parts, and creates the fasteners. Phase three involves checking the data. In phase four, the assembly is made available for simulation.

The Body Fasteners Workbench was developed to help with this process. The workbench concept was chosen because of the framework inherent to the base software. The workbench consists of a collection of functions that are arranged in toolbars and grouped based on the

Year 1980	1990	2000	2010
		Fasteners in 3D Annotations in 3D Embed Knowledge	
Fasteners in 2D Annotations in 2D	Fasteners in 3D Annotations in 2D		

Fig. 1 History of BIW assembly data

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following functions: fastener creation, operations, annotation, and reporting. The software algorithm is explained in a flowchart in Fig. 3.

During the initial stages of the software development, a worldwide team comprised of members from design, information systems, manufacturing, and tooling came together to define some common user requirements for 3D fasteners. Some of the standards that were developed, and used in the specifications for the software, include:

- A global unique identifier for each fastener
- 3D annotations for each fastener type
- A standard report format (CSV)

2.1. Design Phase

In the Design phase, the design engineer loads the parts that make the assembly and adds a part that will hold information about the assembly. Inputs depend on the type of fastener being created, for example, the input for a spot weld is a surface and points at which the welds have to be created. A MIG weld needs two surfaces and a curve. Sealers need two bounding surfaces while bolts need point, surface and a hole. The necessary inputs are referenced (copied in or referenced with a link) from the parts to be assembled. Once these inputs are acquired, the software starts to calculate connected parts.

2.2. Compute Phase

A key aspect of the Compute phase is calculating what parts are being fastened during the assembly process and

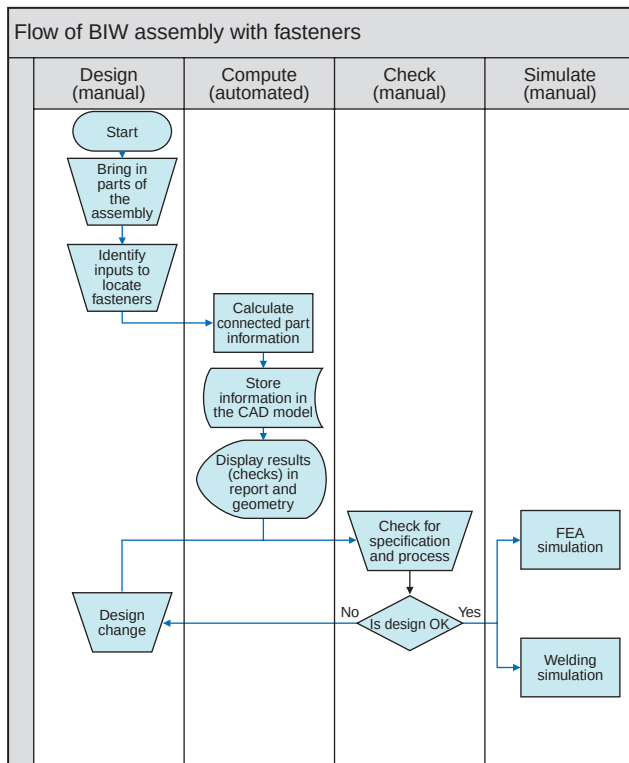


Fig. 2 BIW assembly phases

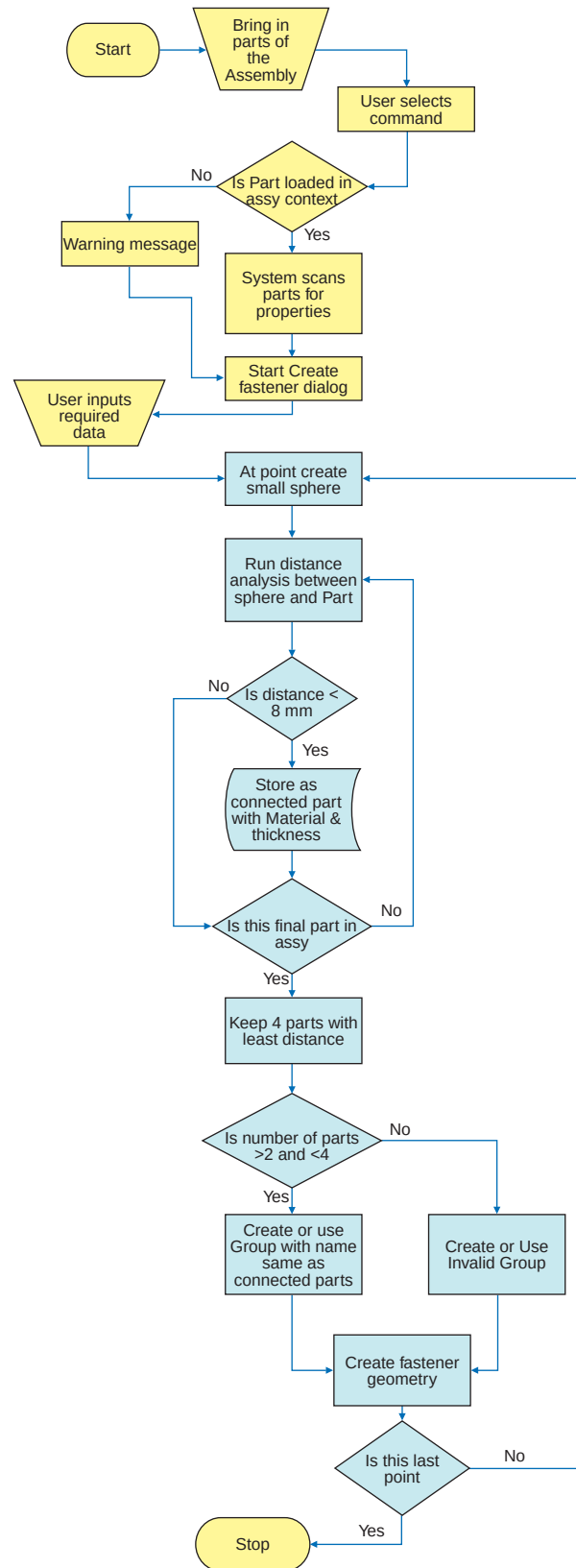


Fig. 3 Flowchart for software algorithm

acquiring their attributes. This could be done by asking the design engineer to select what parts are being connected, but impractical since one assembly might contain hundreds of spot welds. Furthermore, this process needs to be independent of the type of fastener being created. We investigated two methods to accomplish this.

2.2.1. Methods for calculating connected parts

Cylinder Method. At the location where a fastener is needed, a cylinder with 2 mm radius and 10 mm length is created along the normal to the input surface. These dimensions were selected balancing the need to capture the connected parts but remove false positives. The software computes the interference between the cylinder and all parts loaded in the assembly. Parts that interfere with the cylinder are assumed to be connected (Fig. 4).

Sphere Method. At the location where a fastener is needed, a 0.5 mm sphere is created. The software computes the distance between the sphere and all loaded parts. Parts that fall within 8 mm are assumed to be connected (Fig. 5).

Both methods return a list of parts that can be connected. However, the fastener type has to be considered to determine the relevant parts; for example, a MIG weld or sealer can connect two parts while a spot weld can connect up to four parts. Despite such restrictions, the software may still return more parts than expected (Fig. 6). In such cases, the user is prompted to select the relevant parts.

Based on our testing and the variety of fasteners that can be handled, we selected the sphere method for calculating connected parts.

After the connected parts are determined, properties

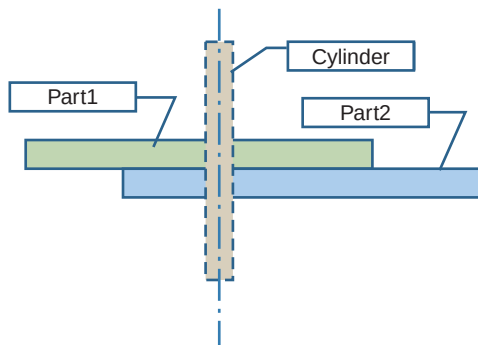


Fig. 4 Cylinder method

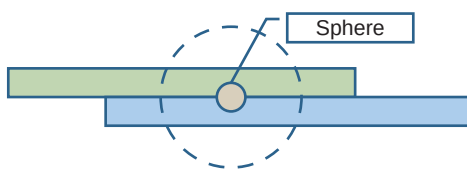


Fig. 5 Sphere method

are interrogated from the model and mapped from a Product Lifecycle Management (PLM) database. Part number, material, and thickness data are filtered and stored on the geometric feature.

2.2.2. Visualization

Each fastener is represented by geometry and annotations that are based on ISO and other standards. These representations have variations. A spot weld is represented based on the number of parts being connected while a MIG weld is based on the length of the weld. Additionally, the geometry has to be created with multiple visualizations, that is, Wire frame and Solids, which aid in downstream use of the data in visualization software or 2D drawing creation. Finally, the design engineer creates annotations for each fastener. Figure 7 shows an example of visualization and annotation on spot welds.

2.2.3. Data organization

A tree structure within the CAD model stores the geometry information. Good organization in the tree structure is important as it enables fast access to information. When the geometry is created, fasteners are

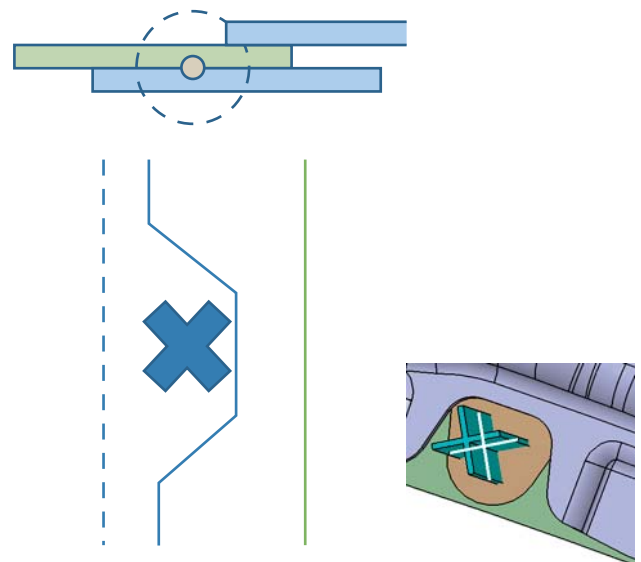


Fig. 6 Example of multiple parts identified to be connected

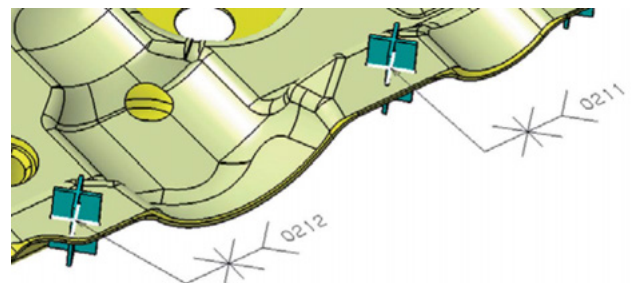


Fig. 7 Visualization and annotation on spot welds

organized in the tree by welds, sealants, bolts, etc. Welds are subdivided into Spot, MIG, and other weld types. Additionally, fasteners are grouped by the parts that are being connected as shown in Fig. 8 by the “PART2_SAE / PART3_SAE” label. All spot welds that connect these two parts are included in this group.

Once the connected parts are computed, the geometry, annotations and the organized tree is created then the data is ready for check phase.

2.3. Check Phase

Once an engineer completes creation of the fasteners, he/she uses a PLM workflow to promote the part’s workflow status and start the check process. The first check is automatic, and if successful, a manual second check is started.

2.3.1. Automated check

An automated program checks for invalid fastener definition, which could involve a mismatch between number of parts and the type of weld, a missing material or thickness, two spots created at the same location, or missing annotations. If problems are found, the part is demoted to the original workflow status and an e-mail sent to the design engineer with a link to the error report.

Errors can be corrected using edit functions provided for the fasteners. Individual fasteners can be modified by editing the inputs or by making corrections to the connected parts. Multiple fasteners can be modified by using a refresh function to re-compute connected parts and collect their modified properties. When there are no errors, the assembly is made available to the checker.

2.3.2. Manual check

To aid with the manual check, the information stored on fasteners can be displayed in several report formats to meet end users’ needs. Such reports contain fastener

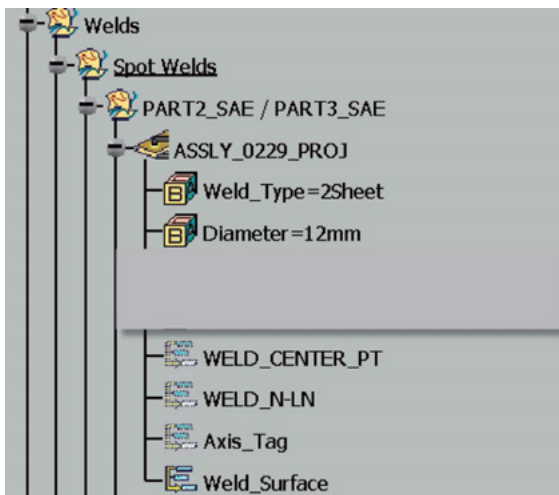


Fig. 8 Tree structure example

information, which includes a unique identifier, location, orientation, the parts being connected, and properties (material and thickness). This report can be saved as a file that can be read by spreadsheets or other applications.

Once the checker is satisfied with the assembly, he/she promotes the file to a locked status and a Spot Weld report file is generated in a comma-separated value (CSV) format (Fig. 9). This is the same information created with the report function. The data is now available for simulation engineers to build finite element models and to fabrication engineers to start offline programming.

2.4. Simulate Phase

2.4.1. Finite element (FE) analysis

Automotive manufacturers perform computer simulations throughout the vehicle development process. These simulations check and enhance overall vehicle performance in areas such as crashworthiness, durability, noise, vibration and handling. To perform these simulations, the engineers first create a computer model of the vehicle that is detailed enough to provide useful performance measurements. The computer model includes FE representations of each part and the corresponding connections. The most common structural connection is the spot weld. Since a typical vehicle contains approximately 4000 spot welds, it is important to have an automated process to create them.

The building of a full vehicle simulation model starts with creating FE part representations. A preprocessing software tool is used to import 3D CAD surface and solid data. As shown in Fig. 10, a mesh for each part is created in a batch process. Once all of the mesh files are created

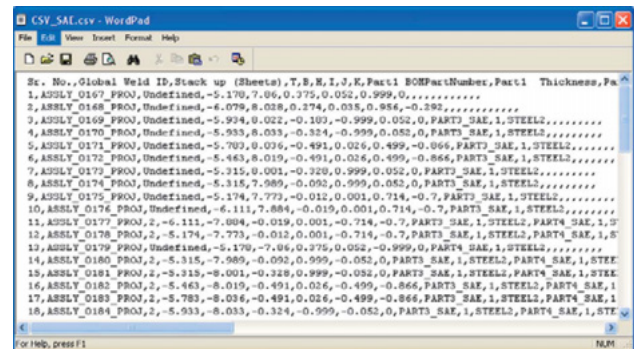


Fig. 9 Sample spot weld CSV file



Fig. 10 Finite element part meshes

for a sub-assembly, the preprocessor loads and places the individual meshes in the correct location and labels each mesh with its corresponding part number, material, and thickness information. In order to ensure simulation results it is important that these mesh properties are consistent with the properties used by the CAD program to define the fasteners. The sub-assembly is now ready to connect the mesh parts to each other.

The connection process for the simulation model starts with the spot weld CSV file, which contains all of the necessary data to build a FE representation of the spot weld. The FE spot weld creation tool reads and processes the unique weld identification number, the number of sheet metal layers connected, the 3D location of the center of the weld, and the part numbers for each of the sheet metal layers being welded. In the simulation model building process, the welds are created on a subassembly-by-subassembly basis (Fig. 11). Once sub-assemblies are complete, groups of sub-assemblies are connected with additional spot weld files. This process continues building

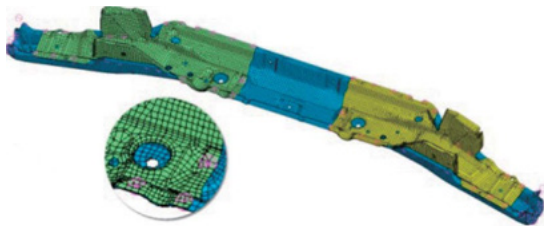


Fig. 11 Single assembly with FE connections

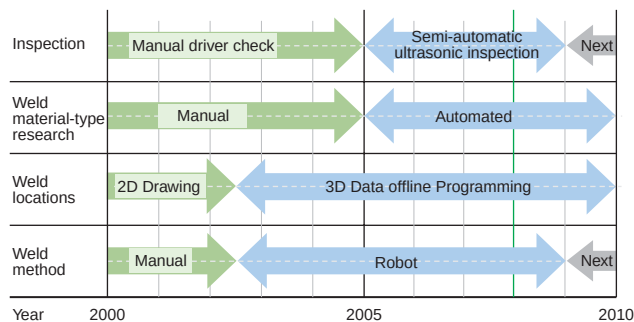


Fig. 12 Application evolutions in prototype processing

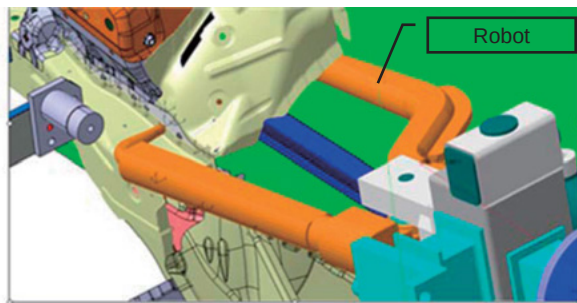


Fig. 13 Welding robot oriented based on imported weld points

until the final assembly is completed. Another method would be to combine all of the spot weld CSV files into one complete vehicle spot weld file and then create all of the FE spot welds at the same time.

2.4.2. Prototype fabrication

Prototype vehicles are built to confirm manufacturability and performance. Before implementing the 3D fastener environment, prototype welding was a manual process of reading individual drawings to build a weld table and printing drawings to create weld templates. The availability of the spot weld CSV file and the introduction of welding robots have reduced the overall preparation time for weld parameter development by approximately 50%. A timeline of the maturation of robotic welding processes is shown in Fig. 12.

The process starts by importing the weld information from the CSV file into the simulation environment. The result is a properly oriented weld tag for each spot weld, which allows for fast orientation and assignment of the welding robot (Fig. 13).

2.5. Software Maturation

The software has matured in multiple versions, leading up to the current version, V4. In the initial release, V1, an interface was developed to create the geometrical data. In this version, the step of creating a CSV file was a secondary process that didn't have any interaction with the design engineer. The next version, V2, implemented real-time information gathering from a PLM system while a design engineer created fasteners. This increased the accuracy of the CSV file as more checks were done before simulation or fabrication staff saw the data. The latest versions, V3 and V4, have support for more operations like symmetry, copy paste with links, and multiple PLM systems.

3. Conclusion

The development and implementation of BIW fasteners has advanced vehicle development in many ways:

- (1) Weld Design has advanced to a knowledge centric approach from the historical focus on geometry.
- (2) The software has shortened the time required for design engineers and checkers to collect and display information about the BIW assembly.
- (3) The task of building and updating simulation models has been simplified.
- (4) The lead time to weld prototype vehicles has been reduced.
- (5) The Body Fasteners software and associated standards have provided enterprise-level efficiency enhancements that benefit all facets of vehicle development.

The next step for BIW fasteners in the PLM environment is to detect changes in the assembly and manage the effect on assemblies.

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GPS Safety Monitoring System for Takasu Proving Ground

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ABSTRACT

A GPS safety monitoring system that uses receiving stations to receive GPS position data, transmitted by vehicles on a test course, has been developed. Data processing by computer enables real time display of vehicle status on monitor screens. At the same time, the system uses vehicle data to judge whether an accident has occurred, specify the location of the accident, and send out an emergency alarm. Honda's Takasu Proving Ground covers a large area of undulating ground, making direct monitoring by camera a challenge. A monitoring system based on transponders and sensors embedded in test courses has therefore been utilized in the proving ground. The number of Takasu test courses has recently been increased, and there have also been increases in the number of vehicles using the courses, bringing the former system to its functional limits. The monitoring system discussed in this paper was therefore introduced. This has enabled monitoring of the entire area of the Takasu Proving Ground, including connecting roads. The new system has increased the safety of the courses and done away with the necessity for inspection tours. The initial cost of introducing the system was one-tenth of the projected cost of extending the previous system.

1. Introduction

Honda's Takasu Proving Ground is a course used mainly for framework performance tests and cold climate tests for cars, motorcycles and ATVs. Takasu covers more than four times the area of the company's Tochigi Proving Ground, and contains an unparalleled range of undulating low-, medium-, and high-speed test courses (Fig. 1). This makes it challenging to directly monitor the courses using cameras. Previously, test vehicles were fitted with transponders^{*1}, and sensors embedded in the courses were used to measure the positions of the vehicles. This system judged that an accident had occurred if a vehicle was stationary on a course for a specified period of time. However, the number of test courses has recently been increased, and the number of motorcycles, cars, and ATVs being tested has also increased, bringing this system to its limits in terms of performance and cost. A new safety monitoring system using the global positioning system (GPS) was therefore developed, enabling monitoring of safety across all the Takasu courses.

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** Standard Co. Ltd.

*1 The term transponder is formed from the words TRANSmitter and resPONDER, and refers to a device that is able to relay and return a response to electrical signals it receives.

2. Development Goals

(1) Increased safety

Transponder sensors are only embedded in two courses on which high-speed tests are conducted, but the aim for the introduction of the GPS safety monitoring system was to enable safety to be monitored on all the courses within the Takasu Proving Ground. In addition, real-time monitoring of all vehicles in the proving ground would not only enable accidents to be detected, but would also enable speed infringements and dangerous driving to be monitored and controlled, thus contributing to the prevention of accidents. Linkage with existing equipment would also enable:

- Preventive strategies for secondary accidents (by means of emergency warning lights and electronic signs)

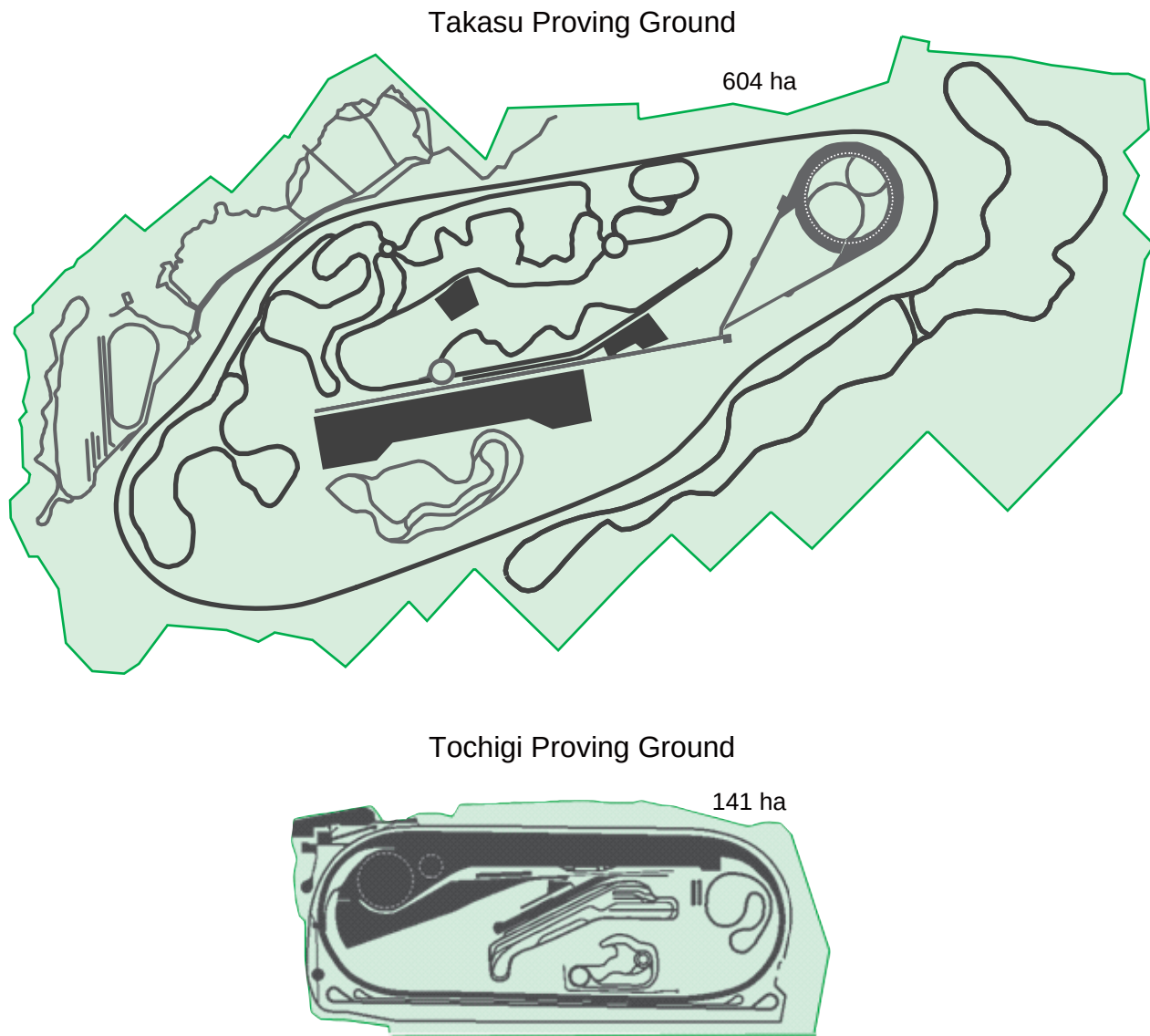


Fig. 1 Honda proving grounds

- Management of vehicle numbers (restriction of vehicle numbers by means of counters and gates)
- Management of motorcycle and car schedules (control by means of electronic displays at course entrances)

In this way, the system would enable the realization of total safety management.

- (2) Reduction of size and weight of transmitting stations
To enable fitting on two-wheeled vehicles, the aim for the transmitting stations was set at a total weight of 200 g or less and a size of 120 mm or less per side.
- (3) Accuracy and reliability of measurements
Snow drifts would affect the performance of the sensors in the previous system, necessitating inspection tours of

the courses during winter. The aim for the GPS safety monitoring system was to function without any issues and to display a high level of reliability in all seasons, and to work as a fully automatic monitoring system, without any need for inspection tours.

- (4) Reduction of initial costs and operating costs
The target for reduction of initial costs was set at implementation of the system at a cost of less than one-tenth of the projected cost, assuming expansion of the use of sensors to a further five courses. The target for operating costs (maintenance, etc.) was set at approximately one-half.

3. System Configuration

Vehicle position and other data transmitted by each of the transmitting stations fitted in test vehicles is received by the nearest receiving station, enabling real-time monitoring of vehicle behavior by the main PC (the safety

monitoring server) (Fig. 2). Data processing enables warnings to be sent out if an accident has occurred, and rescue crews on standby are able to determine where the accident has occurred on a display (Fig. 3) and scramble to the scene. At the same time, the entrance gates to the course are automatically closed, and electronic signs

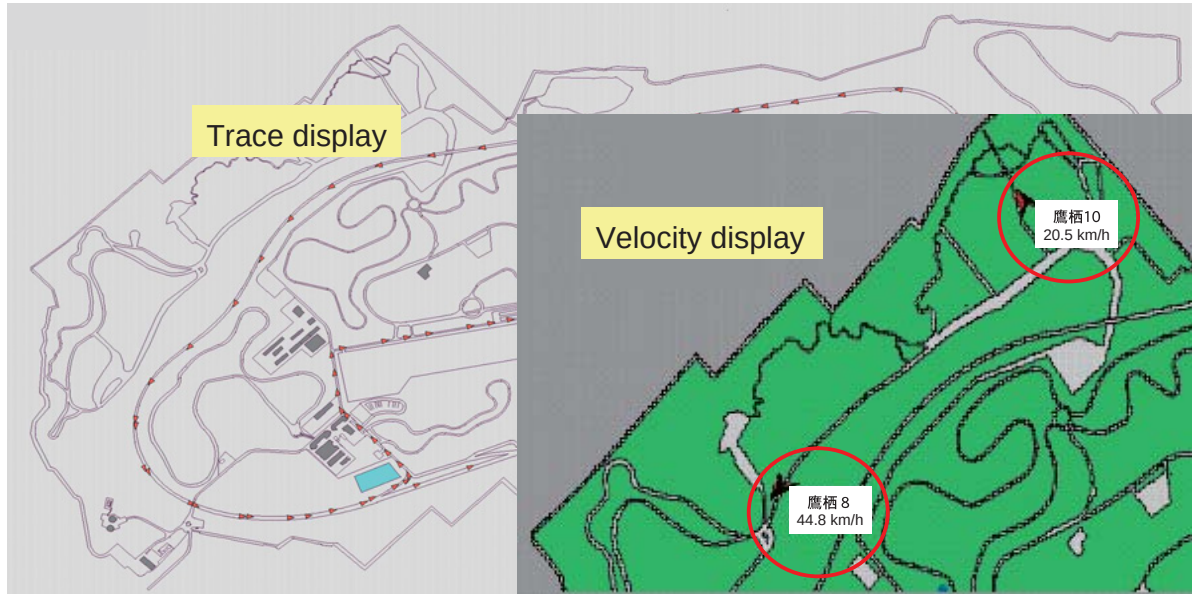


Fig. 2 PC monitor: Trace and velocity display

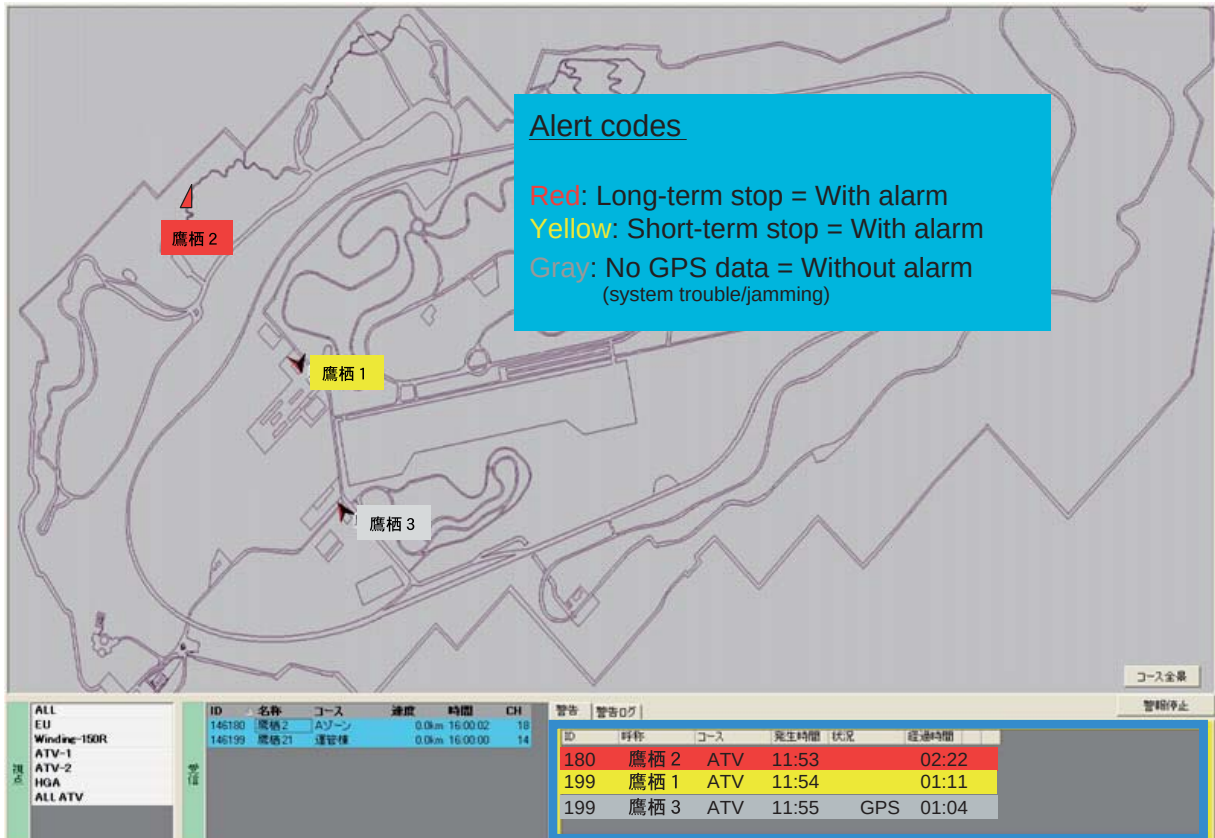


Fig. 3 PC monitor: Warning display

Table 1 Types of wireless transmitter

Type	Access speed	Size	Investment	Transmitting cost per unite
Wireless LAN	54 Mbps	Big	Large	¥0
Cellular phone	7.2 Mbps	Big	Large	¥10,500/month
Land mobile radio	2400 bps	Compact	Small	¥400/year

The specifications of the land mobile radio transmitting stations are as follows:

- Frequency: 400 MHz band; Output: 1 W
- System weight: 190 g (including battery)
- Size: H25 x W108 x D65 (mm)

3.2. Receiving Stations

The system features four receiving stations, a main antenna on a 30 m tower and three sub-antennas. Each of these receiving stations is provided with a control terminal, radio transmitters, a distributor, an amplifier, and an RS232C extension board (Fig. 6).

Private radio is prone to interference, and the positioning of antennas with consideration of the specific area and its geomorphology is therefore important. Interference tests showed that for the area in question, the combination of one main antenna tower and three sub-antennas would provide the optimum transmission environment.

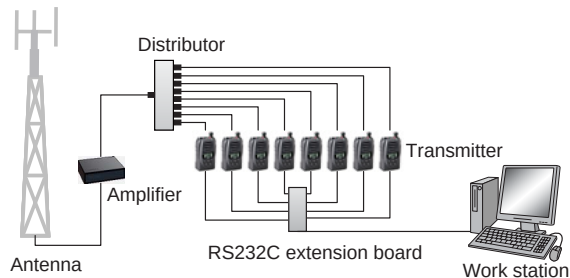
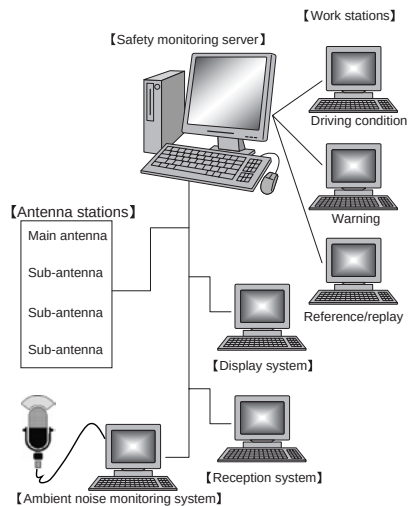


Fig. 6 Receiving stations



(a) Hardware

3.3. Data Processing System

3.3.1. Hardware

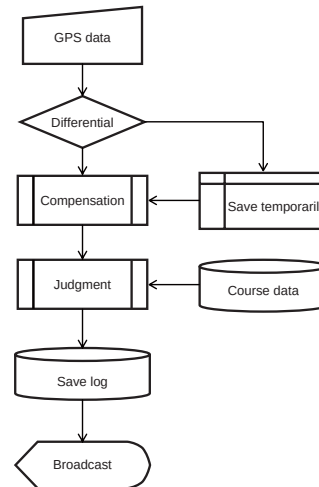
Figure 7(a) shows the configuration of the hardware making up the data processing system.

- (1) Safety monitoring server
- (2) Display system
- (3) Reception system
- (4) Ambient noise monitoring system
- (5) Antenna stations

3.3.2. Main program

Figure 7(b) shows the data processing flow of the main program in the data processing system.

- (1) Data received from the transmitting stations
ID, position data (latitude and longitude), speed, direction, elevation, date, time
- (2) Compensation of position data by post-processing
- (3) Judgment on test course
 - a Judgment on course and area
Judgment on which course the vehicle is using, specification of area
 - b Prioritization of approximate values (historical data) for decision on course
In areas in which multiple courses are contiguous, use of historical data for judgment on course in use
- (4) Logging of course data
- (5) Saving of log
- (6) Broadcast of data



(b) Main program

Fig. 7 Data processing system

4. Technological Issues and Applied Technologies

4.1. Data Transmission Capacity and Number of Transmitting Stations

In order to help ensure sufficient land mobile radio transmission capacity based on the assumption of multiple transmitting stations transmitting data simultaneously, two types of firmware, for low- and medium-speed transmission at 0.1 Hz and fast transmission at 0.2 Hz, have been employed, making it possible to set ten or five transmitting stations for each channel. Data transmission from a maximum of 100-200 transmitting stations is therefore possible. This provides a margin for the growth of the current vehicle capacity of the Takasu Proving Ground by two- to four-fold. In addition, unnecessary transmissions have been avoided through the use of firmware, which reduces the amount of transmissions when a transmitting station has judged from GPS data that a vehicle has stopped.

4.2. Accuracy of GPS Measurements and Judgment of Accidents

GPS normally has an error of around two meters, and accuracy can decline even further depending on the angle of the satellite and other factors. Because of this, judgment on whether a vehicle has left a course is challenging when courses are contiguous. Data processing is therefore used to judge whether a vehicle has left a course from immediately prior historical data and speed data. In order to increase reliability even further, G sensors have been added to the transmitting stations to provide vehicle behavior data, enabling accidents to be judged with a high degree of accuracy.

5. System Reliability and Effects

5.1. Results of Reliability Tests

5.1.1. Suitability of transmitting station units to environment

(1) Temperature tests

The temperature of transmitting station units was increased from -20°C to +60°C in a thermostatic chamber, and the units were left for an hour at each 10°C increment.

(2) Waterproof tests

Leak tests were conducted using a differential pressure sensor. After 30 sec at a negative pressure of 4.9 kpa, the differential pressure leak tester recorded figures of less than 0.05 kpa.

(3) Static electricity tests

When the units were powered up and turned off, ± 20 kV was impressed at the antenna, and ± 15 kV was impressed on the unit.

(4) Vibration tests

- Vibration frequencies: 5-8 Hz / 8-30 Hz
- Total amplitude: 3 mm / 1 mm

- Test time (each test): 15 min x 3 directions x 2 waveforms (Total: 90 min)

(5) Impact tests

Units were dropped onto a concrete floor from a height of 120 cm, one time per side for five sides of each unit.

The results of the temperature, water, static electricity, vibration, and impact tests cleared benchmark figures.

5.1.2. Tracking of vehicle speed

No decline in reception was recorded at vehicle speeds of 250 km/h and above.

5.1.3. Operation of alarm and response time

High-speed driving: Alert within 5 sec after vehicle stopped, alarm raised within 10 sec.

Low-speed driving: Alert within 10 sec after vehicle stopped, alarm raised within 20 sec.

Target figures were achieved in both cases.

5.2. Performance in Operation

The system has been in operation for 4 years in the case of ATVs. It has enabled the realization of fully automatic monitoring in all seasons, and done away with the necessity for inspection tours during winter.

6. Conclusion

The expansion of the test courses in the large area of the Takasu Proving Grounds is continuing today, and further expansion plans are projected for the future. The system discussed in this paper can be made to cover any amount of extension of test courses simply by overwriting software. This is the initial application of the system, and Honda expects to enhance safety management by extending its use to other test courses and training courses. The introduction of the GPS monitoring system discussed here enhances safety management, and test riders and drivers have placed high expectations on it. Test course safety is an ongoing concern in automotive test course management. At the Takasu Proving Ground Honda is putting in place a comprehensive safety management system, which extends from preventive safety to emergency accident response, aiming to achieve the world's highest standard of safety for an automotive test course.

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Study of FACE Design, Lighting System Design for Enhanced Detection Rate of Motorcycles

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ABSTRACT

The FACE (Facial Attention for Conspicuity Enhancement) design, a lighting system design that enhances motorcycle conspicuity with regard to the detection rate from the view of a driver at night, is described in this paper. Past research has shown that there is part of the human brain that reacts to the image of a face and we thought of a method to enhance the detection rate of a motorcycle by incorporating the element of a face in the front design of the motorcycle. The effect of a simple FACE design, an inverted triangular arrangement of lights, is evaluated and its effectiveness is shown. Moreover, we developed a simulation method that could be used to evaluate the enhanced detection rate of a FACE design motorcycle under conditions that are close to some real traffic environments. The method is evaluated by comparing it with the results of a full-scale test and demonstrates the method could be used to evaluate the detection rate of a motorcycle.

1. Introduction

We obtained the motorcycle fatal accident data in which car drivers were deemed most at fault, and thus were designated as the “Primary Party”*, from the database of “Japanese traffic accident statistics”⁽¹⁾. The data was analyzed to determine the cause of each accident. This analysis resulted in a conclusion that a car driver’s failure to detect the motorcycle was one of the key factors in the accidents (Fig. 1).

*Primary Party: In the Japanese integrated database, vehicles whose drivers were most at fault in traffic accidents are called the “primary party,” and the other vehicles are called the “secondary party.”

Compared to a car, a motorcycle is smaller in size and presentment, and the possibility of non-detection is relatively high in a mixed traffic environment where there are many large-sized vehicles, such as trucks and passenger cars. In Japan, a countermeasure against the lack of motorcycle detection, Automatic Headlight On, was mandated in 1998. Its positive effect has been recognized.

However, the positive effect of Automatic Headlight On could be reduced at night when cars are also using their headlights. Moreover, recently, many cars and trucks

are also equipped with Daytime Running Lights (DRLs) and many countries are considering laws that require use of DRLs. Thus, if more and more various types of vehicles are equipped with DRLs, a further reduction of motorcycle conspicuity is possible. Based on these facts, a countermeasure that enhances the conspicuity of a motorcycle under a complicated mixed traffic environment was sought. To this end, we tried to enhance the detection

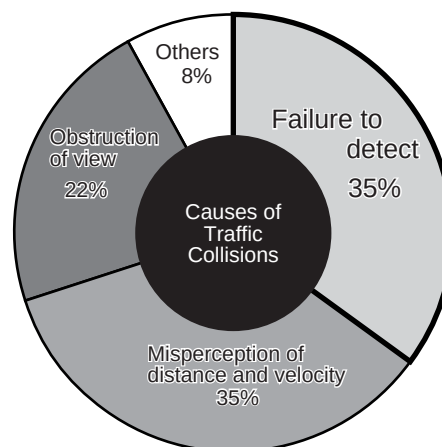


Fig. 1 Analysis of motorcycle traffic accidents in Japan

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rate by incorporating the elements of a face in the front design of a motorcycle because it has been found that people naturally show a high recognition capability to specific figures including a “face”. We decided to call the lighting system designs that utilize the elements of a face to enhance motorcycle detection rate FACE (Facial Attention for Conspicuity Enhancement) design. A simple example of FACE design was evaluated to confirm its effect. The details of the evaluation method developed for this research are also discussed.

2. Enhancement Effect in Conspicuity of FACE

A “face” is one of the stimuli seen most frequently. Humans are able to understand detailed information, such as visual line and facial expressions, in a “face” instantaneously⁽²⁾. Significant research about the high-level facial recognition capability of primates, including human beings, has been performed for many years and several conclusions have been reached. For example, Bruce reported that the part of the brain that reacts to a face picture exists in the lower temporal lobe of a monkey⁽²⁾. Recently, research using Functional Magnetic Resonance Imaging (fMRI) has confirmed that the same kind of reaction also exists in a human’s brain⁽³⁾. It has also been confirmed that the Fusiform Face Area (FFA) of the fusiform gyrus in the temporal lobe and Occipital Face Area (OFA) of the inferior occipital gyrus have a high sensitivity to a face figure⁽⁴⁾. Since part of the human brain specializes in the recognition of a face, it is thought that humans can rapidly recognize a face. Given this, it is reasonable to believe that motorcycle conspicuity might be enhanced by incorporating the elements of a “face” in the front design.

In order to investigate the feasibility of enhanced motorcycle conspicuity by using the elements of a “face” in the front design, we first measured the detection rate of a motorcycle in traffic using an image. Figure 2(a)

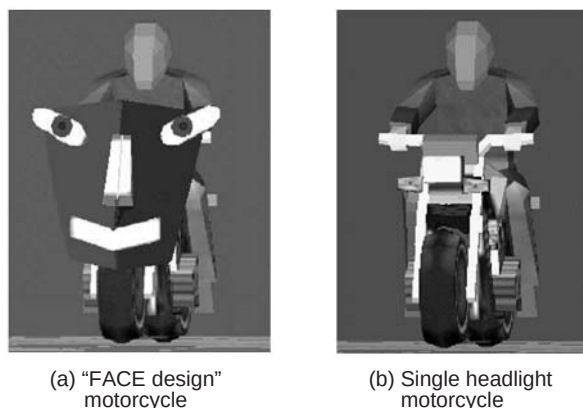


Fig. 2 Motorcycles used for providing our hypothesis that FACE design enhances conspicuity

shows the motorcycle that utilized the elements of a “face” in its front design that was used in the experiment (Hereafter, a motorcycle which uses the elements of a “face” is called a “FACE design” motorcycle.). Figure 2(b) shows a single headlight motorcycle used as the standard for comparison.

Five subjects (four men aged 20 - 40 and one woman in her 20’s) were tested. Each subject drives a car daily. The presentation time of the image was 0.5 seconds. After image presentation, a black screen was presented until the subject answers. 144 measurements per subject were carried out. The results of the measurements are shown in Fig. 3.

Figure 3(a) shows the average motorcycle detection rate by the subjects. The detection rate of a single headlight motorcycle was 47.6% and the detection rate of the FACE design motorcycle was 91.4%.

Figure 3(b) shows the time after a subject was shown the image until a reply button was pushed. The average response time in the case of the single headlight motorcycle was 910 ms, while the average response time in the case of FACE design motorcycle was 706 ms. These results show that the conspicuity of a FACE design motorcycle was increased compared to a single headlight motorcycle and this may enhance the motorcycle’s detection rate by drivers of other vehicles.

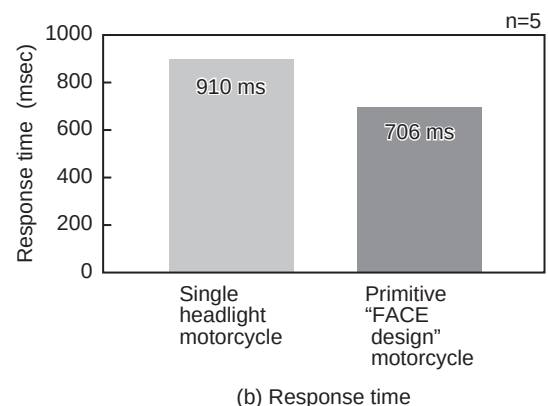
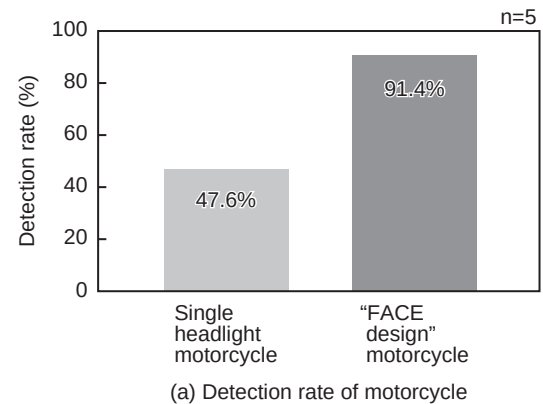


Fig. 3 Enhanced conspicuity by FACE design

3. Motorcycle Detection Rate Evaluation Method

In a past study, Sugawara et al. confirmed that cerebral activation could be measured by using fMRI. It is possible that a quantitative evaluation of Facial levels of the front design of a motorcycle could be carried out⁽⁵⁾. However, fMRI equipment is large-scale and cannot be used for measurement in a real traffic environment. On the other hand, it is difficult to measure the detection of a motorcycle in an actual traffic environment in which large-sized vehicles, such as trucks, and passenger cars are driving. Therefore, we developed a simulation method that can help measure the detection rate in a similar. This section reports on the simulation technique.

For an enhancement in conspicuity at night, the key point of motorcycle front design is the lighting system. One's ability to recognize the form of a vehicle emitting high luminous intensity light, such as from a headlight, is affected by the visual phenomenon referred to as "glare". The overall evaluation of conspicuity requires the evaluation of the lighting system and how it is seen. In this method, paying close attention to "contrast ratio" and "expression of glare", and by calibrating them to a real traffic environment, computer graphics (CG) that is almost equivalent to a real traffic environment was produced. In order to evaluate the simulation method, a CG of the test track was created, and a comparison with a real vehicle was performed. The creation method of the CG and the comparison result between the full-scale test and the simulation test are described below.

3.1. Contrast Ratio

In past research it has been shown that the detection rate of a motorcycle during a short-time presentation can be measured using a simulated computer graphic image as long as the contrast ratio of the real environment and the simulated environment are matched⁽⁶⁾⁻⁽⁸⁾. This information was used to create CG of various vehicle arrangements to be used in the evaluation of the FACE design motorcycle. First, we created CG of the test track. The test truck had less limitation of time, and it was possible to set environment and measuring condition. Thus, it was easy to verify the validity of the simulation method that used CG instead of actual environments. In creating CG, the important elements are the position of the display and its hi-resolution performance. The display was set at a 1.3 m distance from the subject in order to set the horizontal field angle at 45 degrees. The viewing height of the CG was 1.2 m from the ground. The actual measurement luminosity of the test track was 1 cd/m² for the dark part of the road surface and 1500 cd/m² to 3000 cd/m² for a headlight. A display that could reproduce 3000 or more contrast ratios was required. We used a plasma display to satisfy the requirements. The size of this display was 50 inches, luminance was 0.1 cd/m² for the dark area

and 400 cd/m² for the bright area, and it has 4000 contrast ratios. The contrast ratio of the CG of the simulated test track was calibrated with the real environment on this display.

3.2. Glare

Another visual phenomenon important in this research is glare. Glare is the light that appears to be generated around a light source, causing things in the area around the light source to fade to white, such as when people look at a bright light. Since the physical luminosity of the display was limited, it was difficult to actually generate this glare. As an alternative, expressing a high-intensity light in simulation is often performed by adding glare artificially with CG⁽⁹⁾⁻⁽¹³⁾. This research utilized a method of inserting a mathematically generated glare pattern.

The pattern of the glare was verified by comparative experiments with a real vehicle that is described in the next part of this paper.

CG of the simulated test track is shown in Fig. 4.

3.3. Comparative Experiments with a Real Vehicle

In order to verify whether the simulation method was an effective way to evaluate motorcycle conspicuity, we conducted an experiment comparing a simulation environment to one with real vehicles. Figure 5 shows the experiment situation in a real vehicle. The vehicles

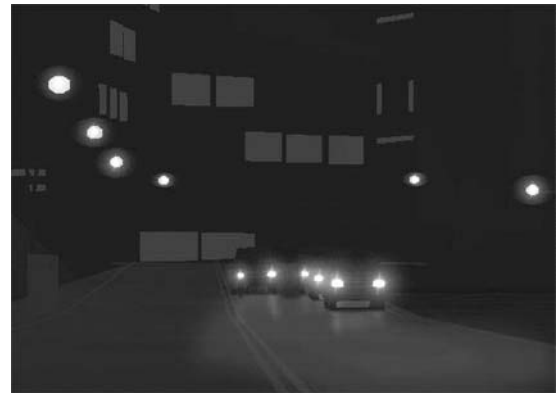


Fig. 4 CG example of test track



Fig. 5 Experiment scene at test track

used for the experiment are four cars and one motorcycle.

The motorcycles used were a single headlight motorcycle and a motorcycle with three lights in an inverted triangle arrangement formed by the headlight and two auxiliary lights (5 W 16 cd for each) (Fig. 6). The reason for using three lights in an inverted triangle arrangement was that it was reported to be a simple arrangement that was reminiscent of a face⁽¹⁴⁾.

There were four arrangements of vehicles utilized for the test (Fig. 7). Three conditions which included a single headlight motorcycle, a FACE design motorcycle and no motorcycle, were used on above mentioned four arrangements.

The subjects were 16 men aged 20 - 40 who operate a car daily. Each subject was shown a vehicle arrangement at random. Each arrangement was shown two times. The time for each subject to observe was adjusted to 0.5 seconds by synchronizing with metronome. The subject then had to identify the number of vehicles and how they were arranged. Twenty-four measurements were taken for each subject.

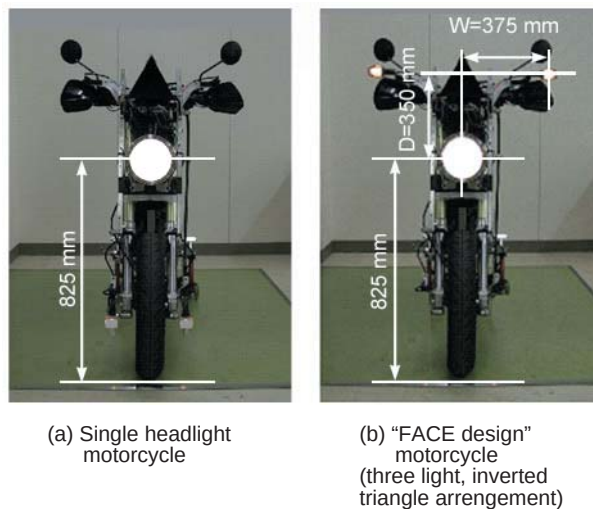


Fig. 6 Motorcycles used for experiment

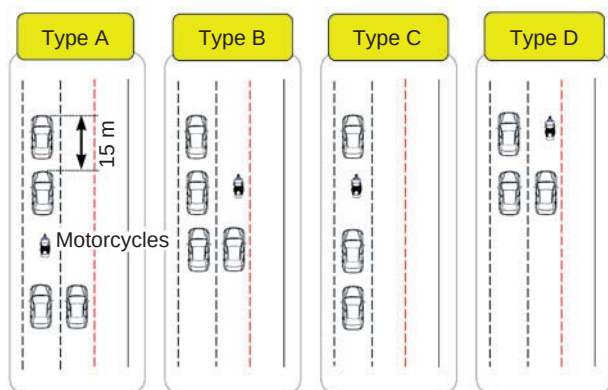


Fig. 7 Arrangements of vehicles used for tests

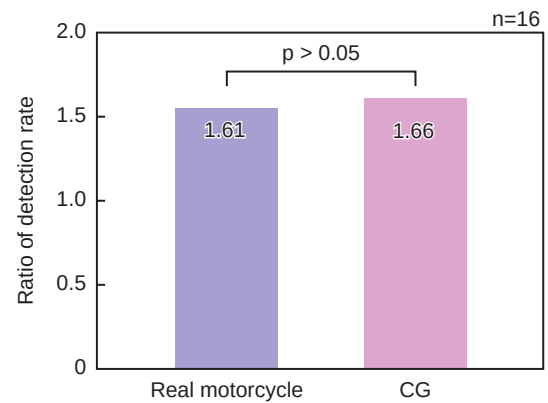


Fig. 8 Comparison of detection rate between real motorcycle and CG

Figure 8 shows a comparison of the FACE design detection rate between tests using actual vehicles and the simulation tests. In order to cancel the influence of the environmental factor, such as the numbers of vehicles, the detection rate of a FACE design motorcycle was shown divided by the detection rate of a single headlight motorcycle.

The results show that there was no statistically significant difference at 5% level, so it was concluded that the simulation can be used as an effective test method.

4. Actual Traffic Environment for Comparison Experiment

Next, in order to carry out the evaluation in a real traffic environment, the image of an actual intersection was created with CG. The intersection has 4 lanes in each direction, and has heavy traffic, including many motorcycles (Fig. 9).

Figure 10 shows two examples of CG. The viewpoint position in the simulations was a car driver who was waiting to make a right-turn (in the left-hand traffic) in the center of an intersection. Two intersections were simulated, and for each intersection images of seven different car and truck traffic arrangements were created.

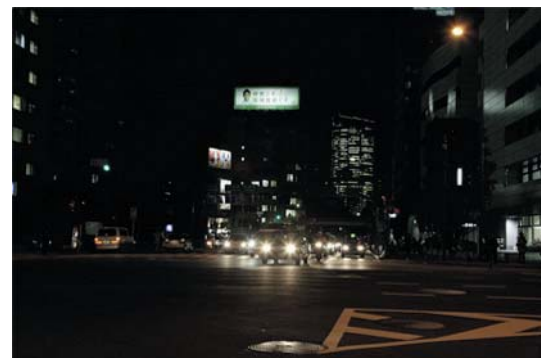


Fig. 9 View of intersection



(a) Example A



(b) Example B

Fig. 10 Examples of CG simulations

The motorcycle was placed 20 to 140 meters from the viewpoint of the car driver. In each of the 14 traffic arrangements, 1 to 3 motorcycles were introduced in the traffic mix for a total of 28 different images. Finally, 84 images were created; 28 with a standard single headlight motorcycle, 28 with a “FACE” design motorcycle and 28 with no motorcycle were included.

5. Effect of Face Element

By using the CG simulations described in the preceding section, the detection rate of the FACE design was measured. The measured FACE design was a lighting-system of three lights in an inverted triangle arrangement. Horizontal distance W from the headlight to the additional light was set to 375 mm, and perpendicular distance D was set to 350 mm. The measured control motorcycle utilized a lighting-system arrangement in which W was set to 375 mm and D was set to 0 mm as a control condition. Luminous intensity of the additional lights was set to 16 cd. The Luminous intensity of the additional light was adjusted based on the distribution of luminous intensity characteristic of position lamps. The color of the additional light was white. The composition of test equipment is shown in Fig. 11.

Twelve men aged 20 - 40 who drive a car daily were selected as subjects. Subjects were shown each of the 84

traffic simulation images for 0.5 seconds at random, and then answered whether a motorcycle appeared on the screen by pressing either Yes or No button on the steering wheel as soon as possible. After the CG was shown, a black screen was presented until the subject answers. Each traffic simulation image was shown 2 times for a total of 168 answers per subject.

Only the cases where the distance of the motorcycle was 80 m or more from the driver were included in the final results. This is because our past research has shown that traffic at 80 m distance from a car turning right is the threshold for making the turn or not⁽¹⁵⁾.

The results are shown in Fig. 12. The figure shows the increase in detection rate of motorcycles with additional lighting compared to a standard single headlight motorcycle.

The FACE design ($W=375$ mm, $D=350$ mm) was detected 2.4 times more often than the standard motorcycle. The control motorcycle lighting system design ($W=375$ mm, $D=0$ mm) was detected 1.6 times more often than the standard single headlight motorcycle.

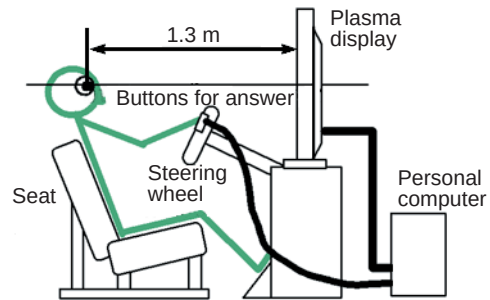


Fig. 11 Composition of experiment system

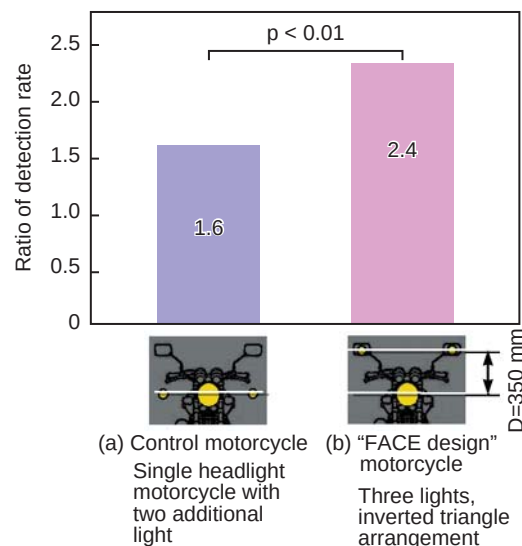


Fig. 12 Comparison of detection rate between FACE design and control motorcycle

6. Conclusion

Under the limited scope of study reported here, it was shown that the FACE design using three lights in an inverted triangle arrangement, which is a simple figure reminiscent of a face, could enhance the detection rate of a motorcycle from the point of view of a car driver.

In order to evaluate the detection rate of the motorcycle by a car driver, a simulation method that reproduced real traffic environments was developed. A comparison between actual vehicles and the simulation was carried out, and it was shown that the simulation was effective.

Additionally, the effect on the detection rate of motorcycles using FACE design motorcycles (using a lighting design of three lights in an inverted triangle arrangement) was measured using this simulation. It is shown that the detection rate of a FACE design is 2.4 times greater than that of a single headlight motorcycle.

We would like to make an effort to further advance "FACE design", to enhance the detection rate of motorcycles in various traffic environments, in the future.

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Analysis and Method of Quantification of Soot in Engine Oil

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ABSTRACT

Soot in engine oil was isolated using a centrifuge and subjected to an intensive analysis. The atomic bonds of the carbon in the soot discharged from the engine under various driving conditions were analyzed, and it was determined that the greatest proportion of the bonds were C-C (carbon-carbon) sp^2 (graphite structure) bonds and H-C (hydrogen-carbon) bonds, with few C-C sp^3 (diamond structure) bonds.

It was shown that the ratio of H and C atoms (the H/C mole ratio) could be used as an alternative indicator for the hardness of the soot. In addition, the project studied the correlation between this alternative indicator of soot hardness and sliding wear in the engine.

A method of removing soft impurities and quantifying the soot components in isolation was also studied as a means of more precisely determining this correlation.

1. Introduction

Attention is today being focused on diesel engines, due to their significant effect in reducing CO₂ emissions. While they do emit less CO₂, diesel engines are also known to emit soot. The soot emitted from the tailpipes of diesel engines is a factor in pollution of the atmosphere^{(1),(2)}. Soot that infiltrates the crankcase as a blow-by gas mixes with engine oil and promotes sliding wear, resulting in a decline in engine durability^{(3),(4)}. Soot production can also increase in gasoline engines, for example when direct injection is used, and is known to promote sliding wear in these cases⁽⁵⁾.

Numerous papers have discussed the wear resulting from soot in engine oil as abrasive wear⁽⁶⁾. The particle diameter, hardness, and quantity of the soot are generally considered to be the factors influencing the degree of wear produced by the soot under conditions of engine lubrication⁽⁷⁾.

However, while many papers have pointed out the correlation between the particle diameter and quantity of soot and the level of sliding wear, almost none have

touched on the correlation between the hardness of soot and sliding wear^{(8),(9)}. This can be considered to result from the fact that because soot particles are microscopic, it is challenging to directly measure their hardness, and the extraction of individual soot particles from engine oil for measurement is impractical.

The research discussed in this paper analyzed the abrasive wear produced by soot in engine oil in relation to particle diameter, hardness, and quantity, the properties of the soot considered to be most relevant. In particular, the research determined an alternative indicator of soot hardness that displays a good correlation with sliding wear. In addition, the research proposed a new method of quantification enabling evaluation of the hard components of the soot, which have a significant effect on wear, in isolation.

2. Method of Procedure

It is necessary to focus on particle diameter, hardness, and quantity in order to understand the sliding wear produced by soot in engine oil. In the present research,

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the distribution of the particle diameters of the soot in engine oil was first analyzed, and the degree of effect on sliding wear within that distribution was determined. Next, to enable an indicator of soot hardness to be formulated, soot was extracted from engine oil and the atomic bonds and composition of the soot were analyzed.

In order to verify the validity of the alternative indicator, engines were subjected to bench durability tests and the correlation between hardness and wear was determined. Finally, focusing on the effect of the quantity of soot, a method of removing soft impurities from the soot to isolate the hard soot components that were considered to more readily promote wear was studied.

3. Tests

3.1. Analysis of Soot Particle Diameter

Engine oil containing soot was diluted with toluene, and laser diffraction scattering was employed to measure the distribution of particle diameters.

3.2. Unit Wear Tests for Particles of Different Diameters

Carbon black of different average particle diameters with a similar structure to soot was prepared and used in unit wear tests in order to determine the effect of soot particle diameter on wear. Block-on-ring and shell-four-

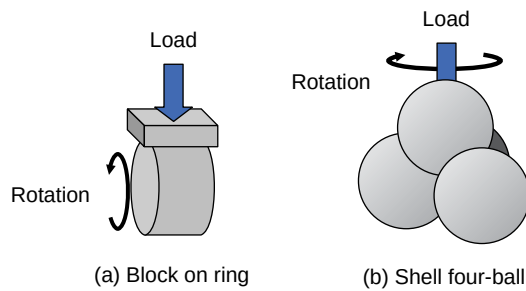
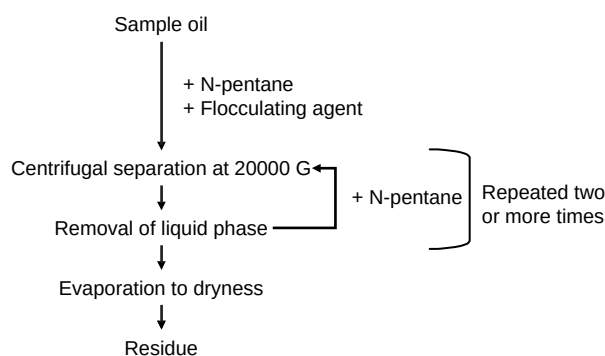
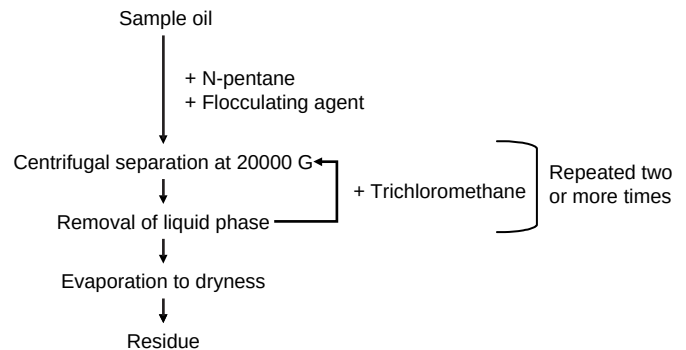


Fig. 1 Schematic of wear tester



(a) N-pentane insoluble method



(b) Trichloromethane insoluble method

Fig. 2 Experimental procedure of soot quantitative analyses

Table 1 Wear test conditions

	LFW-1	Shell four-ball
Engine oil	ILSAC GF-4, 0W-20	ILSAC GF-4, 0W-20
Carbon black concentration (wt%)	0.2	0.2
Mean carbon black particle diameter (nm)	66, 95, 122	66, 95, 122
Load (N)	100	441
Operation time (min.)	180	60
Oil temperature (°C)	80	80
Rotation speed (rpm)	400	1200

ball tests were selected for employment. Figure 1 shows a schematic of the block-on-ring and shell-four-ball tests. Table 1 shows test conditions.

3.3. Method of Extraction and Quantification of Soot

A number of methods are available for quantitative analysis of soot in engine oil, including infrared spectroscopy, TG, and centrifugation⁽⁸⁾⁻⁽¹⁰⁾. Centrifugation was selected for use in the present research, because it enabled soot to be extracted and the properties of the extracted soot to be analyzed following quantitative analysis.

The research employed a centrifugation method in which the pentane-insoluble fraction extracted at a relative centrifugal force of 20 000 G was defined as the quantity of soot⁽¹¹⁾. In addition, the substitution of trichloromethane for pentane in order to remove the sludge precursors in the extracted insoluble fraction was also studied as a proposed method of quantifying soot in engine oil. Figure 2 shows the flow of procedures in the pentane-insoluble and trichloromethane-insoluble methods.

3.4. Analysis of State of Atomic Bonding in Soot

Electron energy loss spectroscopy (EELS) analysis is sometimes employed to identify the structures of representative carbon materials such as DLC⁽¹²⁾. In a broad

Table 2 Engine specifications and test condition

Engine specs.	Number of cylinders and configuration	Inline 4
	Displacement	2354 cm ³
	Bore	87.0 mm
	Stroke	99.0 mm
	Compression ratio	10.5
Test condition	Speed	5000 rpm
	Grade	ILSAC GF-4, 0W-20
Engine oil	Spurious soot concentration (C element)	0.4 wt%
	Mean spurious soot particle diameter	100, 100, 120 nm

sense, the extracted soot can be taken to be a carbon material. An auger electron spectroscopy/reflection electron energy loss spectroscopy (AES-REELS) analysis was therefore conducted on the extracted soot.

Figure 3 shows the principle of AES-REELS. An electron loss energy near structure (EELS) spectrum with the background removed, representing the low energy loss side of the EELS spectrum, was obtained from the electron energy loss spectrum for the extracted soot. Using the spectra of diamond and graphite as benchmark materials, and glassy carbon as an amorphous carbon, a peak fit was performed using the method of least squares. The ratio of hydrogen-carbon (H-C), carbon-carbon (C-C) sp^2 , and carbon-carbon (C-C) sp^3 bonds in the extracted soot was estimated from the peak fit results.

3.5. Analysis of Soot Composition

The insoluble fractions extracted by centrifugation were burned to enable analysis of the organic elements composing them.

3.6. Bench Engine Durability Test Using Oil with Added Artificially-produced Soot

Engine oils to which carbon black had been added were used in a durability test on a K24A engine. Table 2 shows the engine specifications, test conditions, engine oil grade, and carbon black properties.

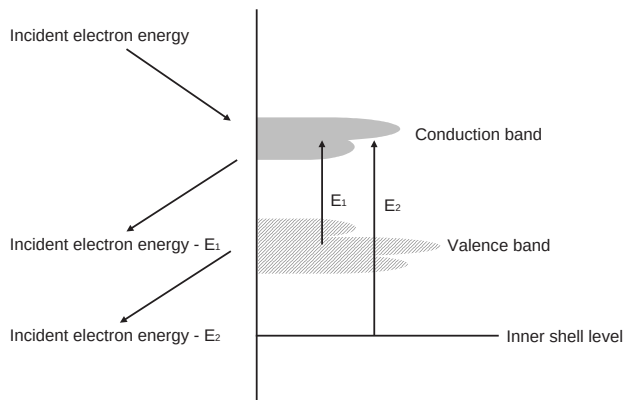


Fig. 3 Principle of EELS (schematic of energy loss and transition process in EELS)

4. Results and Considerations

4.1. Analysis of Properties of Soot in Engine Oil and Determination of Hardness Indicator

Figure 4 shows the results of measurements of the mean particle diameter of soot in engine oils recovered from the market, for both gasoline and diesel engines. Figure 4 indicates that in the case of both gasoline and diesel engines, the mean diameter of soot discharged from the engine that has accumulated in the engine oil is roughly 100 nm.

Unit wear tests were next conducted using carbon black of different mean diameters in order to determine the effect of changes in the diameter of soot particles on wear. Figure 5 shows the results of these unit wear tests. As Fig. 5 shows, under block-on-ring and shell-four-ball sliding conditions, changes in the particle diameter did not produce any observable effect on wear.

Next, the atomic bonding state of the pentane-insoluble fractions, extracted from the engine oils that were recovered from the market, was analyzed in order to determine an indicator for hardness. Figure 6 shows a three-dimensional phase diagram generated from the results of AES-REELS analysis of the pentane-insoluble fractions. The phase diagram shows that if the ratio of C-

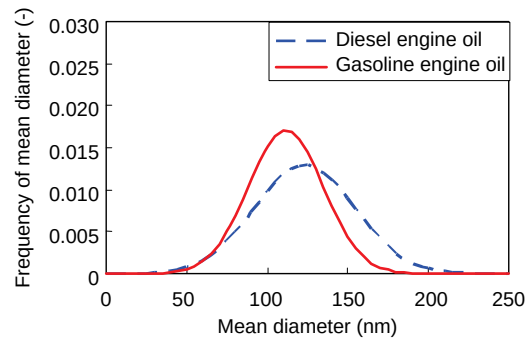


Fig. 4 Field research on mean soot particle diameter in recovered deteriorated diesel and gasoline engine oil

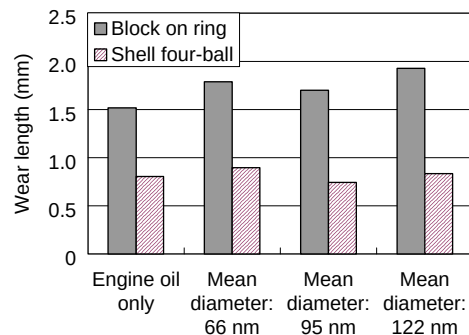


Fig. 5 Wear tester result with carbon black of different mean diameters

C sp^3 bonds increases, the structure becomes closer to that of diamond, and the substance becomes ultra-hard. If the ratio of C-C sp^2 bonds increases, the structure becomes closer to that of graphite, and the substance becomes hard.

However, if the ratio of H-C bonds increases, the substance should become soft. As Fig. 6 shows, analysis of the bonding state of carbon atoms in soot discharged from the engine that had accumulated in engine oil indicated that the soot contains few C-C sp^3 bonds, and a high proportion of C-C sp^2 and H-C bonds. In addition, the distribution width of the C-C sp^2 bond / H-C bond ratio is greater than that of the C-C sp^2 bond / C-C sp^3 bond ratio. Given this, it was conjectured that understanding the ratio of C-C bonds and H-C bonds would be more important than conducting a detailed analysis of the state of C-C bonds in developing an index for the relative hardness of the pentane-insoluble fraction in engine oil. The project therefore focused on the mole ratio of carbon and hydrogen atoms (the H/C mole ratio), and verified the usefulness of the H/C mole ratio as an alternative indicator for hardness. Specifically, artificially-produced soots with different H/C mole ratios were used in engine bench durability tests, and the existence of a positive correlation between the H/C mole ratio and engine sliding wear was demonstrated.

4.2. Verification of Validity of Hardness Indicator in Engine Durability Tests

Three types of artificial soot were prepared and added to engine oils to produce carbon concentrations of 0.4 wt%. These oils were used in engine bench durability tests. The inner rotor of the oil pumps was studied to quantify the level of engine wear. Figure 7 shows a photograph of the complete oil pump. When wear progresses in the inner rotor, the oil pressure in the main

gallery declines. This decline occurs because of idling of the oval-shaped shaft that penetrates the inner rotor and is used for rotor drive. Figure 8 shows photographs of inner rotors following the completion of durability tests. As Fig. 8 shows, there was conspicuous wear of the interiors of the inner rotors for artificial soots with H/C mole ratios of 0.35 and 0.5. No wear could be found in the case of the artificial soot with a H/C mole ratio of 0.6 after 150 hr of testing. These results can be considered to indicate that the earlier the decline in oil pressure occurs, the more severe the wear.

Figure 9 shows the correlation between the time elapsed in durability tests until the decline in oil pressure occurs and the H/C mole ratio. Figure 9 indicates that there is a tendency for the time elapsed until the oil pressure drop to become shorter and the degree of wear more severe the lower the H/C mole ratio and the higher the carbon ratio of the soot. A precise correlation can therefore be established between the H/C mole ratio of the pentane-insoluble fraction of the soot and engine wear, and it can therefore be considered to represent an effective indicator of hardness.

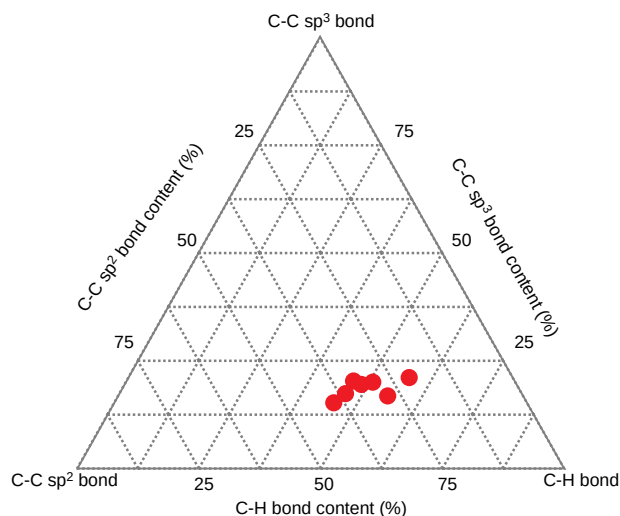


Fig. 6 Phase diagram of carbon atom binding state in soot

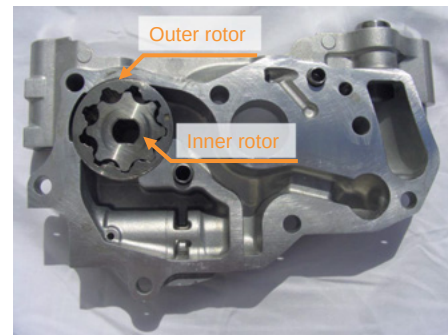


Fig. 7 Oil pump

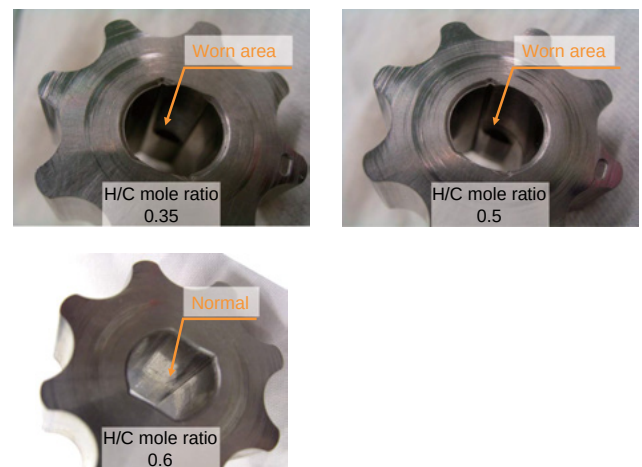


Fig. 8 Worn parts

4.3. Study of Method of Quantification of Soot that Evaluates Hard Components Only

As indicated above, the difference in H/C mole ratios represented an issue when determining a correlation between the quantity of pentane-insoluble substances in engine oil and engine wear. This can be considered to be due to the fact that sludge precursors were extracted from the oil together with the soot. A method of minimizing differences in the H/C mole ratio of the substances extracted from the oil by removing sludge precursors as much as possible and extracting pure soot was therefore proposed.

Figure 10 shows the H/C mole ratios of pentane-insoluble fractions and trichloromethane-insoluble fractions extracted from diesel vehicle and gasoline vehicle engine oils recovered from the market. As Fig. 10 shows, the H/C mole ratios of the trichloromethane-insoluble fractions display a sharper distribution curve than those of the pentane-insoluble fractions. This indicates that the method of using trichloromethane-

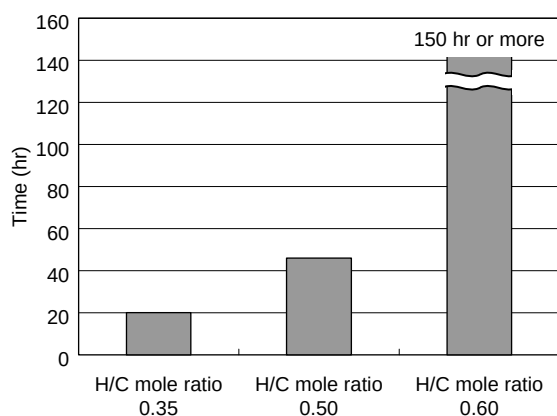


Fig. 9 Time until oil pressure reduction with soot of different H/C mole ratios

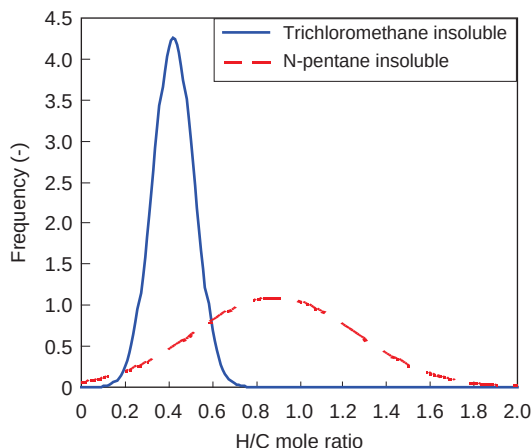


Fig. 10 Result of H/C mole ratio analyses with trichloromethane and n-pentane insoluble

insoluble fractions enables selective quantification of hard soot components and the more precise establishment of a correlation with wear.

5. Conclusion

- (1) It was found that the carbon atoms in soot in engine oil display few carbon-carbon sp^3 bonds (diamond-structure) and a large proportion of carbon-carbon sp^2 (graphite structure) and hydrogen-carbon bonds.
- (2) A correlation was determined between the H/C mole ratio and engine wear, and the H/C mole ratio can therefore be considered a useful indicator of the relative hardness of soot in engine oil.
- (3) The removal of sludge precursors by means of centrifugation using trichloromethane was found to be a useful method of quantification of soot in engine oil.

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Fine Control System for Multi-plate Lock-up Clutch

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ABSTRACT

Expanding the range of operation of lock-up clutch (LC) control to reconcile the achievement of a drive feel with a directness similar to that available from an MT vehicle and increased fuel efficiency has become a trend in the area of automatic transmissions.

The combination of a multi-plate lock-up clutch torque converter (“multi-plate LC TC” below) and an LC direct control hydraulic circuit that provide LC control in response to driving conditions has enabled the realization of a fine control system for an LC that has enhanced the response, cooling, and control performance of the LC.

The application of this LC control system has enabled the range of LC control to be expanded from the previous low throttle opening range to the high throttle opening, low engine speed range. As a result, the time for acceleration from 0-100 km/h at wide-open throttle has been reduced by 0.2 sec, and fuel efficiency in US06 mode and actual fuel efficiency have been increased by approximately 3%.

1. Introduction

Today, as global attention is focused on measures to combat global warming, demands for the reduction of greenhouse gas emissions are increasing. In the automotive area also, reduction of automotive CO₂ emissions is increasingly demanded, in particular through the use of technologies that enhance fuel efficiency. In tandem with this trend, demands are also increasing for the realization of greater ease of driving, and the rate of use of automatic transmissions is consequently increasing. Among these automatic transmissions, there has been a greater diffusion in the past several years of dual clutch transmissions (DCT), which like manual transmissions do not employ a torque converter (TC). Manufacturers are seeking by this means to respond to consumer demands by offering greater driving pleasure through the realization of a drive feel with a sense of directness similar to that of a manual transmission vehicle.

Demands are also being made on TC – the take-off devices used in AT vehicles - for the achievement of performance enhancements such as enhanced drivability and increased fuel efficiency by means of direct torque transmission.

In order to realize these goals, a multi-plate LC TC^{(1),(2)} and LC direct hydraulic control circuit have been employed in combination to enable the achievement of enhanced LC responsiveness, LC heat resistance, and LC controllability by means of the application of LC control that responds to the operating status of the vehicle⁽³⁾.

2. Establishment of Targets for Fine Control

LC control controls the degree of slip in the LC in response to operating conditions including vehicle speed, engine speed, and degree of throttle opening, and controls the transmission of torque by the torque converter. “Fine control” in this paper refers to control of LC slip in response to operating conditions, i.e., control across the entire range of LC operation (Fig. 1). The following development targets were set, based on the projected benefits in terms of enhanced drivability and increased fuel efficiency to be gained from the realization of fine control:

- (1) Expansion of the range of LC control to the entire operating range
- (2) Application of LC slip control in response to vehicle operating conditions

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The range of application of conventional LC is limited (see Fig. 1, “Current AT LC range”). The reason for this limitation is that LC response takes time during deceleration, when the speed ratio is high, and control is applied to turn the LC OFF due to the fact that LC slip generates a large amount of heat, when high torque is generated.

The following performance enhancements were therefore placed on the agenda for the realization of full-range LC control:

- (1) Increased LC response performance
- (2) Increased LC cooling performance

These enhancements were to be achieved through the use of a multi-plate LC TC and an LC direct control hydraulic circuit.

The realization of sufficiently enhanced drivability and increased fuel efficiency from expanding the range of application of LC control to the entire operating range necessitated fine settings for the target slip ratio during vehicle operation. This development agenda would be implemented by means of LC control that responds to the status of vehicle operation.

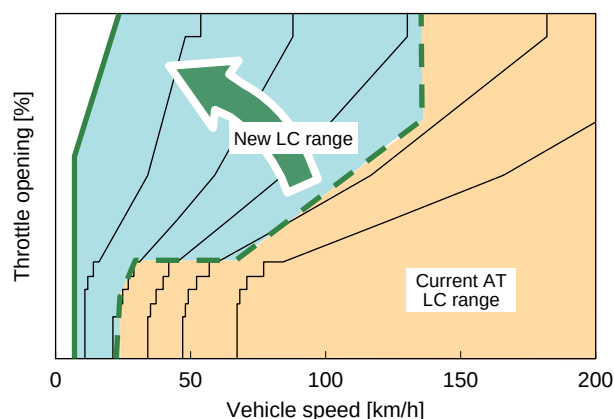


Fig. 1 Lock-up clutch map

3. Multi-Plate LC TC

3.1. Configuration

This section will discuss the features of the multi-plate LC TC (Fig. 2) used in this project. Among the performance parameters demanded from TCs used in FF vehicles are the ability to respond to vehicle hybridization, and their contribution to the reduction of the total length of the AT in order to help ensure collision safety. While the flow channels in standard TCs have a flatness rate of 80%, in 2001 Honda led the world in developing an ultra-flat TC with flow channels with a flatness rate of 60%, and mass-produced the unit as a TC for FF vehicles.

Given that a multi-plate LC is made up of multiple components, including piston chambers, multiple disc plates, and clutch guides, if the conventional flow channel

width was employed, the dimensions of the TC shafts would unavoidably increase. To enable the new TC to be used in FF vehicles, the dimensions of the shafts of the flow channels formed from the blades and torus sections were further reduced, enabling the achievement of a length equivalent to that of a conventional TC.

Another major feature of the TC is that the fact that the piston chamber forms an enclosed space enables the application of torque capacity control equivalent to that applied by the shift clutches.

3.2. LC Response Performance

The achievement of enhanced LC response performance was an important factor in the achievement of full-range LC control. This section will first discuss the operating state of LC control. Figures 3 and 4 respectively show a single-plate and a multi-plate LC. Both types of LC control the operation of the LC pistons by means of the difference between the LC operating pressure and the TC pressure. The achievement of enhanced hydraulic response performance for the LC operating pressure and the TC pressure is therefore a factor in the achievement of enhanced LC response performance. In a single-plate LC, the facts that the flow channels for LC operating pressure and TC pressure are reversed in the transition from LC OFF [Fig. 3(a)] to LC ON [Fig. 3(b)] and that the LC operating pressure and the TC pressure come together in the LC piston section are factors in the delay in the response characteristic of the LC pistons. The response performance of the LC pistons is enhanced in a multi-plate LC, in which the control hydraulic pressure moves in the same direction in LC OFF [Fig. 4(a)] and LC ON [Fig. 4(b)], by maintaining the TC pressure at a constant level and controlling the LC operating pressure, the precision of which has been increased, in relation to the transient state in LC ON.

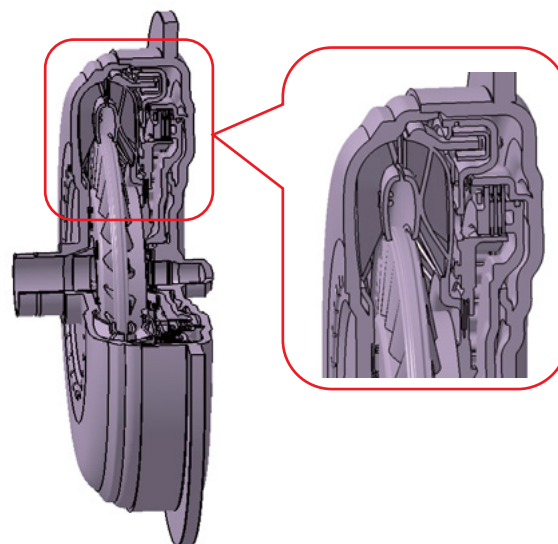


Fig. 2 Side view of developed torque converter

3.3. LC Cooling Performance

The cooling performance of the LC facings is another factor that has a strong effect on full-range LC control. The ATF lubrication is used for the cooling of the LC facings. In a single-plate LC, when the LC is ON, the facings seal the LC operating pressure and the TC pressure [Fig. 3(b)], and it is therefore challenging to achieve an effective flow of the ATF lubrication over the facings. In a multi-plate LC, because the LC pistons form spaces that are always closed, there is no need to seal the TC and LC operating pressure, and lubrication grooves can be employed on the surface of the LC facings [Fig. 4(b)].

The supply of ATF lubrication to the grooves using TC pressure and the use of TC pressure flow channels extending from the inner to the outer diameter of the pistons has enabled the achievement of a smooth flow of

ATF lubrication by means of centrifugal hydraulic pressure. In addition, the use of lubrication holes in the gear hubs in the inner sections of the pistons has also increased cooling performance by enabling an efficient flow of ATF lubrication.

4. LC Direct Hydraulic Control Circuit

4.1. LC Response Performance

In order to enhance LC response performance, the newly developed hydraulic circuit has been provided with a dedicated control valve, the purpose of which is to increase the accuracy of the LC operating pressure to the same level as that of the shift clutches. Figure 5 shows the new hydraulic circuit.

A conventional hydraulic circuit is shown in Fig. 6. LC operating pressure and TC pressure are initially

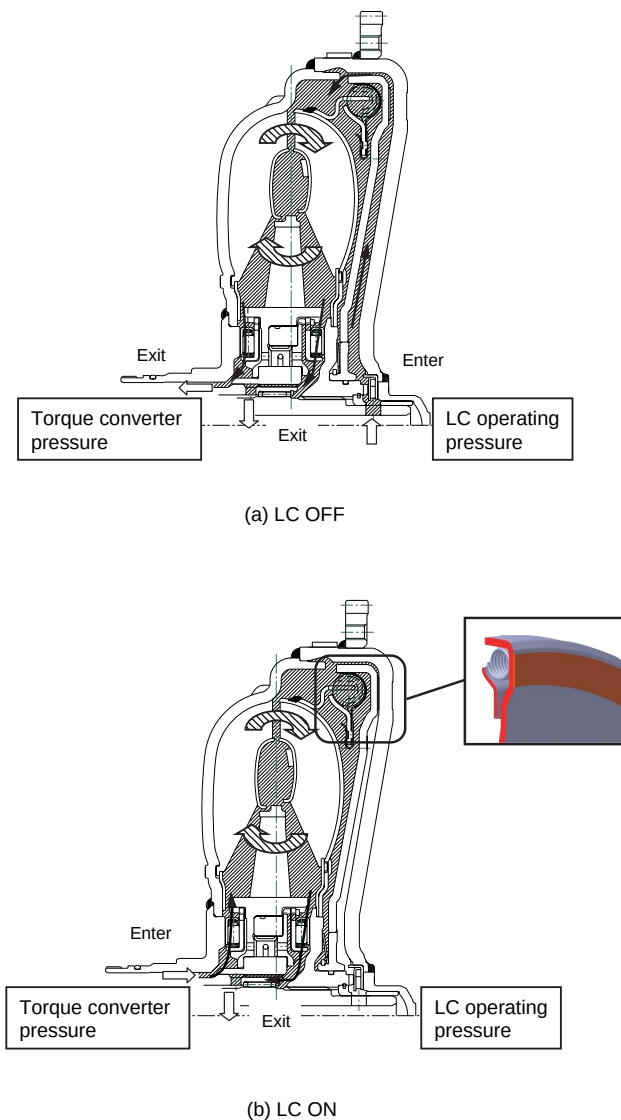


Fig. 3 Oil flow of torque converter with single plate LC (previous)

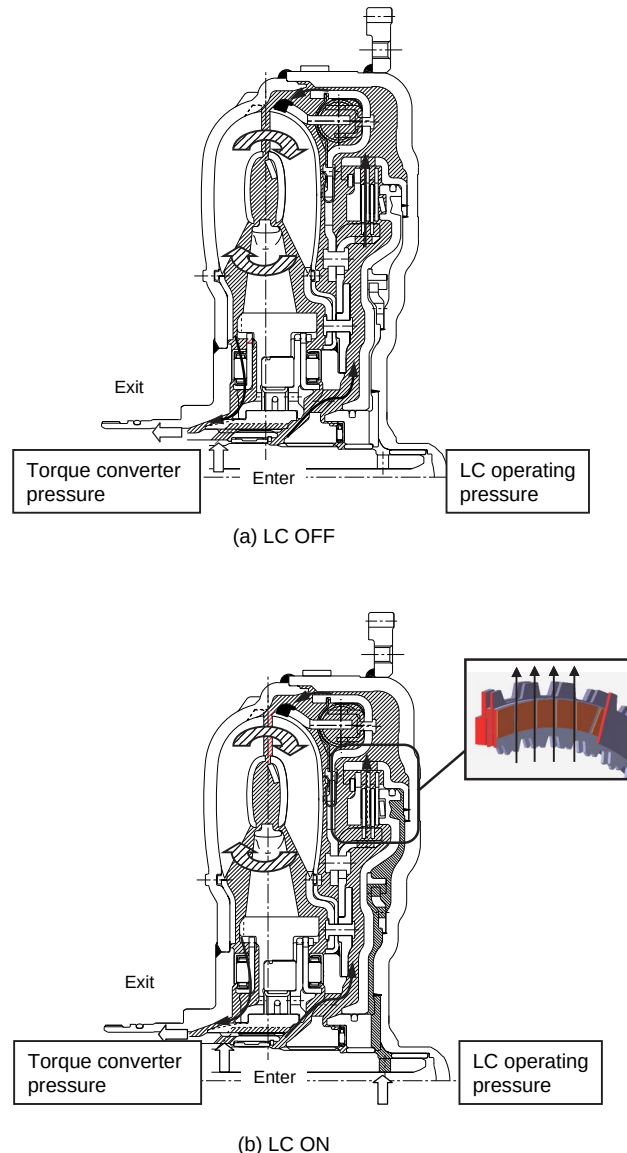


Fig. 4 Oil flow of torque converter with multi plate LC

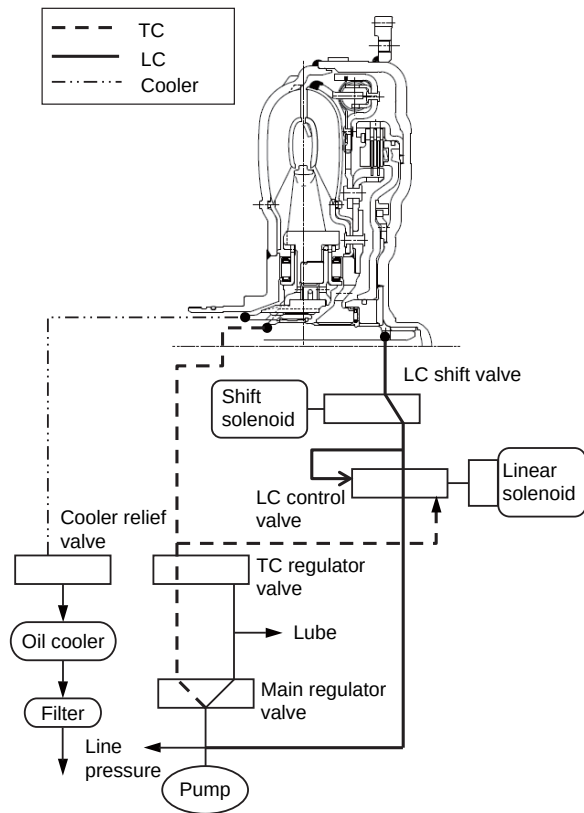


Fig. 5 Multi-plate type hydraulic circuit

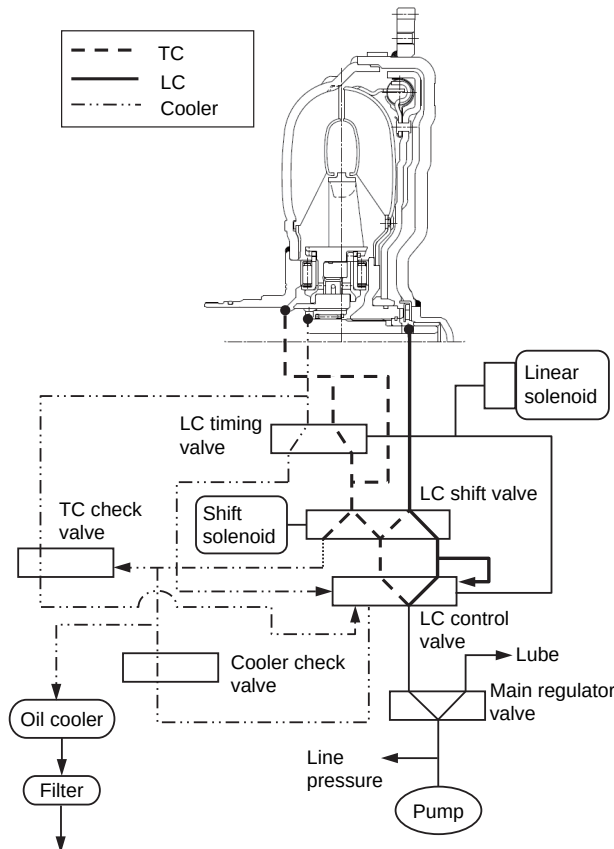


Fig. 6 Single-plate type hydraulic circuit (previous)

identical, but LC operating pressure control generates a pressure differential by means of an LC control valve. Because of this, when the LC pistons are in operation, the TC pressure fluctuates simultaneously with fluctuation in the LC operating pressure, and this is a factor in the delay in the response of the LC pistons. The LC direct hydraulic control circuit uses the LC valve exclusively for control of the LC operating pressure, enabling the LC pistons to be controlled by the LC operating pressure alone, thus increasing controllability to the level of that of the shift clutch pressure.

Because LC control functions by means of a balance between LC operating pressure and TC pressure, it is important to enable LC operating pressure to be compensated by TC pressure. Conventionally, system settings have attempted to create conditions in which changes in the TC pressure affect the LC operating pressure, using the TC pressure on the outlet side to operate the LC control valve. However, the use of TC pressure made LC control more challenging due to the fact that TC pressure is affected by the operation of the LC pistons, and that TC pressure is also changed by vehicle operating conditions, because it is hydraulic pressure that has first passed through the TC. The LC direct hydraulic control circuit helps avoid these LC control issues by means of the fact that the TC pressure is constant in multi-plate lock-up clutches, and by using the inlet-side TC pressure as the pressure acting on the LC control valve. This results in enhanced controllability of LC pressure, with no change to the compensation of LC operating pressure using TC pressure.

4.2. LC Cooling Performance

The internal pressure of the TC has also been increased in the new hydraulic circuit in order to enhance the cooling performance of the LC facings.

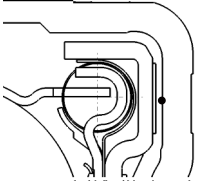
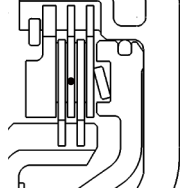
A dedicated TC regulator valve has been employed to maintain the hydraulic pressure in the TC at 570 kPa and to help ensure a TC flow rate of 6 L/min, thus enhancing cooling performance by constantly cooling the LC facings.

5. LC Control in Response to Vehicle Operating Status

5.1. Commercial Appeal of LC

The new control circuit has enhanced the cooling performance of the LC facings (Fig. 7) and expanded the degree of freedom of slip ratio control against that of a single-plate LC. Table 1 shows the conditions employed in temperature measurements of the LC. The enhanced cooling performance has enabled the achievement of a direct response to operation of the accelerator pedal ("AP" below), and the realization of powerful acceleration as a result of increased transmission efficiency. This has reduced the time for acceleration from 0-100 km/h at wide-open throttle by 0.2 sec, and increased fuel

Table 1 Test conditions

Measurement point : ● Single-plate type (previous) 		Multi-plate type 	
ATF temperature (°C)		100	
LC transmitted power (W)		3100	
Cooling flow rate (L/min)		4	

efficiency in US06 mode and actual fuel efficiency by approximately 3%.

In addition, the selection of an appropriate slip ratio for hill climbing and other driving conditions has helped to ensure torque linearity at the same time that the optimization of the slip ratio has balanced enhanced acceleration performance with enhanced ATF lubrication cooling performance.

5.1.1. Setting of target slip ratios

The following three conditions were established for target values for the slip ratios (Fig. 8) in order to balance fuel efficiency, drive feel, cooling performance, and responsiveness to the intentions of the driver:

- (1) Shift position: In order to respond to the driver's intentions, the slip ratio changes when D range, S range, or manual range are selected. The slip ratio settings for S range and manual range are tighter than for D range, in order to respond to the driver's desire for a sporty drive feel. Here, a tighter setting refers to a setting in which the slip ratio is lower.
- (2) Hill climbing: Hill climbing involves a continuous high degree of throttle opening and low vehicle speed, and a slip ratio, which would prevent the temperature of the LC facings from increasing, was therefore selected for

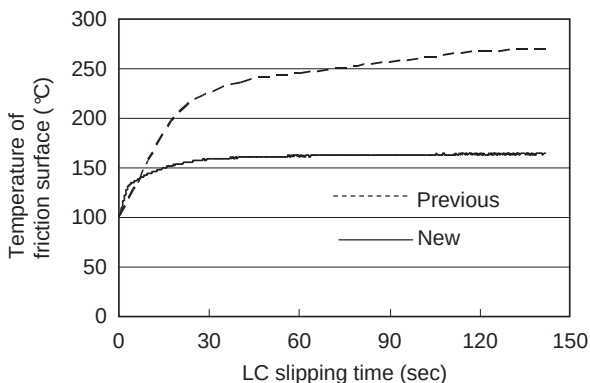


Fig. 7 Test results for facing temperature

this mode. In addition, down-shifting in cooperation with shift control enables the engine speed to be increased and a tighter slip ratio setting to be employed, thus reconciling cooling performance with a satisfactory drive feel.

- (3) Slip control prior to kick-down: Increasing the engine speed before the commencement of down-shifting when the driver intends to accelerate has done away with a sense of sluggishness, while at the same time reducing shift shock.

5.1.2. Control during deceleration

The employment of a configuration in the new multi-plate LC TC that limits the effect of the flow in the TC on the operation of the LC pistons has reduced the time for which the LC is in operation, and enabled the realization of a stable LC response in relation to the speed ratio (Fig. 9).

The reduction of LC response time in the operating range in which the speed ratio is high (Fig. 8) has enabled engagement of the LC during deceleration, thus expanding the area for operation of the engine brake against a conventional AT vehicle. Exploiting this feature, the

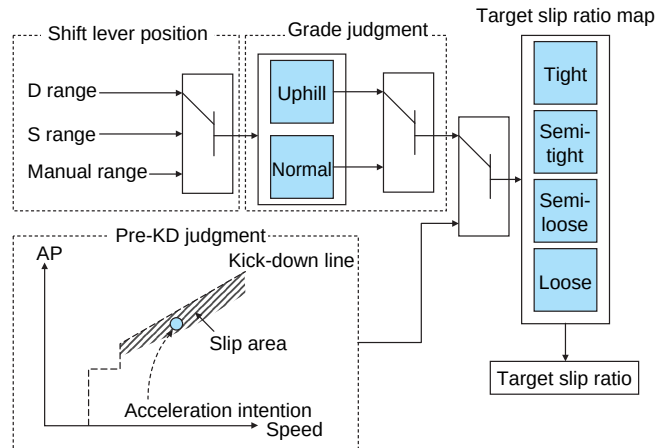


Fig. 8 System diagram of LC target slip ratio

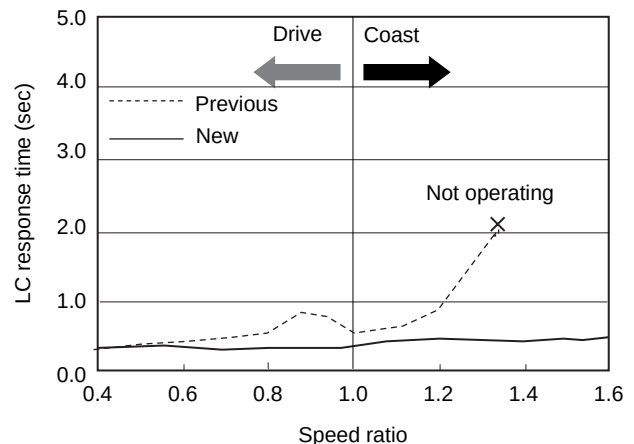


Fig. 9 Test results for LC response time

application of LC ON control in 2nd gear when the system judges that the vehicle is descending a hill enables sufficient braking performance to be realized, enabling the low-hold (L/H) function to be done away with. The conditions set for the application of LC ON control in 2nd gear are the driver's selection of 2nd gear in manual mode and the detection of hill descent. After the system detects that the LC is ON, cooperative control cuts the fuel, enabling the realization of stable engine brake performance (Fig. 10).

Doing away with the L/H function has enabled the achievement of a weight saving of approximately 1 kg and resulted in reduced friction, thereby contributing to increased fuel efficiency.

5.1.3. Control when shifting

Shift shock is an issue when attempting to realize full-range LC control. Conventionally, the transmission of torque fluctuations to the vehicle has been eased by turning the LC OFF during shift, but in the new system, shift shock has been reduced by the application of control to optimize the slip ratio in response to the operating status of the vehicle (Fig. 11).

- (1) Power on, up-shift: The timing of the commencement of the inertia phase (a) and the engagement of the shift clutch (b) is detected, and shift shock is reduced by slightly changing the LC ratio in order to control the LC capacity. In addition, the feeling of directness has been enhanced and fuel consumption has been reduced by maintaining the engagement of the LC after shift.
- (2) Power on, downshift: Reducing the capacity of the LC at the commencement of shift (c) enhances response performance by generating an appropriate level of slip and accelerating the increase in engine speed. In addition, controlling the capacity of the LC by turning the LC ON when clutch engagement (d) is detected in order to help prevent the engine speed from increasing at the conclusion of shift has reconciled the achievement of a smooth shift feel, a direct feel of acceleration, and a

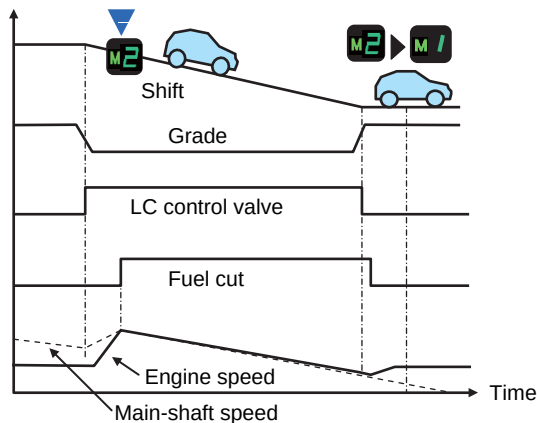
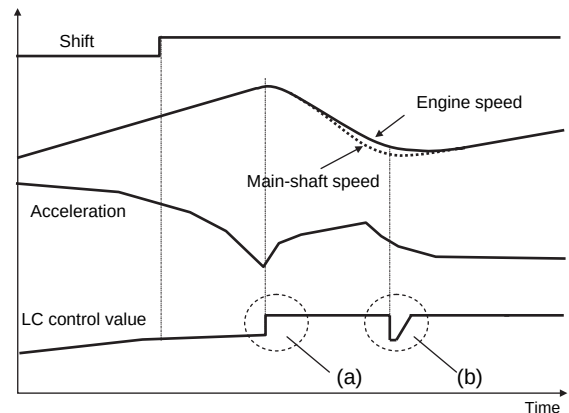


Fig. 10 Engine brake system with use of LC downhill detection

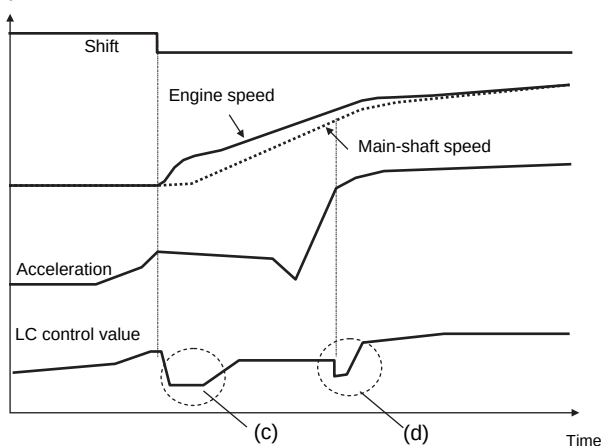
reduction in fuel consumption.

- (3) Power off, downshift: When cooperative control with DBW is engaged (e), the induction of slip in the LC reduces shift shock and noise. Switching the LC ON when the shift clutch engages (f) enables the realization of engine braking like an MT vehicle when AP is OFF, and the achievement of a smooth acceleration feel when AP is ON by means of reducing the increase in engine speed.

(1) Power on up-shift



(2) Power on downshift



(3) Power off downshift

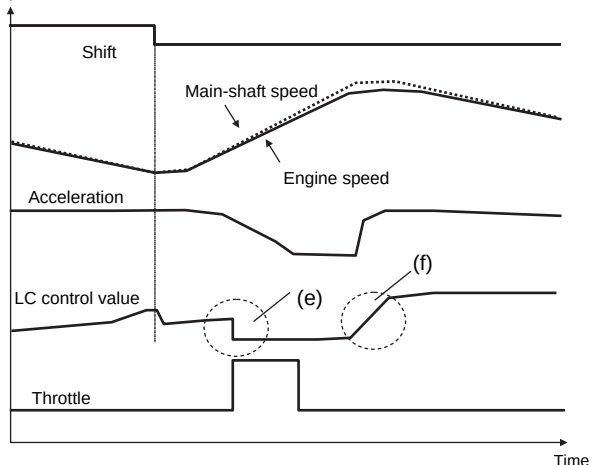


Fig. 11 Test results for LC response time

6. Conclusion

The development of a system of fine control for a lock-up clutch has enhanced drivability and increased fuel efficiency.

- (1) LC responsiveness has been enhanced through the use of a multi-plate LC TC and an LC direct control hydraulic circuit.
- (2) The use of the multi-plate LC TC and LC direct control hydraulic circuit have also enabled the achievement of enhanced LC cooling performance.
- (3) Expanding the range of operation of LC control has enabled the setting of target LC slip ratios in response to vehicle operating conditions.

The use of these technologies has reduced the time for acceleration from 0-100 km/h at wide-open throttle by 0.2 sec, and increased fuel efficiency in US06 mode and actual fuel efficiency by approximately 3%.

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Small, Thin-film Electric Potential Sensor for In-situ Evaluation of Fuel Cell Stack

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ABSTRACT

Measurement of electric potential is an effective means of monitoring changes in the characteristics of the materials used in fuel cells and of obtaining an understanding of the internal environments of the cells. In addition, measurement of the distribution of electric potential is important for the optimal design of fuel cells. However, it is necessary to supply hydrogen to conventional electric potential sensors to obtain a reference electric potential, and structural constraints limit the number of points at which they can be used for internal measurements. A new small, thin-film, self-hydrogen-generating sensor has been developed in order to address these issues. The new sensor can measure potential in any part of a fuel cell stack, and enables more accurate in-situ evaluation of the gas and water environments in the fuel cells.

1. Introduction

Development efforts are proceeding in the area of non-fossil fuel technologies, looking towards the realization of CO₂-free and zero emission motoring, in order to ameliorate environmental issues such as global warming and air pollution. As part of these efforts, Honda has developed a proprietary fuel cell stack that utilizes pure hydrogen as fuel.

Chemical reactions between hydrogen and oxygen in the fuel cells generate electricity, in addition to water as by-product. Figure 1 shows the configuration of a fuel cell. Fuel cells are composed of multiple micron-order layers: Bipolar plates, which serve as the gas flow paths, gas diffusion layers (GDL), which diffuse the gases to the electrodes, catalyst layers (CL), in which catalytic reactions are performed, and a proton exchange membrane (PEM)⁽¹⁾. Hydrogen at the anode electrode and oxygen at the cathode electrode react on the catalyst layers, generating a voltage in the cell. The movement of protons through the PEM and the movement of electrons generate electricity and water.

When utilizing fuel cells, it is necessary not only to attempt to secure the movement of ions and electrons and other electrical exchanges, but also to provide the cells

that supply reaction gases and water uniformly, and to promote the smooth expulsion of the water formed by the chemical reactions. However, it is challenging to confirm the status of gases and water in the microscopic space of the electrodes. Nevertheless, these reactions affect the performance of the fuel cells, so an accurate understanding of each environment and its function, and the formulation of designs on this basis, are vital to the realization of high-performance and high-quality fuel cells.

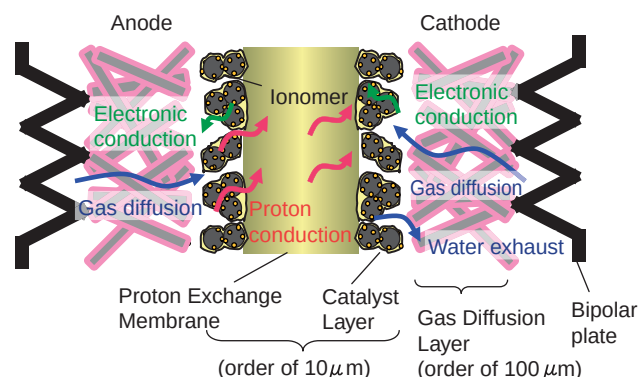


Fig. 1 Schematic of fuel cell

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2. Issues of Measurement of Potential Distribution in Fuel Cell Stacks

2.1. Necessity for Measuring Potential Distribution

Cell voltage is one of the parameters enabling an understanding of cell performance, but the status of the reactions in the cell cannot be accurately grasped from the cell voltage alone. To understand the internal status of fuel cells, therefore, research on a number of associated parameters is conducted, rather than just measuring cell voltage. Measuring potential is one way to estimate the status of the catalyst and gas environments. Also, recently, the number of reports looking at this parameter for assessing the deterioration of fuel cell materials and understanding the reaction environment inside the cells has increased.

Fuel cells are used under a variety of operating conditions, including start-up, shutdown, and air purge. In each of these states, declines in generation performance due to changes in the characteristics of the materials can be observed. Figure 2 shows a transmission electron microscope (TEM) photograph of the electrode catalyst of a fuel cell that had been put through a start-stop cycle, as an example of a change in material characteristics. The photograph shows that the Pt grain diameter is larger on the gas outlet side than the gas inlet side. Enlargement of the Pt grain diameter may lead to a decline in the activity of the catalyst, and is one factor that may cause a decline in cell performance. The distribution of changes like this in the characteristics of the cell materials is an effect of the distribution of potential (which results mainly from differences in environments, such as the gases and water in the electrodes), and is thought to affect the durability of the fuel cells⁽²⁾.

To enable a high operating voltage to be obtained, automotive fuel cell stacks are formed from layered stacks of several hundred fuel cell units (single cells). Because of this, variations occur in parameters including gas distribution, water discharge, and temperature environments in different areas of the stack, and this results in differences in potential.

The fact that the environment inside the fuel cells is

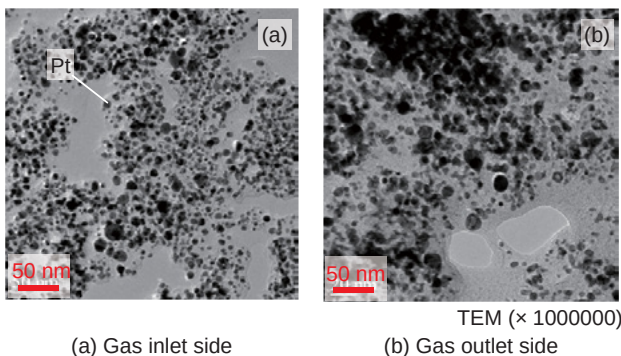


Fig. 2 TEM image of catalyst after start-stop cycle

not uniform makes it challenging to obtain an accurate understanding of the internal environment of the cells by measuring a potential in one area of the stack. Therefore, it is crucial in fuel cell stack design for the distribution of potential at multiple sites to be monitored, to allow the internal environment of the cells to be better understood.

2.2. Issues of Conventional Potential Measurements

Figure 3 shows a single fuel cell, used in conventional measurements of potential. A Pt foil or wire is positioned close to the hydrogen inlet flow path, and this is made the reference electrode for potential. The equilibrium potential of the adsorption and dissociation reaction of hydrogen on the surface of the Pt is considered to be 0 V, the reference potential, and the difference in the potential in the measured area against the reference potential is the environmental potential. Because of this, the reference electrode is termed a reversible hydrogen electrode (RHE) (Fig. 4)^{(3),(4)}. However, several issues exist in relation to these potential measurements using RHE reference: First, the reference potential cannot be maintained without a continuous supply of fresh hydrogen to the reference electrode; second, the distance of the reference electrode from the desired actual points for potential measurements will increase; and third, due to these reasons, errors may increase in measurements. When RHE is used, it is necessary to supply hydrogen to the position of the reference electrode, and the position of the reference electrode and the area for potential measurements should be close. Given these limitations on

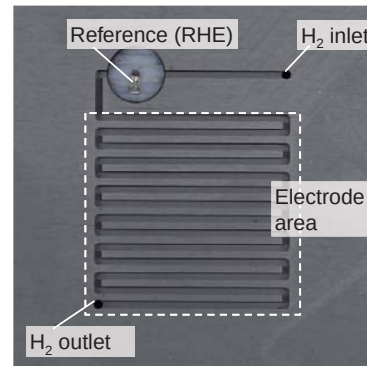


Fig. 3 Example of fuel cell with RHE

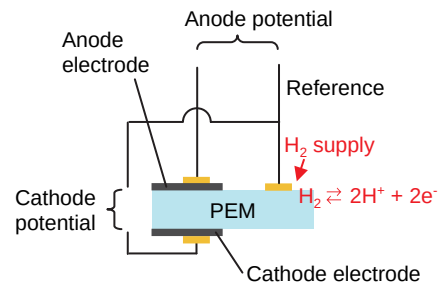


Fig. 4 Schematic of RHE

the positioning of the reference electrode and measurement conditions in conventional potential measurements, the majority of reports on this method focus on comparatively small single cells for testing use.

In addition, when the hydrogen used for power generation is also used for the reference electrode, the reference electrode needs to be placed close to the hydrogen gas inlet (upstream), based on the first RHE measurement issue discussed above (Fig. 3). In order to extend the range of potential measurements further toward gas outlet side of the cell or to another location, it is necessary to use a special gas line to the reference electrode⁽⁵⁾, but this is impractical method in an actual stack.

Introducing reference electrodes to a cell can also cause gas leaks and affects the actual generation reaction, which is counter to the purpose of using the electrodes. As this discussion indicates, numerous issues should be addressed in relation to potential measurements in fuel cell stacks.

3. Aims in Development of Small, Thin-film Potential Sensors

In order to overcome the issues discussed in Chapter 2, and to measure potential at any part of a fuel cell stack, it was necessary to miniaturize the measurement system used in the conventional method, including the reference electrode and the measurement section by integrating them into a sensor. Research was conducted with the following conditions established for the sensor:

- (1) Configuration of reference electrode
 - No requirement for fresh hydrogen supply for reference electrode
 - Provision of reference electrode with a hydrogen-generating section, because measurements should also be conducted when the stack is not generating
- (2) Shape of sensor
 - No interference with generating environment: Status close to that of actual operation (No major reduction in generating area, no impediment to gas flow)
 - The thickness of the sensor should not cause seal performance to decline, for prevention of leaks around the structure used for retrieval of the sensor
- (3) Sensor materials
 - No changes in materials such as deformation or contamination of generating environment (hot water, low-pH environment)
 - Good insulation and withstand voltage

4. Results of Application of Small, Thin-film Potential Sensor

4.1. Development of Potential Sensor

Figure 5 shows the external appearance of the small,

thin-film potential sensor when it is introduced to the membrane electrode assembly (MEA). The sensor incorporates a reference electrode and electrodes for measurement of potential, and is integrated by a thin film that supports these electrodes. This configuration enables the sensor to measure potential at any insert location.

A liquid crystal polymer (LCP) is used as the material for the film, due to its strong resistance to hot-water and acidic environments. Patterning the electrodes and the lead sections on the film realizes a sensor thin enough not to affect seal performance and increase electrical resistance. In addition, a multi-layered structure has been employed in order to help ensure a withstand voltage by maintaining the distance between the sensor electrodes.

The sensors are positioned on both sides of the CL that sandwich the PEM, and are covered by the GDL. In order to help prevent interfering with generation in the fuel cells, the sensor was designed to assure that it would occupy only a minimal area on the CL and maintain a stable reference potential.

A dynamic hydrogen electrode (DHE), which produces hydrogen from water by electrolysis, has been employed as the reference electrode (Fig. 6). This hydrogen-producing reference electrode necessitates the use of a separate power source for electrolysis, but it offers the advantage of enabling measurements to be taken when no hydrogen is supplied, for example when the stack is soaked or just before start-up, and it can thus measure potential in virtually all the environments occurring in fuel cells.

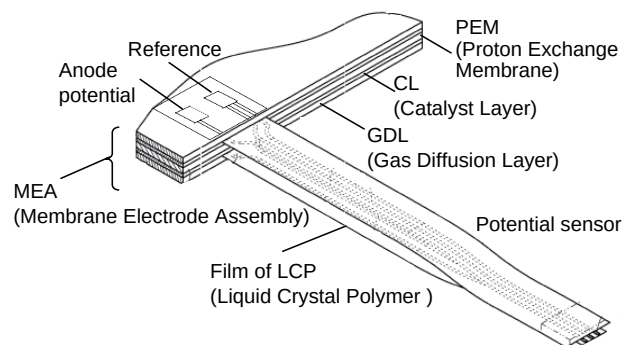


Fig. 5 Configuration of potential sensor

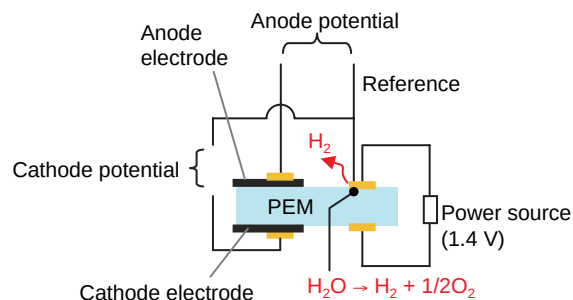


Fig. 6 Schematic of DHE

Table 1 Anode potential under H₂ and air condition

No	Anode potential (V)	
	H ₂ condition	Air condition
1	0.01	1.06
2	0.00	1.03
3	0.00	1.07
4	0.01	1.05

*At 25°C, atmospheric pressure, 100% RH

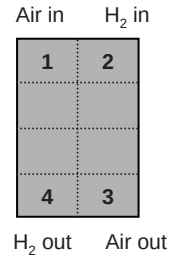
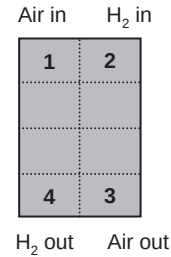


Table 2 Relation between difference of cathode and anode potential and cell potential

No	Potential (V)			
	(a) Anode	(b) Cathode	(c) (b)-(a)	(d) Cell
1	-0.01	0.79	0.80	0.79
2	0.00	0.80	0.80	
3	-0.01	0.79	0.80	
4	-0.01	0.78	0.79	

*At 25°C, atmospheric pressure, 100% RH



4.2. Verification of Functioning of Potential Sensor

The following method was used to confirm whether the new sensor would accurately measure potential. Sensors were positioned at eight points on MEA, from the gas inlet side to the gas outlet side. Cathode potential and anode potential at each of these points and cell voltage were measured (Fig. 7).

The reference electrode is expected to display a stable reference potential under any conditions. RHE-type reference electrodes require a constant supply of the hydrogen used for power generation in order to maintain a stable potential, but DHE-type reference electrodes produce a reference potential using hydrogen produced by water electrolysis. Because of this, the electrode should accurately show 0 V for anode potential in each measurement position, whether or not there is a supply of hydrogen for generation. In addition, the difference

between the anode potential and cathode potential in each measurement position should match the cell voltage.

First, the anode potential was measured in the electrode at the inlet and outlet sides in a hydrogen environment and an air environment in order to verify the reference potential. The measurement results are shown in Table 1.

The measurements under a hydrogen environment were all basically 0 V, while the measurements under an air environment were all basically 1 V (close to the oxidation-reduction potential of oxygen), indicating that the reference electrode was functioning properly.

The difference in potential between the anodes and cathodes and the cell voltage during generation were also measured and verified. The results of these measurements are shown in Table 2. The differences in potential between the anodes and cathodes basically match the cell voltage, indicating that the potential measurements are correct.

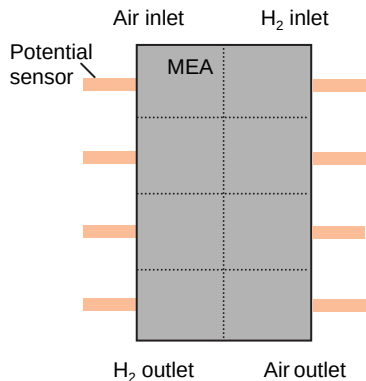


Fig. 7 Layout of potential sensor

4.3. Measurement of Distribution of Potential Using the Potential Sensor

Figure 8 shows the measurement results of the potential distribution in a single actual cell. In order to make the graph easier to read, only representative data for the inlet and outlet sections is shown. Low-stoichiometry and high-moisture operating conditions were employed during the measurements in order to produce a large difference in the potential distribution.

The respective potentials change in response to the generating load. As the load becomes higher, the potential distribution in the electrodes changes significantly, and the

anode potential at the outlet side increases. It is conjectured that this increase in the potential of the anode side occurs as a result of the fact that the level of hydrogen diminishes and the level of water produced increases in proportion to the proximity to the outlet side, and submersion therefore occurs due to flooding. The results show that it was possible to measure the potential distribution within the electrodes.

4.4. Results of Application in a Fuel Cell Stack

Figure 9 shows the measurement results of the potential distribution at start-up. If some time has elapsed since the stack was shut down, the hydrogen in the anode is consumed, and an air environment forms in both electrodes. At start-up, air and hydrogen are mixed at the anode side. The internal potential distribution follows the flow of hydrogen (shown by the arrow). The potential of the opposed electrode, the cathode, becomes high, with its maximum potential exceeding 1.4 V under certain conditions. The high potential is maintained for the longest period close to the outlet, where gas exchange is slow. This result matches the results of the analysis of changes in material characteristics discussed above. A certain control system is needed in order to prevent high potential. The consideration of changes in potential has, as outlined above, rendered the flow of gases in the cell

visible, and might thus provide important suggestions for the design of flow paths that increase the efficiency of gas substitution, and the design of materials possessing high withstand potential.

Figure 10 shows the measurement results of potential distribution during the air purge to the anode electrode immediately following stack shutdown. Similar to the results for measurement during start-up, the potential distribution follows the flow of air within the anode (shown by the arrow), and a high potential is generated on the cathode side. The potential is highest on the inlet side, and this also matches the results of the analysis of changes in material characteristics.

In addition, the potentials at different layers within the stack (Fig. 11) before start-up differ, layer by layer. This indicates that the gas environment and concentration within the stack differs with soak time. This data is important in extending the life of fuel cells by controlling the stack shutdown procedure or applying the design considerations to gas manifolds.

The reference electrodes in general use for potential measurements (the RHE discussed above) require a supply of hydrogen, and therefore cannot be used for measurement of potential when a stack is shut down and hydrogen is not being supplied. However, the new sensor is a self-hydrogen generating type, and thus offers the

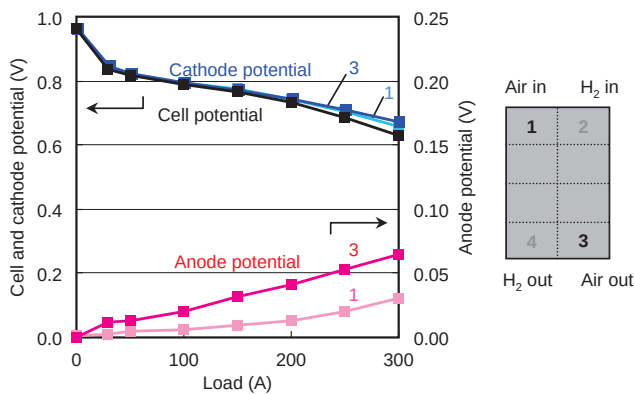


Fig. 8 Potential distribution during generation

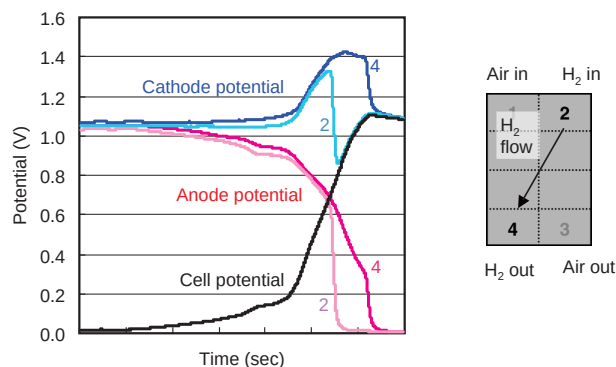


Fig. 9 Potential distribution at start-up

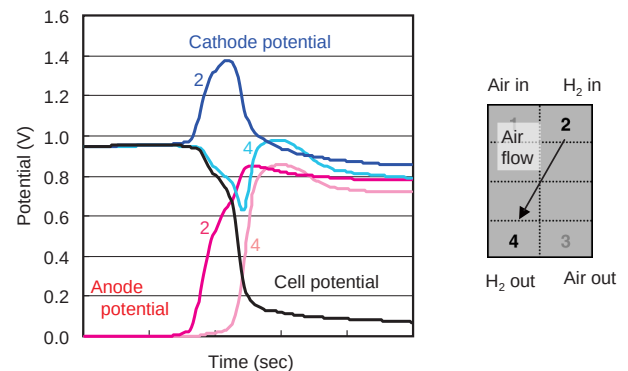


Fig. 10 Potential distribution at purge

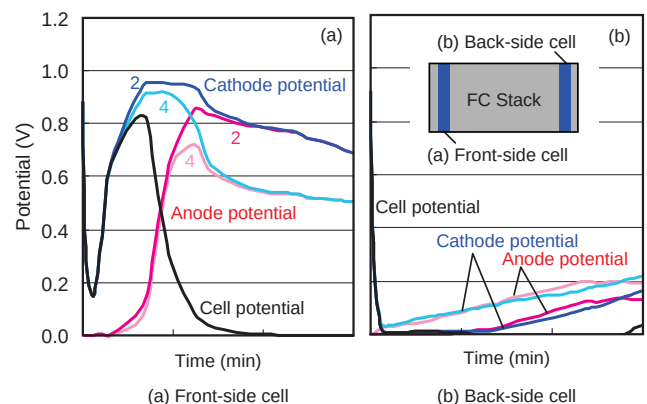


Fig. 11 Potential distribution before start-up

advantage of enabling measurements to be taken in an environment without hydrogen supply (when the stack is shut down).

5. Conclusion

An original potential measurement sensor has been developed, enabling measurements of the potential distribution in the cells and the differences in environmental conditions between the different layers in the actual fuel cell stack, which previously were not possible. The confirmation experiment indicates the effectiveness of this sensor as a strong tool in fuel cell development, such as when attempting to understand changes in material characteristics and the generating environment in fuel cells.

- (1) The development of a small, thin-film potential sensor able to self-generate hydrogen has enabled potential measurements to be taken in virtually all operating environments, and has also enabled measurements to be taken in an actual fuel cell stack, which previously represented a challenge.
- (2) The new sensor has enabled detailed measurements, in an actual fuel cell stack, of the potential distribution in the electrodes and the potential distribution due to the position of the cell in the stack, which previously could not be accurately evaluated, and has clarified the relationship between potential distribution, areas of electrode deterioration, and changes in the characteristics of the cell materials under a variety of operating conditions.
- (3) Tests demonstrated that the sensor displays a high degree of versatility, able to be used for measurements in a single cell and an entire fuel cell stack.

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Development of Lead-free Bearing for High-speed, High-load Engine

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ABSTRACT

A lead-free bearing was developed for use in high-speed and high-load gasoline engines made by Honda.

The development method involved the application of a new resin coating material with optimized surface roughness and solid lubricant arrangement ratio to an existing aluminum alloy bearing surface, which realized a lead-free bearing.

The new resin coating bearings achieved performance (seizure resistance and fatigue resistance) equal to or better than that of the lead alloy plating bearings conventionally used in high-speed and high-load gasoline engines.

1. Introduction

To support recent increases in engine capacity and control of exhaust gases, and to enhance fuel economy, bearing unit loads are tending to rise, oil film thicknesses are becoming thinner, and bearing environments, typified by sliding velocity and unit load, are becoming more severe⁽¹⁾⁻⁽⁴⁾.

The connecting rod bearings of high-speed and high-load gasoline engines for automobiles normally use a three-layer copper alloy, and the overlay generally uses electroplated lead alloy plating material.

However, lead is an environmentally hazardous substance, and the End-of-Life Vehicles (ELV) directive is scheduled to take effect in Europe from July 2011, at which time it will no longer be possible to use lead alloy plating material. However, durability in high-speed and high-load gasoline engines with a sliding velocity of 20 m/s or more is an issue for existing lead-free bearings used in automobile engines. The concerns when changing to lead-free bearings are deformation due to fluctuating load, and a drop in running-in characteristics that indicates restoration with respect to melting and re-solidification during local heating. Lead-free technologies include methods such as lead substitution plating and sputtering⁽⁵⁾. However, liquid waste disposal is an issue for plating, and the high price of sputtering equipment gives rise to cost issues when applied to parts. For these reasons, a lead-free bearing capable of withstanding high-speed and high-load gasoline engine specifications was developed by

using a resin coating material with optimized surface roughness and solid lubricant arrangement ratio aimed at achieving seizure resistance equal to or better than that of lead alloy plating material. This paper reports the technologies involved.

2. Development Concept of Bearing for High-speed and High-load Gasoline Engine

Figure 1 shows the operating range of existing lead-free bearings. Honda mass-produces high-speed and high-load gasoline engines with a sliding velocity of 20 m/s

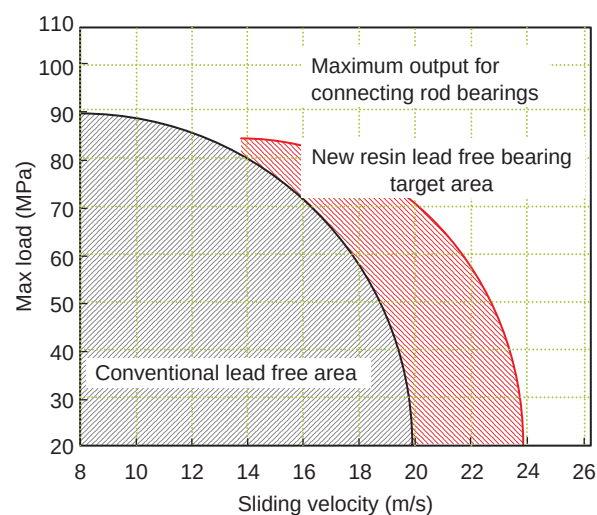
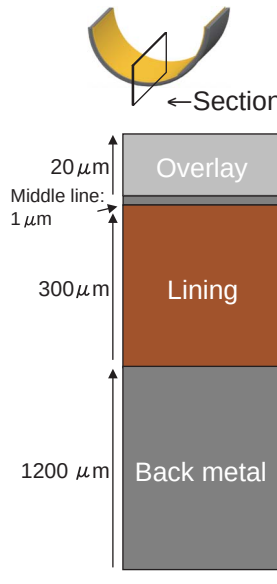


Fig. 1 Correlation of sliding velocity and max load

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Table 1 Bearing specification comparison



		Lead alloy plating	New coating material
Overlay	Material	Pb-4.5Sn-8.5In	MoS ₂ : 72 mass% ± 2 mass% + PAI
	Thickness	20 μm	5 ± 2 μm
	Surface form	–	(0,0,0) c axis arrangement
Middle line	Material	Ni plating (1 μm)	–
	Thickness	–	–
Lining	Material	Cu-3.5Sn-15Pb	Al-7Sn-3.7Si-1.5Cu
	Thickness	–	–
Back metal	Material	S20C	S20C
	Thickness	–	–

or more, and it is necessary for bearings used in this range to have the following characteristics:

- (1) Load resistance and seizure resistance
- (2) Running-in characteristics with respect to impact loads
- (3) Solid lubricity in case of oil film out

Table 1 shows the specifications of the newly developed resin coating bearing with respect to these necessary characteristics. The conventional lead alloy plating bearing specifications are also shown for comparison.

The new resin coating material combined a certain amount or more of polyamide-imide (PAI) to enhance the running-in characteristics of the aluminum alloy bearing surface, and molybdenum disulfide (MoS₂) to enhance solid lubricity. The coating thickness was set at 5 ± 2 μm. Load resistance focused on the surface roughness and MoS₂ crystal direction, and resin coating specifications that increased the load resistance were set as a development concept.

3. Technical Contents

3.1. Enhancement of Load Resistance and Seizure Resistance by Optimization of Surface Roughness

Bearing static load tests were performed using the bearing rig tester shown in Fig. 2 to verify the seizure resistance of the new resin coating material. This bearing rig tester can evaluate the seizure resistance and fatigue resistance of isolated bearings by rotating a test shaft to apply a fluctuating load. The effect of the resin coating material surface condition on seizure resistance was verified under the conditions shown in Table 2.

Attempting to prevent oil film out on the bearing surface is considered important for increasing load resistance, so the coating surface roughness was

Table 2 Seizure test conditions

Sliding velocity	20 m/s
Bearing dimension	φ48 mm
Oil temperature	80 °C
Oil pressure	0.1 MPa
Clearance	65 μm
Loaded	3 kN step-up

investigated. Figure 3 shows the results. Seizure resistance becomes lower as the surface roughness ($R_{z,IS}^{(6)}$) becomes rougher. This is thought to be because when momentary oil film out occurs due to impact load or other factors, and solid contact occurs between the bearing and the crankshaft, the convex portions of the coating, shown in the SEM surface observation results on the right side of Fig. 4 (the black dotted lines indicate the peaks), become hot due to local contact, leading to seizure. Figure 5 shows the convex form of the perpendicular section of the dotted line portions in Fig. 4. On the other hand, the seizure resistance target was met when the surface roughness is smooth, which confirmed the effects of smoothing.

Based on the results of the above bearing seizure rig

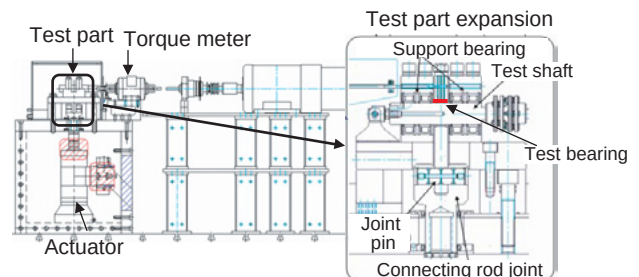


Fig. 2 Bearing rig tester

tests, the surface roughness after coating was set at Rz_{JIS} : 2.5 μm or less, which satisfies the target seizure unit load.

3.2. Enhancement of Load Resistance and Seizure Resistance by Optimization of Arrangement Ratio

When the a and b axes indicated by the Miller index of crystal direction are aligned with the bearing circumference direction as shown in Fig. 6, MoS_2 is known to possess cleavage characteristics in these directions. For this reason, the c axis direction, which is in the bearing center circle direction perpendicular to the a and b axes, is expected to have better load resistance. Therefore, the percentage of MoS_2 particles that are arranged in an orderly manner (arrangement ratio) was optimized with the aim of enhancing load resistance by aligning the c axis of the MoS_2 particles. Figure 7 shows the bearing static load rig test results, which indicate a positive correlation between the arrangement ratio and the seizing unit load. This is because MoS_2 has a layered

crystal structure with a hexagonal system, so the coupling between the sulfur in adjacent layers is weak, and when shearing force is applied, cleavage tends to easily occur in the a and b axis directions; that is to say, the bearing circumference direction. On the other hand, the coupling between the molybdenum and sulfur is strong, which gives the c axis (0,0, ℓ) surface better load resistance. It is thought, therefore, that the cleavage characteristics of MoS_2 particles arranged in an orderly manner will provide good solid lubricity. The coating conditions were set to level the squamous MoS_2 particles after coating application in order to arrange the MoS_2 particles, and the arrangement ratio was set at 80% or more.

Static load tests for isolated bearings were performed using the bearing rig tester at sliding velocities from 17.5 up to 25.0 m/s, and the seizure resistance was verified. Figure 8 shows the results compared with lead alloy

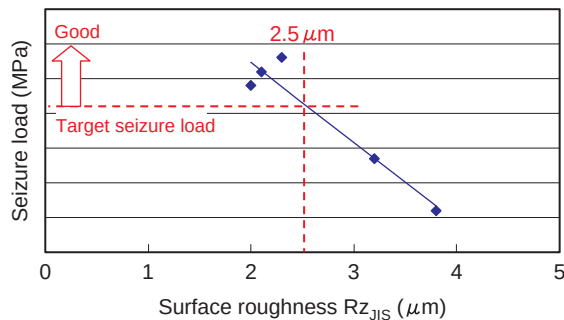


Fig. 3 Seizure resistance and surface roughness

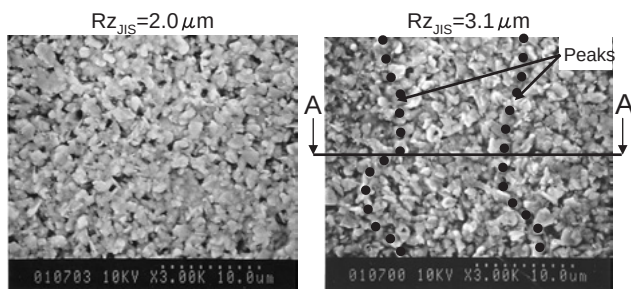


Fig. 4 SEM images of MoS_2 coating surface

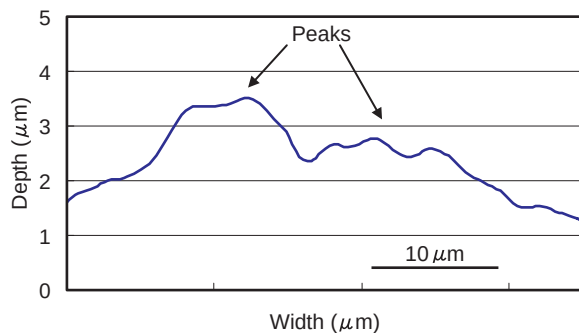


Fig. 5 A-A cross section

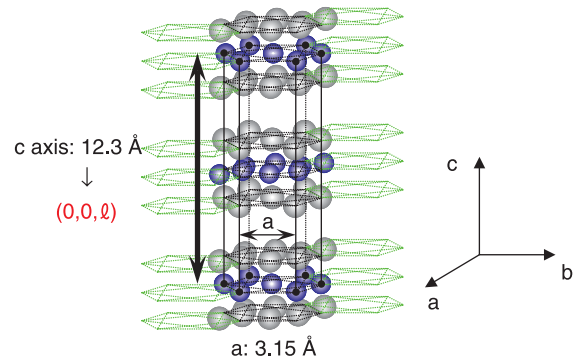


Fig. 6 MoS_2 crystal structure

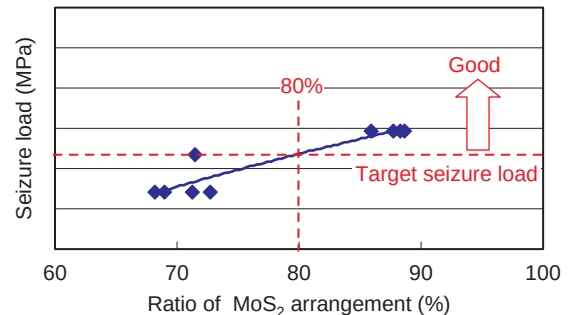


Fig. 7 Seizure resistance and MoS_2 arrangement ratio

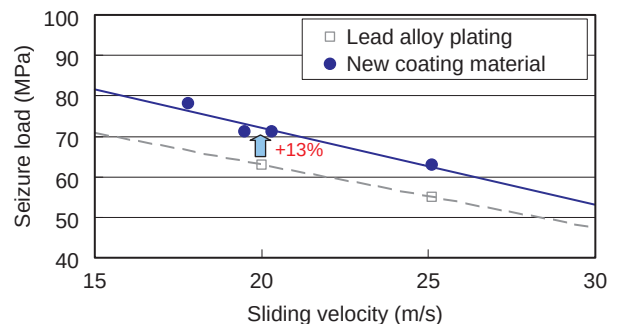


Fig. 8 Seizure resistance and sliding velocity

Table 3 Fatigue test conditions

Sliding velocity	23.3 m/s
Bearing dimension	$\phi 48$ mm
Oil temperature	100 °C
Oil flow-rate	1 L/min
Clearance	75 μ m
Loaded	100 MPa $\times$ 300 Hz sine wave

plating material. The new resin coating material obtained seizure resistance equal to or better than that of the lead alloy plating material over the entire range from low to high sliding velocities. In particular, setting a MoS₂ particle arrangement ratio of 80% or more is thought to have effectively increased the load resistance.

In addition, the bearing fatigue characteristics were tested using the bearing rig tester, under the conditions shown in Table 3. The results were compared up to a repeat count of 1×10^7 times, and showed that fatigue resistance equal to or greater than that of lead alloy plating bearings was obtained. In particular, smoothing of the surface roughness is thought to have suppressed the striking that involves solid contact between the crankshaft and the bearing, which meant that oil film out does not easily occur, so there was less heat generation due to local solid contact.

3.3. Running-in Characteristics with respect to Impact Loads

To secure running-in without seizing when an impact load is applied to the bearing overlay at a high sliding

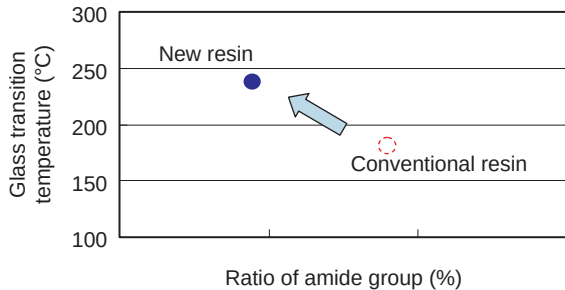


Fig. 9 Correlation of amide ratio and glass transition

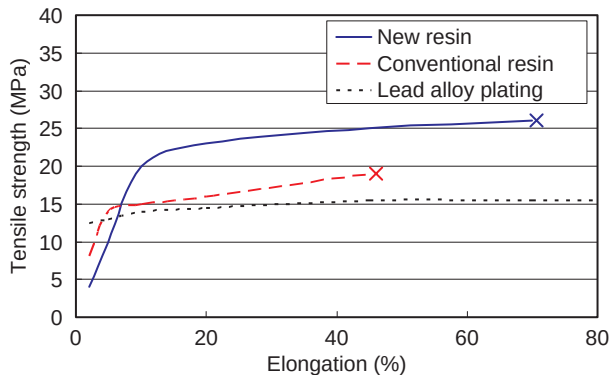


Fig. 10 Correlation of elongation and strength at 200 °C

velocity, the overlay should possess sufficient heat resistance and modification ability, the latter of which is an index for elongation and strength, to a level close to those of lead.

Figure 9 shows the relationship between the ratio of amide group and the glass transition temperature in the resin materials. Heat resistance is thought to be an issue for resin with a high ratio of amide group, as reported at JSAE⁽⁷⁾, resin (PAI) with a low ratio of amide group was selected that has a heat resistance temperature near that of lead (lead melting point: 327°C). Next, Fig. 10 shows the relationship between the resin elongation and strength at 200°C. While the highly heat resistant resin mentioned above has elongation that is half or less than that of lead, the modified PAI is known to have elongation equivalent to that of lead.

3.4. Solid Lubricity in case of Oil Film Out

With respect to solid lubricity, the compatibility of three different solid lubricants was confirmed in order to guarantee tribological properties in case of oil film out. Stick slip tests were performed as shown in Fig. 11. As shown in Fig. 12, the wear of the opposing material after the test was low in the case of MoS₂, which has cleavage characteristics. In addition, as reported at JSAE⁽⁷⁾, the combination amount was set based on measurements of the wear experienced by the MoS₂-coated test specimen and the steel ball. The test results in Fig. 13 show that steel ball wear was low at a MoS₂ combination amount

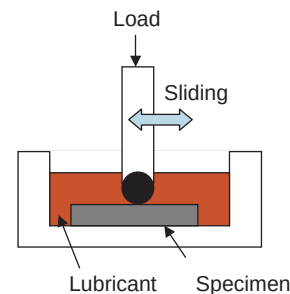


Fig. 11 Stick-slip tester

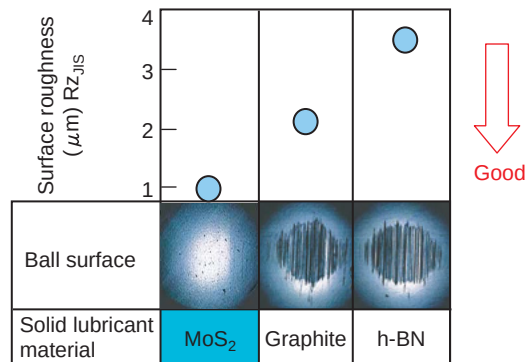
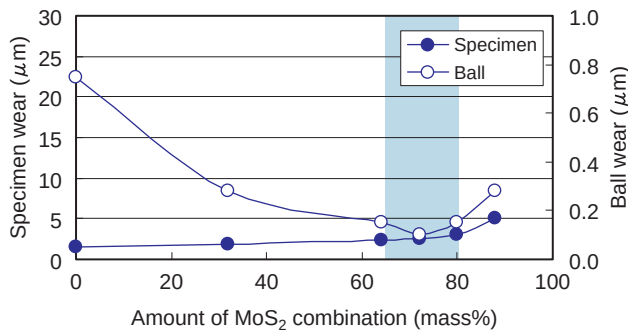


Fig. 12 Correlation of solid lubricant material and surface roughness

Fig. 13 Correlation of MoS₂ combination and wear

of 72 mass%. Therefore, the combination ratio of MoS₂, the solid lubricant to be combined into the resin coating, was set at 72 mass%.

4. Confirmation of Bearing Durability

4.1. Verification of Seizure Resistance after Coating Abrasion

Seizure resistance was confirmed under the assumption that the new coating material on the overlay had abraded. The relationship with the lining exposure rate after coating abrasion was confirmed under the conditions given in Table 2. Figure 14 shows that the new resin coating bearings have seizure resistance equal to or better than that of lead alloy plating bearings. This is thought to be affected by the presence of an adhesive layer between the overlay and the lining. Lead alloy plating bearings have a 1 μm nickel plating layer to help prevent counter diffusion between the tin in the overlay and that in the

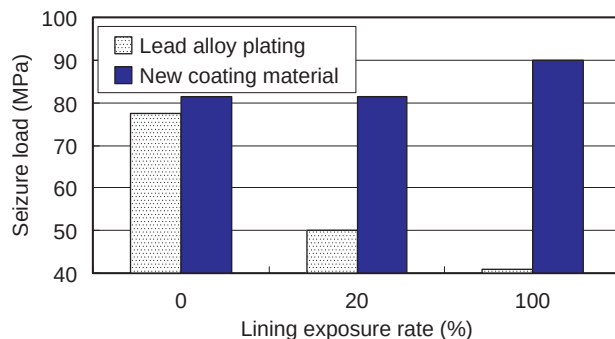


Fig. 14 Seizure resistance of lining exposure rate

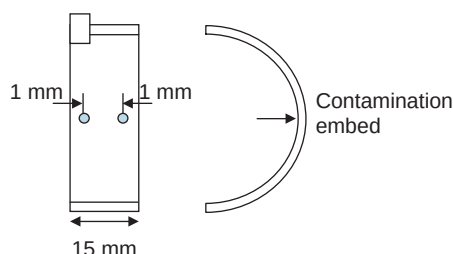


Fig. 15 Contamination trap position

Table 4 Contamination toughness test conditions

Sliding velocity	20 m/s
Bearing dimension	φ48 mm
Oil temperature	140 °C
Oil pressure	1.0 MPa
Clearance	60 μm
Loaded	3 kN step-up

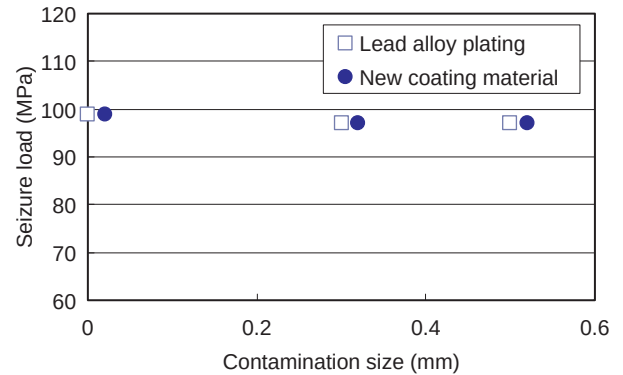


Fig. 16 Seizure resistance and contamination size

lining, and to increase the plating adhesion. This nickel plating layer has low tribological properties, and the seizure resistance decreases when it is exposed. The new resin coating material does not have an intermediate layer between the overlay and the lining, enabling use of an aluminum alloy lining that maintains the tribological properties even when the coating abrades.

4.2. Verification of Seizure Resistance with respect to Contaminant

Seizure resistance was confirmed with respect to contaminant inside the engine. Table 4 shows the conditions tested using the bearing rig tester. Contaminant is thought to affect bearing performance when it becomes embedded in the sliding surface, so seizing tests were performed by embedding contaminant directly onto the sliding surface as shown in Fig. 15.

Actual chips occurring during crankshaft machining were gathered as contaminant, and were sorted by length in the longitudinal direction. The results showed that seizure resistance was the same as that of lead alloy plating material up to a contaminant size of 0.5 mm (Fig. 16). This is because the elongation properties, surface roughness and MoS₂ particle arrangement ratio of the binder resin were enhanced, so the running-in characteristics, including solid lubricity, were equivalent to those of lead alloy plating bearings.

5. Confirmation of Compatibility in an Actual Engine

A 3.7-liter V6 engine was used to verify the compatibility of the newly developed resin coating

Table 5 Engine test conditions

Engine	3.7L V6 gasoline	
No.	(1)	(2)
Rotations	6200 rpm*WOT	6800 rpm*WOT

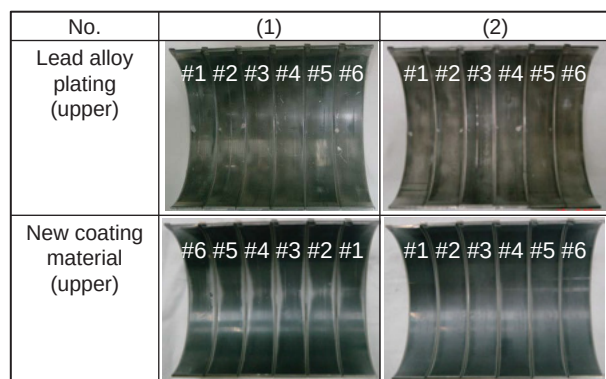


Fig. 17 Appearance of bearings after engine test

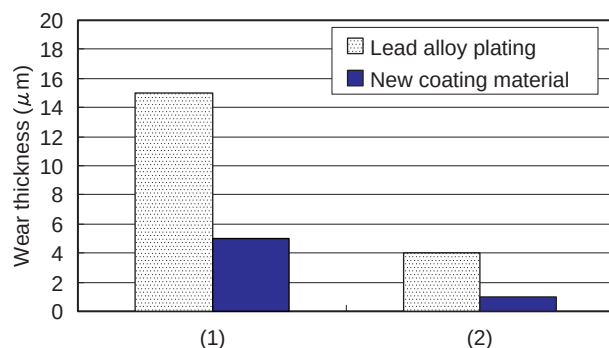


Fig. 18 Wear of durability test

bearings in an actual engine. Durability tests were performed, and the connecting rod bearings are used for verification. Table 5 shows the test conditions at wide open throttle (WOT).

Figure 17 shows the appearance of the bearings after the test. The sliding surfaces of the bearings were in good condition, and there was no seizing or fatigue cracking in any of the tests. In addition, Fig. 18 shows the bearing wear (damage) amount. The results showed wear of 4 to 5 μm under condition (1), and 1 to 2 μm under condition (2), indicating a wear resistance better than that of lead alloy plating bearings.

6. Conclusion

- (1) The surface roughness and MoS_2 particle arrangement ratio of a new resin coating material were optimized to increase the load resistance and seizure resistance. The surface roughness was set at $R_{z_{\text{JIS}}} = 2.5 \mu\text{m}$ or less, and the MoS_2 arrangement ratio was set at 80% or more.
- (2) The seizure resistance of the new resin coating bearings

with respect to contaminant was verified, and found to be the same as that of lead alloy plating material up to a contaminant size of 0.5 mm (maximum length).

- (3) Durability tests were performed for the new resin coating bearings in an actual engine. Seizing and fatigue cracking did not occur, and results equal to or better than those of conventional lead alloy plating bearings were obtained.

New resin coating lead-free bearings were developed that have performance equal to or better than that of lead alloy plating bearings for high-speed and high-load gasoline engines. These new bearings were applied to the connecting rods of the 2008 model year ACURA RL.

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Takashi SHIRAIISHI

Numerical Analysis of Turbocharger Response Delay Mechanism

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Shinrak PARK*

Nobuyuki ODA*

ABSTRACT

Social demands for increased automotive fuel efficiency are today increasing. Turbocharged downsized engines have attracted attention as one technological means of responding to these demands. Boosting technology using a turbocharger is effective in increasing fuel efficiency, but these turbochargers also display a response delay characteristic known as turbo lag, which may cause engine performance to decline. This issue impedes the broader application of this technology. The research discussed in this paper focused on turbo lag, and adopted a numerical approach to analyzing the detailed mechanism of this phenomenon. The study concluded that turbo lag is a delay in the boost pressure response that originates from a combination of factors. The primary factor in turbo lag is a delay that is due to a physical property of the turbocharger system; the secondary factor is a decreased turbine effective energy caused by a shift of operating point, resulting from the primary factors.

1. Introduction

The demands of society for the achievement of increased automotive fuel efficiency are increasing today, against the background of the need to reduce CO₂ emissions in order to address the issue of global warming and the spiraling cost of oil. In addition, the trend towards the establishment on the national level of fuel efficiency-related laws and regulations aiming towards the reduction of CO₂ emissions – including the 2015 Japanese fuel economy standards, European regulations on CO₂ emissions, and the U.S. new CAFE regulations – is expanding rapidly⁽¹⁾⁻⁽³⁾. Given this, the realization of increased fuel efficiency is, together with the achievement of cleaner exhaust emissions, a social responsibility for automakers.

Among available methods of increasing fuel efficiency, engine hybridization and turbocharging and downsizing are presently attracting a great deal of attention. While the rate of improvement of fuel efficiency achieved using turbocharging and downsizing is lower than that achieved by hybridization, the technology is lightweight, compact, and comparatively low-cost. For these reasons, automakers are focusing considerable attention on turbocharging and downsizing as a technology to increase the fuel efficiency of their vehicle line-ups, and its application is projected

to increase in the mid- to long-term⁽⁴⁾.

Among turbocharged downsized engines, turbocharging is a technology that is applied to increase fuel efficiency and displays a high level of system efficiency because it enables exhaust energy to be regenerated and reused. However, boosting using a turbocharger is also known to induce a decline in engine performance across a wide driving range due to a response delay characteristic known as turbo lag. In particular, turbochargers display insufficient responsiveness at low engine speeds, when exhaust energy is relatively low. The delay in response in this driving range, which is used frequently in actual driving, is a factor in performance decline in terms of drivability, fuel efficiency, and emissions. The enhancement of turbocharger response will be a key factor in enabling turbocharged downsized engines to be used in future as substitutes for natural aspiration engines (“NA engines” below), and to play a central role in the achievement of a new era of fuel efficiency.

Numerous attempts have been made to date to enhance turbocharger response, and papers have been published discussing a variety of methods of doing so⁽⁵⁾⁻⁽⁸⁾. However, few of these have focused centrally on the mechanism of turbo lag. This is due to the fact that turbochargers contain a large number of non-linear

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elements, and operate recurrently, making it challenging to analyze the phenomenon in an actual turbocharger unit. The research discussed in this paper constructed a physical model of a turbocharger and adopted a numerical approach to the analysis of the detailed behavior of the turbocharger under transient operating conditions and the mechanism of turbo lag.

2. Effect of Turbocharger Response Delay on Turbocharged Downsized Engines

2.1. Fuel Efficiency Increases in Turbocharged Downsized Engines and Current Trends

In order to illustrate the effect of turbocharging and downsizing on fuel efficiency, representative turbocharged downsized engines and NA engines, currently available on the market, were selected and their displacement against rated power (Fig. 1) and fuel efficiency in NEDC mode⁽⁹⁾ (Fig. 2) were compared. With regard to engine displacement, turbocharged engines achieve an identical rated power to NA engines at a lower displacement. For example, while a displacement of approximately 2.8 L is necessary for a NA engine to achieve a rated power of 150 kW, the turbocharged engine is able to achieve the same rated power at a displacement of approximately 2.0

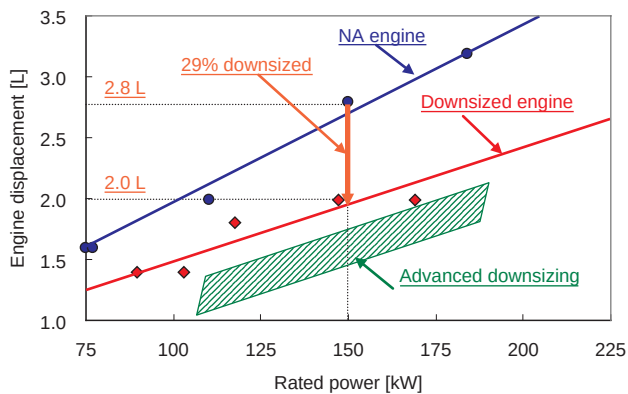


Fig. 1 Comparison of engine displacement

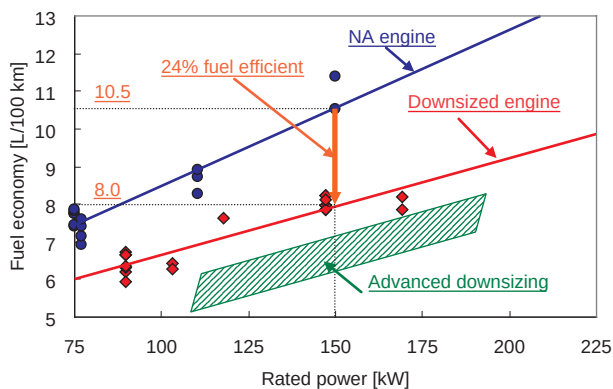


Fig. 2 Comparison of fuel consumption rate of turbocharged engine and NA engine

L, approximately 29% lower. Comparing fuel efficiency at the same rated power of 150 kW, the vehicle using a turbocharged downsized engine displays an approximately 24% higher level of fuel efficiency than the vehicle using a NA engine. This result originates in the fact that turbocharging increases power density, enabling a lower-displacement engine than a NA engine to be used, thus reducing mechanical loss and pumping loss. Given this, it can be conjectured that the effect of turbocharging and downsizing in increasing fuel efficiency is dependent on the rate of reduction of displacement (the rate of downsizing). Figure 1 shows that the rate of downsizing in turbocharged engines currently available on the market is basically 25-30%. However, downsizing to a rate of around 50% has recently been proposed as a method of achieving further gains in fuel efficiency, and there is a trend towards the development of engines in which a higher rate of downsizing is enabled by the achievement of increased boost pressure and increased power density⁽¹⁰⁾.

2.2. Limitation on Rate of Downsizing due to Turbocharger Responsiveness

Increasing the rate of downsizing by achieving increased boost pressure and power density is the key to the achievement of further increases in fuel efficiency, and this is becoming a trend in engine development. The power density of turbocharged engines can be increased relatively easily by altering the set boost pressure. The achievement of increased power density therefore does not present any major issues. However, when the transient response of a turbocharged engine is considered, issues of drivability limit the achievement of an increased rate of downsizing by increasing boost pressure. Figure 3 shows a contour diagram of boost pressure response time in an in-line 4-cylinder engine fitted with a single variable-vane turbocharger. This contour diagram shows the time taken for the boost pressure to reach the set level when the load is changed in one step from no load to full load for each

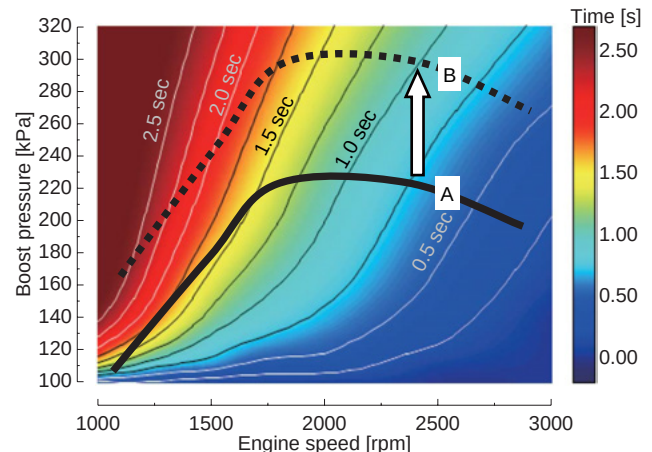


Fig. 3 Boost response time

engine speed. These results show that the lower the engine speed, the slower the boost pressure response. For example, at an engine speed of 1500 rpm, the time taken to reach the target boost pressure (curve A), going from no load to full load, is approximately 1.5 sec. When the target boost pressure is increased to the pressure shown by curve B, assuming that the rate of downsizing was increased by around 30%, it will take approximately 2 sec to reach the target boost pressure at the same engine speed of 1500 rpm, representing a decline of approximately 33% in boost pressure response. The enhancement of turbocharger responsiveness is therefore a major issue in terms of achieving a higher rate of downsizing by means of increasing boost pressure.

3. Numerical Modeling of Turbochargers

3.1. Necessity of Numerical Modeling

The system formed by an engine using a turbocharger is generally formed recurrently from the engine, turbine, and compressor, via mechanical or fluid energy, and when the engine is in operation, the system operates while maintaining a balance of energy between its various elements. Analyses of actual turbocharger units are limited to the measurement of only particular physical quantities, and while these analyses are able to evaluate representative physical quantities such as response delay time, it is challenging for them to obtain a grasp of the behavior of the system in terms of the energy exchange, mutual interaction, and other relationships between the various recurrent influencing factors. The use of numerical models is an effective method of analyzing these relationships and elucidating the detailed mechanism of turbocharger response delay.

3.2. Overview of Numerical Model of Turbocharger

Figure 4 shows a schematic diagram of the constituents of the system formed by an engine-

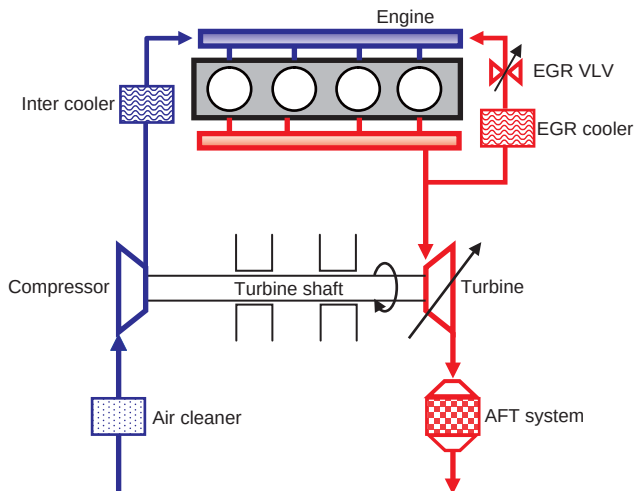


Fig. 4 Schematic diagram of turbocharger system

turbocharger combination. Broadly speaking, the system is made up of three main elements, a compressor, an engine, and a turbine, and the parts that connect these elements, pipes, an air cleaner, an inter-cooler, an EGR valve, and an after-treatment system. In order to create a numerical model of the system, a physical model of turbocharger expressed by Eqs. (1)-(3) was created, and the intake and exhaust elements were modeled using the flow coefficient, as shown by Eq. (4). The model was created with consideration of satisfying the principles of conservation of energy and conservation of mass between the elements of the system.

Below, the main issue of this section, the numerical treatment of the turbocharger, will be discussed. The governing equation of the system is expressed as Eq. (1).

$$\frac{dN_{TC}}{dt} = \frac{60}{2\pi I_{TC} N_{TC}} (P_T - P_C - P_f) \quad (1)$$

The effective turbine work, P_t , and the compressor compression work, P_c , are determined from Eqs. (2) and (3) respectively, using the flow rate, pressure ratio characteristic, and efficiency characteristic as determined from the inlet and outlet boundary conditions and the results of steady-state unit tests.

$$P_T = m_T \eta_T c_p T_3 \left(1 - \pi_t^{\frac{1-\gamma}{\gamma}} \right) \quad (2)$$

$$P_C = \frac{1}{\eta_c} m_c c_p T_1 \left(\pi_c^{\frac{\gamma-1}{\gamma}} - 1 \right) \quad (3)$$

$$Q = C_d A \sqrt{\frac{2\Delta p}{\rho}} \quad (4)$$

Due to the limitations of measurement devices, the turbine and compressor flow characteristics obtained from steady-state unit tests generally do not cover the range of conditions needed for transient analysis. In this project, a unique linearized algorithm was therefore used in order to parameterize these characteristics.

MATLAB Simulink, produced by the Math Works, Inc., was used as the platform for the numerical model (Fig. 5), and the composition of the turbocharged engine system shown in Fig. 4 was reflected in it.

3.3. Verification of Numerical Model

In order to verify the numerical model, a numerical model of an in-line 4-cylinder 2.2 L engine with a single variable-vane turbocharger was formulated, and the behavior of the turbocharger as predicted by the model was compared with the behavior of a turbocharger in an actual vehicle.

Figures 6 and 7 respectively show comparisons of measured and predicted boost pressure and turbocharger shaft speed during operation at FTP75⁽¹¹⁾. In both cases, the values predicted by the numerical model reproduce the actually measured values with a comparatively high degree of accuracy. In addition, Fig. 6 shows that a delay in reaching target boost pressure occurs in the actual vehicle, and the boost pressure as estimated by the numerical model reproduces this phenomenon well. The model was therefore employed in this project to analyze the mechanism of delay in boost pressure response.

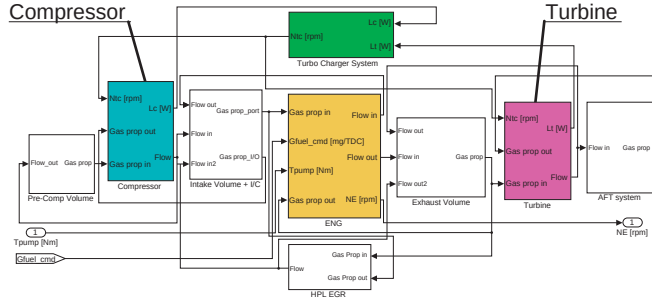


Fig. 5 Schematic diagram of Simulink model

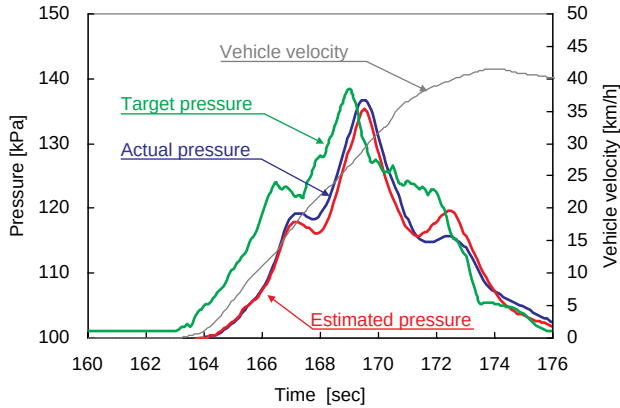


Fig. 6 Comparison of actual and estimated intake manifold pressure at FTP75

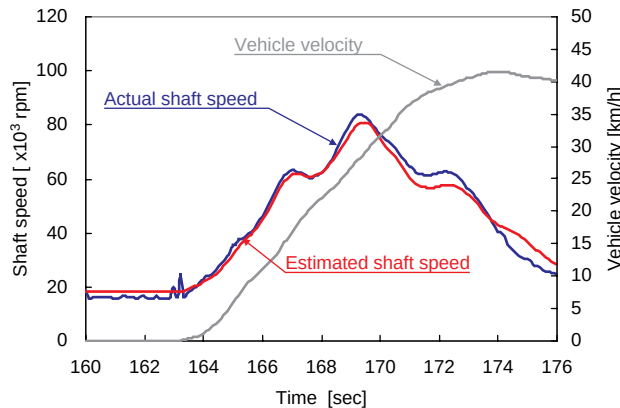


Fig. 7 Comparison of actual and estimated turbine shaft speed at FTP75

4. Analysis of Mechanism of Turbo Lag Using Numerical Model

This chapter will discuss the analysis of the mechanism of the delay in boost pressure response during operation under transient conditions (turbo lag) using the numerical turbocharger model. The analysis employed the numerical model of a diesel engine with a single variable-vane turbocharger that had been proven accurate, and analyzed the low engine speed range that has a particularly significant effect on the transient response of turbochargers.

4.1. Results of Estimation of Delay in Turbocharger Response

Figures 8 and 9 respectively show the change over time in boost pressure and turbocharger shaft speed when the degree of accelerator opening is increased in one step from 10% to 80% at an engine speed of 1750 rpm. As Fig. 8 shows, the target boost pressure increases in one step with the increase in the degree of accelerator opening, but the actual boost pressure does not trace this change, reaching the target boost pressure with a 1.37 sec delay. The turbocharger shaft speed also transitions towards its steady-state value with a 1.37 sec delay.

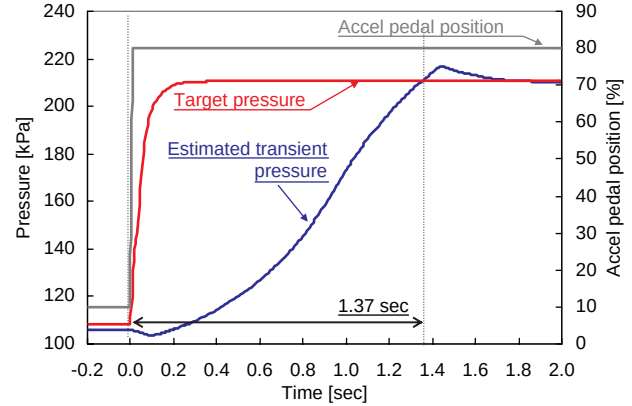


Fig. 8 Estimated intake manifold pressure response under step load condition at 1750 rpm

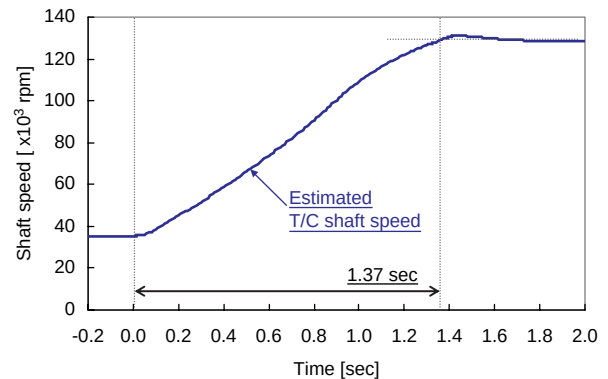


Fig. 9 Estimated shaft speed response under step load condition at 1750 rpm

4.2. Energy Balance during Transient Operation

Because turbochargers are a type of energy converter, converting exhaust energy into intake compression energy, the study of the energy balance in each part of the system is useful in the analysis of turbo lag behavior. Figure 10 shows the work and the different types of loss in each part of the turbocharger system during transient operation under the conditions discussed in the previous section, as estimated using the numerical model.

Figure 10 shows that, due to a variety of factors, the level of effective turbocharger work is reduced under transient operating conditions in comparison to steady-state operation. Considering the results at the point 0.6 sec following the change in the accelerator pedal position, virtually the median point in the time for transition from transient to steady-state operation, there is a decline of approximately 91% in effective turbocharger work under transient operation in comparison to steady-state operation. The two types of transient loss – shaft inertia loss and intake volume loss – which are generally considered as factors in turbocharger response delay, respectively account for declines of 14.3% and 12.3% in effective work. Given this, these two types of loss alone could not fully explain the decline in effective work in the turbocharger. The most significant contribution to the decline in effective work under transient operating conditions was the decline in effective turbine work, which generated a decline of approximately 64.4% in effective work. This made it clear that the behavior of the turbine under transient operating conditions has a significant effect on the transient boost pressure response.

4.3. Mechanism of Decline in Effective Turbine Work

Six factors in the decline in effective turbine work were determined through the use of Eq. (2), the effective turbine work equation derived from thermodynamic relationships. Two of these factors, specific heat under constant pressure and the specific heat ratio, did not change significantly in the projected temperature range, narrowing the factors to be considered in relation to the

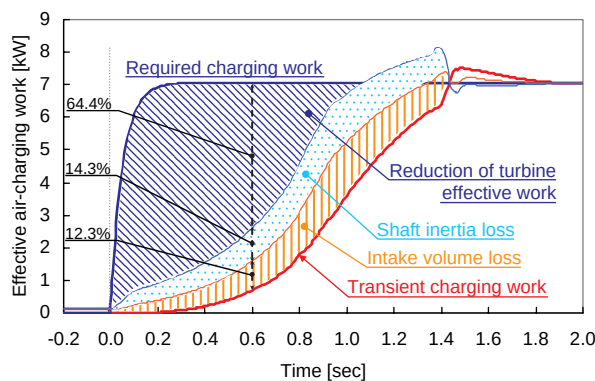


Fig. 10 Analysis of energy distribution in turbocharger system

Table 1 Variation of turbine work-related parameters under transient condition

		Steady state	Transient	Variation [%]
Mass flow rate	[kg/s]	0.0992	0.059	-41
Turbine efficiency	[%]	70.0	42.1	-39.9
Expansion ratio	[-]	1.98	2.04	+3
Inlet gas temperature	[K]	899	981	+9

decline in effective turbine work during transient operation to four: the mass flow rate of turbine working gas, turbine efficiency, the turbine expansion ratio, and the inlet gas temperature. The mechanism of the decline in effective turbine work was sought by comparing the ways in which these four physical quantities changed at 0.6 sec following the change in the position of the accelerator pedal.

As Table 1 shows, the mass flow rate of turbine working gas and turbine efficiency display a significant decline under transient operating conditions as compared to steady-state operation.

Focusing on the mass flow rate first, the table shows that during transient operation the flow rate falls by 41% compared to steady-state operation. While it is easy to speculate that the decline in the mass flow rate of turbine working gas, i.e., a decline in the volume of engine intake, originates in a decline in engine charging efficiency due to the delay in boost pressure response, a reconsideration of the factors in the decline in boost pressure response leads back full circle to the decline in the mass flow rate of turbine working gas. As Fig. 11 shows, this phenomenon originates in the recurrent circulation of energy among the turbine operating gas supply (the engine), the exhaust energy recovery device (the turbine), and the intake air compression device (the compressor). In this type of system, the effects of a decline in one section of the energy flow will propagate recurrently, resulting in a decline in the level of energy flowing in the entire system.

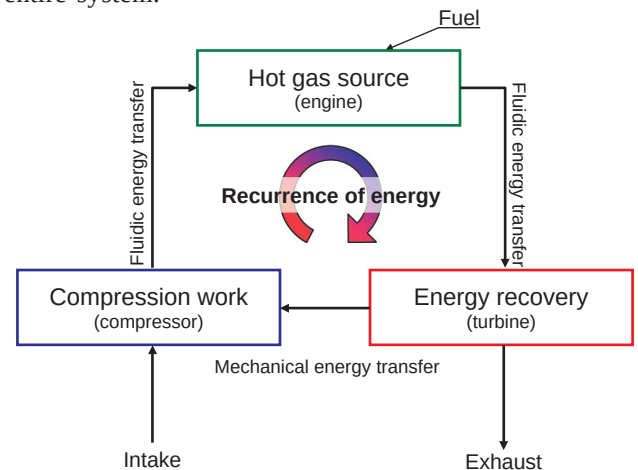


Fig. 11 Schematic diagram of recurrent energy flow in turbocharger system

The decline in turbine efficiency during transient operation will be considered next. A 39.9% decline in turbine efficiency against steady-state operation is observable at the 0.6 sec mark. An analysis of the transition in turbine efficiency over time shown in Fig. 12 indicates that turbine efficiency declines rapidly at the commencement of acceleration, and the efficiency level recovers as the system approaches steady-state operation.

In order to analyze this phenomenon, it is necessary to consider the hydrodynamic properties of the turbine. As Fig. 13 shows, results for turbine efficiency at corrected

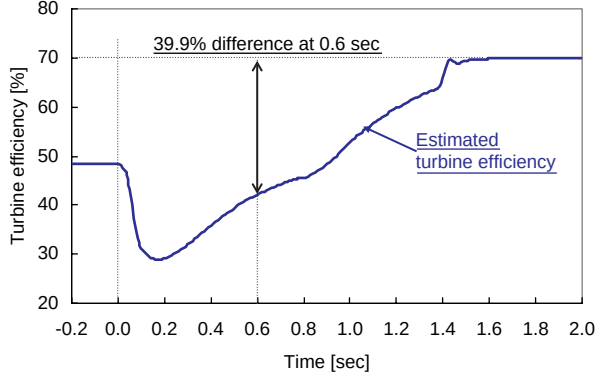


Fig. 12 Behavior of turbine efficiency under transient condition

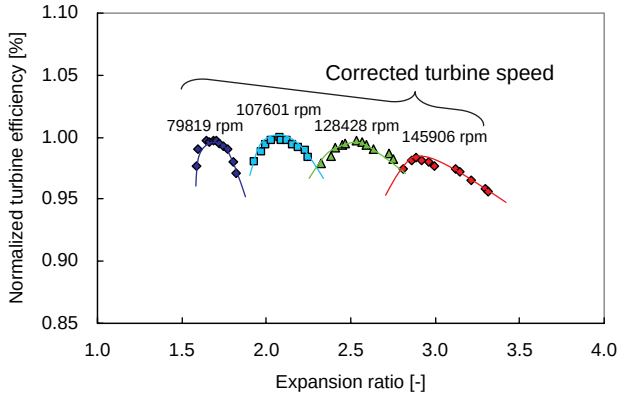


Fig. 13 Expansion ratio-dependency of turbine efficiency

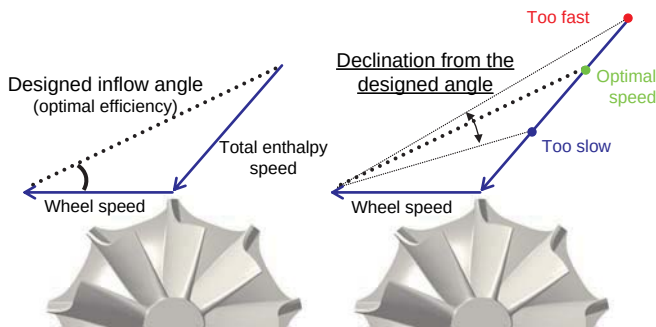


Fig. 14 Relationship between turbine efficiency and speed triangle

turbine speeds display a tendency to group into mountain-shaped patterns in relation to the turbine expansion ratio. As shown in Fig. 14, because of the geometric shape of the turbine, there is an optimum inflow angle for working gas in relation to the turbine blades (the design inflow angle), and if the total enthalpy speed, C in Eq.(5), which expresses the equivalent inflow speed of the working gas, is either too fast or too slow in relation to the peripheral speed of the turbine blades, turbine efficiency will decline.

$$C = \sqrt{2c_p T_3 \left(1 - \pi_t^{\frac{1-\gamma}{\gamma}} \right)} \quad (5)$$

The figure obtained by dividing the peripheral speed of the turbine by the total enthalpy speed of the inflowing gas is generally known as the blade speed ratio (BSR)⁽¹²⁾. As Fig. 15 shows, the BSR can be used to normalize turbine efficiency in relation to turbine speed. A consideration of the transition in the BSR over time under transient operating conditions (Fig. 16) shows that the BSR reaches its minimum value at the commencement of acceleration, and approaches 1 as operation converges on steady-state.

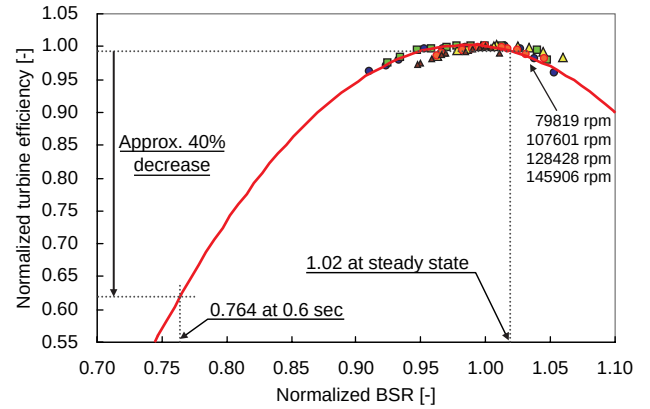


Fig. 15 Normalization of turbine efficiency in relation to turbine speed

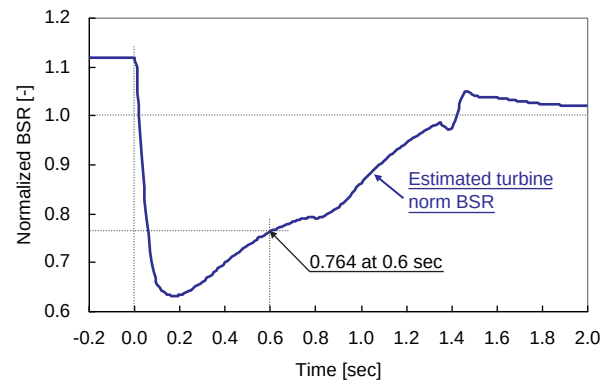


Fig. 16 Behavior of turbine BSR under transient condition

Because the variable vane mechanism generates a comparatively rapid increase in exhaust pressure when the engine operating load increases, the total enthalpy speed of the turbine working gas increases rapidly, but because the peripheral speed of the turbine blades increases more gradually due to the effect of the inertia of the turbine shaft (Fig. 9), the total enthalpy speed transiently exceeds the peripheral speed of the turbine. This means that under transient operating conditions, the BSR declines, and the turbine operates in a range of low efficiency. Figure 16 shows that the BSR of the turbine at 0.6 sec following the change in the position of the accelerator pedal is 0.764. Figure 15 indicates that at this BSR, turbine efficiency declines by approximately 40%. This figure matches the decline in turbine efficiency under transient operating conditions, indicating that the phenomenon can be explained by a change in an operating point (the BSR) of the turbine.

5. Mutual Interaction of Factors in Turbocharger Response Delay

As discussed above, in a standard engine-turbocharger combination, the engine, turbine, and compressor are recurrently connected by mechanical or fluid energy, and the turbocharger operates at the point of energy balance in this recurrence model. Up to this point, three factors in turbocharger delay response have been considered: transient loss, decline in the mass flow rate of turbine working gas, and decline in turbine efficiency. These factors do not only individually affect the turbocharger response, but also produce mutual effects on each other. It is therefore important to elucidate the mutual relationships between these factors in order to fully understand the phenomenon of turbo lag. This chapter will offer an example of the mutual interaction between factors in response delay, and create a model of these factors and the causal relationships between them.

5.1. Reduction in Mass Flow Rate of Turbine Working Gas Induced by Decline in Turbine Efficiency

First, the phenomenon of the delay in the increase in boost pressure due to the decline in turbine efficiency will be considered. As Fig. 17 shows, under transient

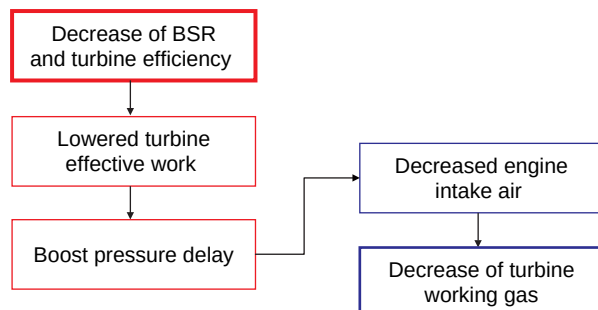


Fig. 17 Propagation of delay factors

operating conditions, due to a rapid increase in exhaust pressure, the turbine BSR decreases and turbine efficiency and the energy recovered by the turbine decline, with the ultimate result that the increase in boost pressure is delayed. This delay in the increase in boost pressure is related to a decline in the volume of engine intake air and the mass flow rate of turbine working gas. In other words, the decline in turbine efficiency induces a decline in the mass flow rate of turbine working gas, another factor in the delay in turbocharger response.

5.2. Model of Factors in Boost Pressure Response Delay and Relationships between Factors

This section will discuss the factors in turbocharger response delay determined up to this point and the causal relationship between these factors, using a multiple recurrence model that contains two coupled recurrence models.

The multiple recurrence model of turbocharger response delay is shown in Fig. 18. This model is made up of a transient loss model, representing the origin of turbocharger response delay, and two recurrence models, a model of the decline in the mass flow rate of turbine working gas and a model of the decline in turbine efficiency. The physical phenomena occurring in the turbocharger that are related to the delay in turbocharger response, and the causal relationships between these phenomena, are connected in Fig. 18 by arrows.

This section will provide a step-by-step explanation of the model, assuming a transition in the engine operating conditions from steady-state to high-load, and a transition from the occurrence of a turbocharger response delay to a state in which the delay no longer occurs.

First, no delay in boost pressure response occurs in steady-state operation. When there is a transition from this state to a state of acceleration, first the transient losses, shaft inertia loss and intake volume loss, occur (A in Fig. 18). As a result, there is a delay in the increase in turbocharger shaft speed, and the turbine efficiency declines due to the hydrodynamic properties of the turbine

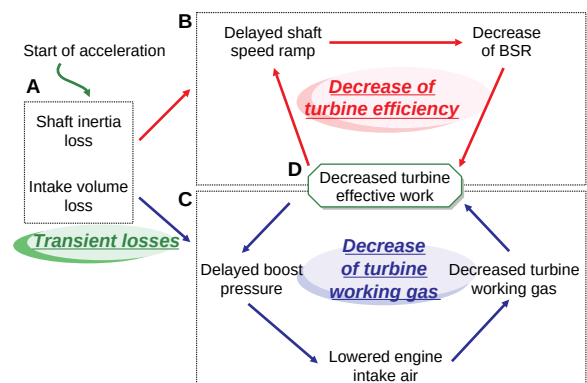


Fig. 18 Multiple recurrence model of turbocharger delay mechanism

(B in Fig. 18). At the same time, the intake volume loss results in a delay in the increase in boost pressure, as a result of which the mass flow rate of turbine working gas declines (C in Fig. 18). As the model shows, these factors in turbocharger response delay act recurrently on each other. Because the respective effects of B and C result in a decline in the effective turbine work (D in Fig. 18), these two factors in response delay can be seen to be connected from the perspective of energy by the decline in the effective work of the turbine.

Because the values of shaft speed and boost pressure depart significantly from their steady-state values at the commencement of acceleration, each of the factors in response delay exerts a mutual effect on each other and the energy flowing through the system as a whole declines. Because of this, there is a significant delay in boost response, but as time elapses, the values of the integral elements, the shaft speed and the boost pressure, increase and ultimately converge on their steady-state values. The factors in response delay that originated with these causal factors - the decline in the mass flow rate of turbine working gas and the decline in turbine efficiency – cease to occur, and the turbocharger therefore arrives at steady-state operation.

As the discussion above indicates, physical factors, the degree of inertia of the shaft and the capacity of the intake system, are the primary factors in the delay in turbocharger response, while a shift in the turbocharger operating point originating in these primary factors results in a decline in turbine efficiency and the mass flow rate of turbine working gas, which become secondary factors in response delay. In addition, these two secondary factors have a mutual effect on each other through the decline in the energy recovered by the turbine.

6. Conclusion

The research discussed in this paper created a numerical model of a turbocharger in order to analyze the mechanism of the delay in boost response occurring in turbochargers. It was verified that the numerical model reproduced the boost response characteristic in an actual vehicle well.

The numerical model was used in the analysis of the mechanism of delay in boost response, with the following results:

- (1) The delay in boost response occurs as a result of three main factors: transient loss, a decline in the mass flow rate of turbine working gas, and a decline in turbine efficiency.
- (2) The decline in the mass flow rate of turbine working gas and the decline in turbine efficiency display recurrent behavior.
- (3) The three factors in the boost response delay are linked by energy flows, and mutually affect each other.

Based on the results of the numerical analysis, it was

concluded that turbo lag is a delay in boost pressure response originating in multiple factors, made up of a delay resulting from primary factors – the shaft inertia loss and intake volume loss collectively termed transient losses – and a delay resulting from secondary factors – a decline in the mass flow rate of turbine working gas and a decline in turbine efficiency.

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Editorial Afterword

Communicating the outcome of one's research to others in writing is not an easy task. In addition, the *Technical Review* is frequently referred to by readers working in different fields of specialization, and the writers must therefore also consider how to communicate in a manner that is both precise and easy to understand.

I have the impression that again, most of our authors commenced with a broad conception of their papers, and expended a good deal of time on honing their expression through numerous rewrites. The difficulty of bringing a paper together must have been brought home to many, especially among our first-time authors. I am delighted that we have now been able to bring this volume, the fruit of their efforts, to our readers, and I can only hope that this experience will serve as a spur to take our authors to new heights of achievement.

Finally, I would like to take this opportunity to offer my sincere thanks to everyone involved in the publication of this volume, who generously offered their assistance despite their own busy schedules. I am fortunate to have been involved in the process of editing the *Technical Review*, a journal which now has a significant history behind it, and I feel inspired to work in the future to achieve an even higher level of quality.

(Hisako Majima)

The years seem to have flown by since I first became involved with the *Technical Review*. I remember my initial period working on the journal as one of daily bewilderment, faced with completely new tasks.

The fact that each issue of the *Technical Review* nevertheless reaches publication is a result of the cooperation of many people, including of course the writers themselves, but also the writing advisors in the relevant labs and departments, the review committee, and everyone involved with the editing of the texts, among many others. I am sincerely grateful for their cooperation.

Times have changed, digital technologies are now commonplace, and many tasks have been made easier. Despite this, it would be impossible to publish the *Technical Review* without the assistance of those many people.

For myself, I will continue giving my best to my editing duties, always bearing in mind the high expectations held for the *Technical Review*.

(Masako Shiraki)

For this volume, we asked two members of the editing staff to offer us some of their thoughts about the *Technical Review*.

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