

Honda R&D



Technical Review

DREAM



April 2008

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Comment on the Cover

Dream

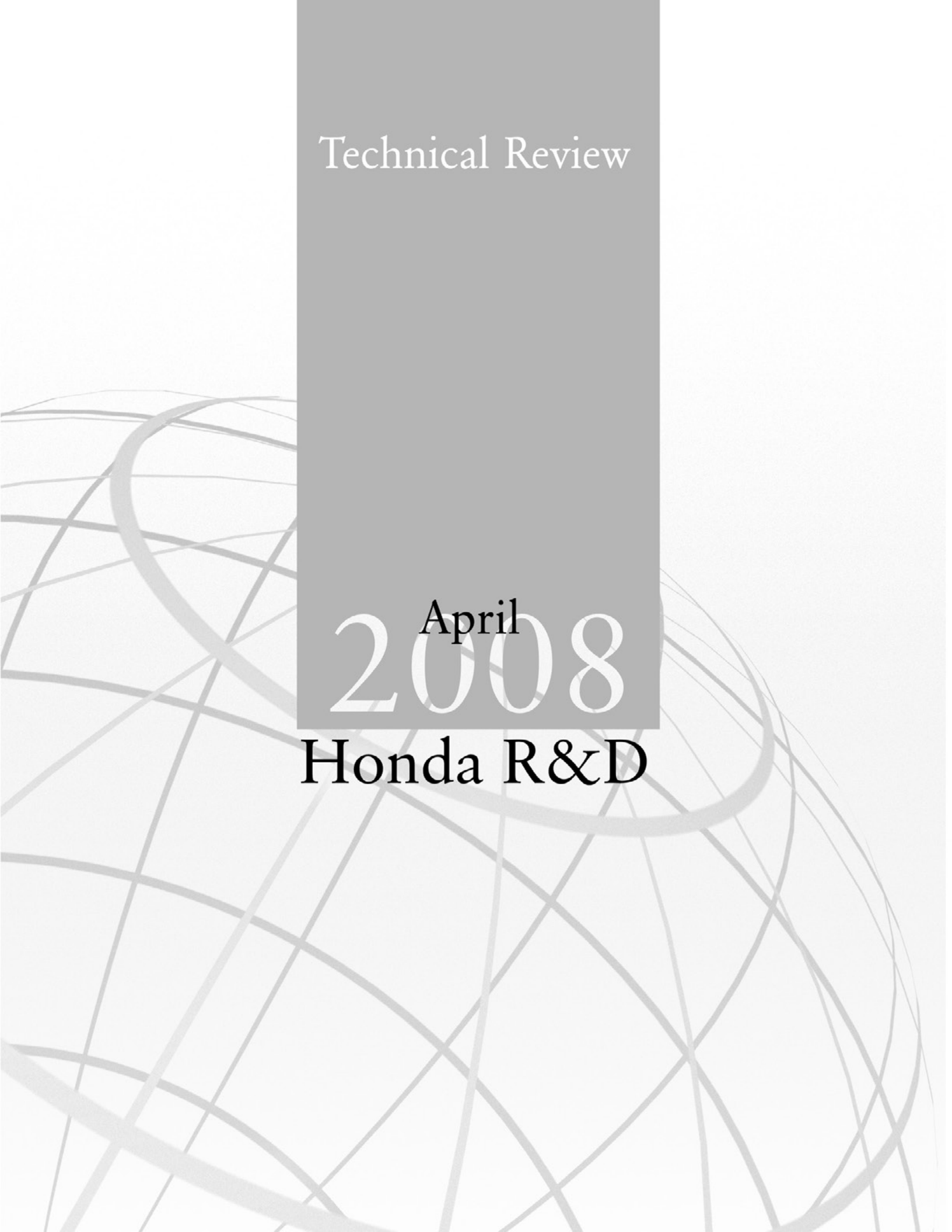
I see Honda products everywhere and it makes me happy that we are successful.

It is my dream to always have the Challenging Spirit! This cover design represents that dream.

I tried to put youthful energy and free spirit into this design.



HONDA R&D AMERICAS, INC.
Michael Furst

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

Technical Review

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Marking the 20th Anniversary Issue of the Honda R&D Technical Review



- A Record of Honda's Way of Life -

This year Honda will celebrate 60 years of existence. The history of the products that Honda has presented to its customers, and of the technologies incorporated in those products, is an embodiment of the company's thinking, its aspirations, and the challenges that it has taken on throughout its existence. It is no exaggeration to say that it is a record of Honda's way of life, and the fact that Honda has grown to become a manufacturer chosen by more than 23 million customers per year is further affirmation of that way of life.

However, this very success presents a considerable challenge when viewed with consideration of the status of the global environment. The majority of Honda's products use engines that burn fossil fuels. Honda is therefore continuously striving to increase the efficiency of these engines, and we are advancing research and development with the ultimate goal of eliminating the use of fossil fuels – this is our social responsibility as the world's largest manufacturer of engines. Achieving this goal is essential, not only to our ability to continue to offer appealing and safety-providing technologies, that enable our customers to fully experience the joy of owning a Honda product, but also to ensure that the foundation for Honda's way of life will continue to be honored by our customers and society for years to come.

This year will also mark the 20th anniversary of the Honda R&D Technical Review, which was established by a team of volunteers in 1989. Publication in the Technical Review is one of the goals toward which a Honda engineer is expected to aim. The Technical Review provides a forum enabling other specialists, both within Honda and outside the company, to objectively evaluate the effectiveness and advancement of the technologies that the authors have created. It is also an important learning resource, providing young engineers with access to technological information. Moreover, with each issue, the content of the Technical Review deepens and the technological scope broadens, making the journal a precious record of Honda's way of life - a life that cannot be grasped directly from the products themselves.

There has never been an era in which the importance of technology, as a powerful means of confronting and overcoming challenges, has been as keenly felt as the present era. Every engineer in Honda's research and development centers is striving to generate knowledge, working step-by-step to resolve complex technological issues. As a result, the Technical Review is becoming ever richer as a record of Honda's way of life, and it is our hope that it will prove to be a valuable resource to an ever-increasing number of people.

Masaaki Kato

A stylized, handwritten signature in black ink that reads "M. Kato".

President, Honda R&D Co., Ltd.

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Design of New FIT

Toshiyuki OKUMOTO*

Yoshiya KITAJIMA*

ABSTRACT

The new FIT, designed with the goal of making it the “best compact car,” was created under the overall concept of the “Next New Small.” Universal values demanded the world over were realized in its compact-automobile design, engine performance (agility), economic value, versatility (space), safety, and eco-friendliness.

The design team created an exterior design that incorporates roominess with the advanced “super-forward cabin.” They combined it all with the “super-forwarding form” concept that expresses the dynamic ruggedness of the frontward-leaning frame giving the new FIT a unique feel and look.

For the interior, the designers created the new cabin under the concept of an “advanced-feel personal interior,” with the fusion of a compact cockpit and a roomy, exhilarating space. The result is enhanced functionality, including an easy-to-use, simple seat arrangement, in a new FIT that is a thrill to drive each time you slide behind the wheel.

1. Introduction

Released on June 21, 2001, the first generation Fit was developed out of the desire to create a compact car that would be accepted the world over based on a “compact revolution.” The car became a huge hit with its concept incorporating the three maximums a compact car - Maximum fuel efficiency, maximum fun, and maximum cool. The Fit is now sold in 115 countries and has become much loved by countless car owners.

Now, more than six years later, the value of a multipurpose, compartmentalized car has become more accepted, thanks to changes in lifestyle and increased environmental concerns that have led to a worldwide trend toward downsizing. The role of compact-class cars has also been transformed from “something to get around in” to “a primary car.” The designers of the new FIT, aiming to make it the global standard for compact cars, became further convinced of the need to meet demands for the universal values associated with compact cars - design, engine performance (agility), economic value, versatility (space), safety, and eco-friendliness - and to evolve them further.

With regard to the design, its roomy cabin, smooth ride, versatility and package design have greatly evolved from the frame up. We developed the new FIT with the objective of creating a high-quality vehicle that would accentuate the individuality of the owners of these

compact cars. This is the concept that should be applied to all compact vehicles. By realizing this at a high level we will be creating the “Best Compact Car.”

2. Package Layout

The concept for the package design “Zenshin—Cabin Compact” is a fusion of a cabin that is both full-bodied and forward-leaning, focusing on a strong, sporty stance, spacious cabin, and evolved usability, crating a new rugged small car. (Fig. 1)



Fig. 1 Package concept

* Automobile R&D Center

To help achieve this, the wheelbase dimension was increased by 50 mm over the first-generation Fit and the tread size was increased on the large tires. The tires were moved to the corners of the car giving it a lower center of gravity and a more stable feel.

Meanwhile, the bottom of the windshield was moved approximately 100 mm forward creating an advanced “one-motion form,” producing a wider forward space. All this resulted in a spacious, exhilarating vehicle that exceeds the level of its class.

The distance between the front and rear seats of the new FIT has increased, as compared to the prior Fit, and by using a recessed headrest the designers have realized “dive-down” seats in one swift motion with the simple and easy-to-use “ultra seat.” Furthermore, by taking advantage of the space used for the spare tire, the designers have included an under box; an under-floor storage compartment that can hold up to about 60 L. This allows the driver to use the limited space of the small car to its fullest advantage making the car both more convenient and more versatile.

3. Exterior Design

For the exterior design, the designers of the new FIT chose to fuse the roominess of the first-generation Fit with the dynamism of its smooth ride into the “Super-Forwarding Form.” The unique advanced-feel monoform frame - with its forward leaning dynamic body that appears as if it’s being pushed from behind - is an exciting design that is instantly recognizable as the new FIT. (Fig. 2)

The exterior design derives from the three-dimensional cabin space that extends from the more forward positioned pillar to just behind the space above the rear seats. The rear fender combines with a rugged rear bumper protruding from the body, and a sharp character from the surface molding gives the FIT a blocky look. By incorporating these aspects into the design of the new FIT the designers were able to realize high quality and a

uniquely innovative and uplifting form, and at the same time creating a car that takes into consideration fuel efficiency and aerodynamics.

The FIT also includes expansive side window graphics, a narrow bowed front pillar and a large front corner glass, giving the car an enhanced field of vision. (Fig. 3)



Fig. 3 Side view



Fig. 4 Front view



Fig. 5 Final rendering

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Fig. 2 Super-forwarding form

The large, angular headlights have been extended toward the grill giving the new FIT an undaunted, yet familiar look - one of youth and excitement - while at the same time bringing in the corners making it easier to take tight turns. The new lights provide a wider area of illumination to the sides of the new FIT thus allowing the driver to see more and make it easier to take tighter turns. (Fig. 4)

By bringing in the rear of the cabin and extending bumper form to the sides, the FIT has been given both a personalized image and a stable, strong sporty stance. (Fig. 5)

4. Interior Design

We call the interior “forward personal interior.” It is a concept forged from the fusion of a new type of spacious, open cockpit, and a more compact space. (Fig. 6)

The upper faces of the instrument panel have been lowered while the nuances of the dash’s sculptured design have been accentuated resulting in a perception of wider surroundings, and an instrument panel that appears wider than it actually is.

With the front pillars moved forward, the front corner glass has been made larger, and the width of the pillar in the field of vision has been decreased by 25 mm. This accentuates the new FIT’s panoramic field of view giving it a feeling of openness, and enhancing visibility.

As for visibility, the three-dimensional, large gauges are easier to see. Control functions have been moved to the upper part of the driver’s side making them easier to use and emphasize the FIT’s driver-oriented sportiness. Other parts of the instrument panel look spacious. All these elements combined to create the revolutionary cockpit of the new FIT (Fig. 7).

Furthermore, by including a variable lid for the under box storage room located under the floor in the luggage



Fig. 6 Advanced feel personal interior

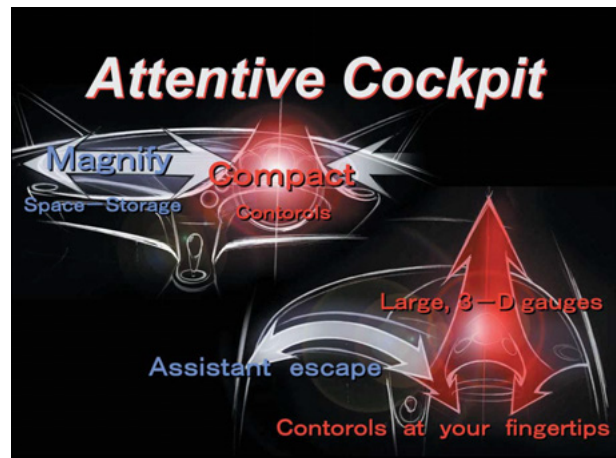


Fig. 7 Attentive cockpit



Fig. 8 Ultra luggage

space, the upper and lower part of the luggage space can be split in two, an idea dubbed “ultra luggage.” (Fig. 8) With the glove compartment also designed using the two-level system, the vehicle’s storage space has been made exceptionally versatile.

The designers of the new FIT have also increased the comfort of the seats and reshaped the seatbacks, giving the seats the refreshing roomy sensation of a higher-class car.

5. Color Design

5.1. Exterior

To communicate the sporty and advanced design of the exterior, we have developed strong, transparent “Brilliant Exterior Colors,” based on the theme “brilliance.”

The newly developed “Brilliant Sky M” has been chosen as the theme color for the 1.3 L model FIT. Using a vibrant blue that evokes the exhilaration of a blue sky, the color was given punch by emphasizing the tough

body's variability with a color that has red highlights on the shaded parts of the car.

Four other colors have been developed with premium interiors and exteriors in mind. Including already existing colors, owners can choose from 12 color options. (Fig. 9)

5.2. Interior

The theme of "brilliance" has been carried over into the interior. Through the concept of "Brilliant Interior Color," the designers have continued their pursuit of higher quality and innovation. The designers sought an "emotional coordination" by including seats with decorations that make them stand out instantly in the black interior.

The seat material in the 1.3 L FIT includes lamé and a dotted pattern, as well as embossing, creating a rich, shining crisscross pattern. Adding further accessories in gunmetal, the cabin space is given a casual, sporty feel. (Fig. 10)

Image not displayed for copyright reasons.

Fig. 9 Exterior colors

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Fig. 10 Interior colors

6. RS Design

The RS has been designed for certain types of drivers, including those who want a sporty, youthful car or car buffs who are interested in downsizing. For these drivers, we have designed a strong and dynamic looking exterior and a sporty, quality interior.

The new FIT was designed to have a strong presence and drive, as if sailing majestically down the road, making it stand out from others in its class.

6.1. Exterior

With the concept of "more dynamic" and "stronger," we sought to give the new FIT a solid presence that predicts a powerful ride emphasized by its low center of gravity and wide stance.

Silver metallic molding has been placed on the gunmetal upper grill. With the wide-open lower grill and low, wide prominent bumper design unique to this model, an image of fearlessness has been realized.

The large tires have been further enhanced with a 16-inch aluminum wheel design, while the lowered vibrant side garnish gives it a more virile, sportier design.

In addition, the rear defuser on the new FIT has been placed in a lower position and has been given a black motif. Coupled with the bumper design, the result is a sportiness that gives the car a powerful presence. (Fig. 11)



Fig. 11 RS exterior design

The theme color for the RS model is “PREMIUM DEEP VIOLET M,” which uses glass particles to create a shimmering effect. The unique transparency and depth of glass provides a brilliance fit for the true “downsizing” enthusiast - the target drivers.

6.2. Interior

Based on the idea of a refined “Adult Contemporary” mood, the interior of the new FIT has been designed to reflect a mature, high-quality sportiness. The seats are covered with a suede-like fabric with single stitching, as well as the same lamé and dotted pattern found in the 1.3 L, placing it on equal footing with higher-class cars. The seats are representative of the overall high quality.

The center panel includes brown satin fittings, while the areas around the controls, gauges and steering wheel have been given a sharp look with metal fittings—all contrasting with the dark, stylish interior. (Fig. 12)



Fig. 12 RS interior design

7. Conclusion

The much loved and highly valued first generation Fit belongs to the compact class, which contains many worthy and highly competitive cars.

With the new FIT we aimed to create the “best compact car.” The new FIT has been thoroughly redesigned from its frame and package design up emphasizing its strengths of compact car values - its design, engine performance (agility), economic value, versatility (space), safety and eco-friendliness.

We truly believe that the result of our work is expressed in the charm of the new FIT’s futuristic form, which is dynamic and expresses the joy of driving, as well as in the cabin, which creates the sensation of a higher class of car.

We hope that the new FIT will fit into the lives of our customers the world over, just as the first-generation Fit did, and will continue to be loved.

■ Author ■



Toshiyuki OKUMOTO



Yoshiya KITAJIMA

Development of i-VTEC Gasoline Engine for 2008 Model Year Honda FIT

Ryutaro TAGISHI*

Tsutomu SATO*

Hiroshi KAWAGUCHI*

Yoshiharu HAGIWARA*

ABSTRACT

Lightweight, compact 1.3-L and 1.5-L 4-cylinder SOHC i-VTEC gasoline engines were developed that achieve a balance of environmental performance (low fuel consumption, low exhaust emissions) and high output. The 1.3-L model employs a 4-valve cylinder head, VTEC that operates with one intake valve inactive for rapid combustion, and friction reduction technology. As a result, it achieves 24-km/L fuel consumption in 10-15 mode as well as high power with 73 kW of maximum output and 127 Nm of maximum torque. The 1.5-L model has a high-output VTEC for a maximum output of 88 kW and maximum torque of 145 Nm, the same friction reduction technology as that of the 1.3-L model, and achieves 19.6 km/L fuel consumption in 10-15 mode. The technology for low exhaust emissions includes a close-coupled catalyst, high-accuracy adaptive air-fuel control, and a cylinder head with integrated exhaust manifold, the same as that employed in the CIVIC. As a result, using the 10-15 and JC08C mode, the engines to be used in all 2008 FIT models have achieved an emissions level 75% below the level required by Japanese 2005 regulations.

1. Introduction

The development of technology to lower exhaust emissions in order to protect the environment and the development of technology to lower fuel consumption in order to reduce CO₂, which is a causal factor in global warming, have taken on growing importance in recent years. The technology adopted to address these requirements was the L13A 1.3-L 4-cylinder SOHC 2-valve dual and sequential ignition (i-DSI).⁽¹⁾ Installed on the engine for the 2002 model year Fit, this uses two spark plugs for each cylinder and controls the timing of the spark according to the engine operating conditions in order to achieve rapid combustion. The 1.5-L model added in 2003 adopted the L15A 1.5-L 4-cylinder SOHC 4-valve VTEC (VTEC that operates with one intake valve inactive), which controls the amount of lift on one intake valve in the low-speed range to achieve rapid combustion. The 1.3-L i-DSI is a 2-valve type, however, and although it provides lower fuel consumption through rapid combustion, there was demand for higher output for greater appeal as a product. There was also demand for still better drive performance in the 1.5-L model. These demands were met by the development of a new model

engine for the 2008 model year FIT with a 4-valve head common to the 1.3-L and 1.5-L versions to achieve higher output. The new engine also balances that with low fuel consumption by the application of friction reduction technology and combustion enhancement technology. The following report describes the technology adopted for the new model engine, with a focus on the 1.3-L version.

2. Development Goals

The distinctive characteristics of this engine were clearly identified in terms of the engine displacement as 1.3-L for fuel consumption and 1.5-L for driving, and the specific development objectives were set as follows:

1.3-L development objectives

- (1) Fuel consumption of 24-km/L in 10-15 mode to put it at the top of its class
- (2) High output and high torque at the top level in its class

1.5-L development objectives

- (1) High output at the top level in its class
- (2) Higher performance in fuel consumption of 19.6 km/L in 10-15 mode

* Automobile R&D Center

Table 1 1.3L engine specification

	2008 model FIT	2002 model Fit
Engine code	L13A (Developed)	L13A (Conventional)
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	73.0 × 80.0	73.0 × 80.0
Displacement (cm ³)	1339	1339
Compression ratio	10.5 : 1	10.8 : 1
Valve train	SOHC i-VTEC 1 intake valve inactive	SOHC i-DSI
Number of valves	4 per cylinder	2 per cylinder
Valve diameter (mm)	In. 28 × 2	32 × 1
	Ex. 23 × 2	28 × 1
Gasoline	Regular (RON91)	Regular (RON91)
Max. power (kW/rpm)	73 / 6000	63 / 5700
Max. torque (Nm/rpm)	127 / 4800	119 / 2800

3. 1.3-L i-VTEC

3.1. Overview of Engine and Major Specifications

Table 1 shows the major specifications of the 1.3-L engine in comparison with the previous model.

The distinctive features of this engine are the higher output that has been achieved by adopting a 4-valve cylinder head as opposed to the 2-valve i-DSI, and the lower fuel consumption achieved by adopting enhanced combustion technology, including VTEC that operates with one intake valve inactive, and friction reduction technology.

3.1.1. Cylinder head

The new model engine adopted a 4-valve cylinder head to raise intake efficiency at high speeds in order to achieve higher output. Figure 1 shows a section view of the cylinder head. The cylinder head is of the exhaust manifold-integrated type that is intended to yield faster light-off of the catalyst by reducing the heat mass of the exhaust system up to the catalyst. This structure constitutes technology that was applied to the 2006 model year CIVIC.⁽²⁾

The basic structure of the valve assembly is as shown in Fig. 2. Like the previous model, this engine has one rocker shaft, and that single shaft supports two aluminum rocker arms on the intake side and two on the exhaust side.

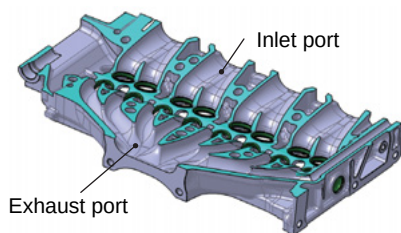


Fig. 1 Section view of exhaust manifold-integrated cylinder head

3.1.2. Intake system and exhaust system

The configuration of the intake system is shown in Fig. 3. It is equipped with an electronically controlled throttle (drive by wire: DBW) and an air flow meter (AFM) to implement highly precise torque control and air-fuel ratio control when the intake air volume fluctuates, such as, for example, when the engine shifts from operation with one intake valve inactive to operation with two valves. The engine also has an intake manifold chamber made of plastic that has been integrated with a resonator for better torque, as well as an intake manifold made of aluminum with a built-in EGR passage, contributing to a reduction in weight.

Figure 4 shows the configuration of the exhaust system. This employs an exhaust manifold-integrated cylinder head with one catalytic converter containing a three-way catalyst located directly under the cylinder head, thus reducing the heat mass of the exhaust system up to the catalyst in order to yield faster light-off of the catalyst. The air-fuel ratio controllability has also been enhanced by placing a universal exhaust gas oxygen (UEGO) sensor

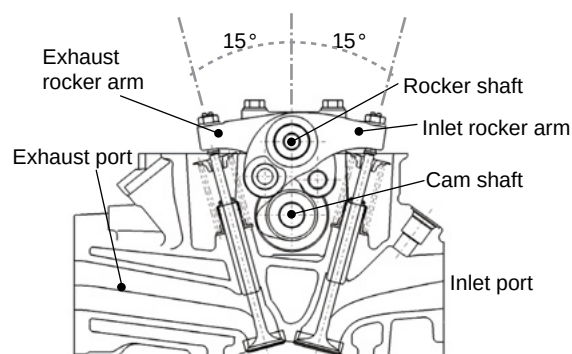


Fig. 2 Section view of exhaust manifold-integrated cylinder head

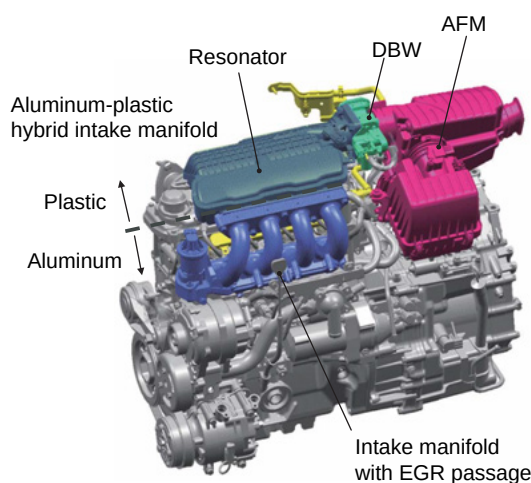


Fig. 3 Configuration of air intake system

upstream from the close-coupled catalyst and a heated exhaust gas oxygen (HEGO) sensor upstream from the under-floor catalytic converter. This provides more precise control of air-fuel ratio, which has reduced exhaust emissions.

3.2. Fuel Consumption Enhancement Technology

The application of combustion enhancement technology, friction reduction technology, and knocking reduction technology have resulted in a reduction of approximately 5% in engine standalone fuel consumption relative to the previous model.

3.2.1. Combustion enhancement technology

Adoption of the combustion enhancement technologies shown below resulted in a reduction of approximately 2% in engine standalone fuel consumption relative to the previous model.

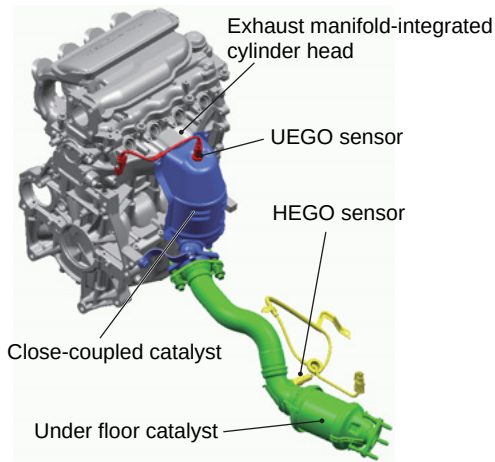


Fig. 4 Configuration of exhaust system

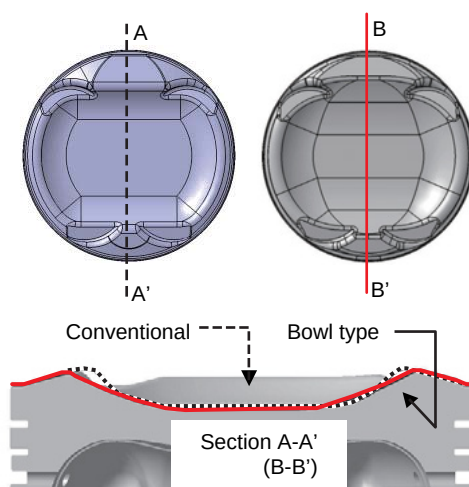


Fig. 5 Comparison of conventional and modified top form of piston

- Optimization of piston top shape
- Adoption of VTEC that operates with one intake valve inactive
- High-ignitability spark plugs

- (1) Optimization of piston top shape: The combustion chamber was made more compact and the in-cylinder flow was strengthened in order to enhance combustion. The shape of the piston top was optimized for this purpose. Figure 5 shows the piston top shape compared with the previous model. The top of the piston has been given a more bowl-type shape than the piston in the previous model. This shape provides an advantage in generating a tumbling flow while simultaneously reducing the surface area of the combustion chamber. Figure 6 shows the heat balance resulting from different piston top shapes with the engine at 1500 rpm and BMEP of 175 kPa. The adoption of a bowl-type shape has brought about a reduction in time loss and heat loss, and enabled a decrease of approximately 0.7% in fuel consumption.
- (2) VTEC that operates with one intake valve inactive: Intensifying the swirling flow is effective in enhancing combustion stability and ignitability during EGR. The adoption of four valves, however, reduces the swirling flow relative to the previous two-valve model, and this reduces the EGR flow volume that can be recirculated. This engine employs VTEC that operates with one intake valve inactive to reinforce swirling, thus assuring combustion stability during EGR. Figure 7 shows the valve timing characteristics and the calculated results for turbulence energy inside the cylinder resulting from differences in valve timing characteristics with the engine operating at 1500 rpm and intake manifold pressure of -45 kPa. The previous 1.5-L model already employed

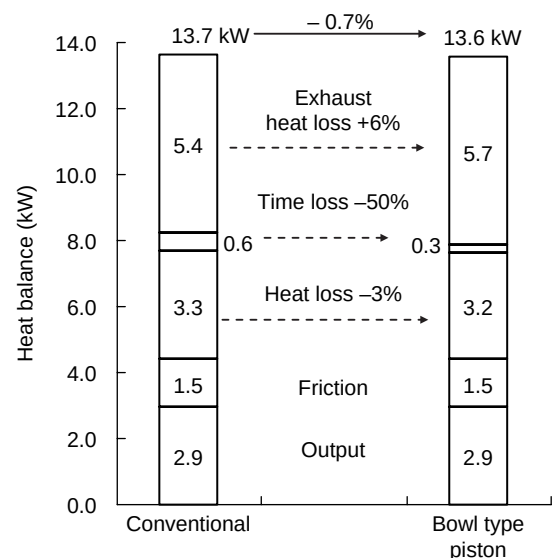


Fig. 6 Comparison of heat balance at partial load

VTEC that operates with one intake valve inactive, but in the new model engine, the inactive valve cam phase was retarded 20° relative to the previous model in order to strengthen the in-cylinder flow. The amount of lift in the inactive valve is reduced at a crank angle of around 90° , when the piston speed is at a maximum, and this increased turbulence energy inside the cylinder. An increase of approximately 5% in turbulence energy was also obtained at a crank angle of around 320° , where ignition occurs. Figure 8 shows the results of testing for fuel consumption and combustion stability during EGR with the engine operating at 1500 rpm and BMEP of 175 kPa. Combustion stability during EGR was enhanced, and a reduction of approximately 1% in fuel consumption was attained.

The switch between operating with one valve inactive and operating with four valves is controlled by the engine speed and load. In the normal operating range, the engine will operate with one valve inactive and EGR will be used to lower fuel consumption. In a range where torque is needed, it will switch over to four-valve operation.

3.2.2. Friction reduction technology

The following technologies were adopted for friction reduction, yielding a reduction in friction of approximately 7% relative to the previous model.

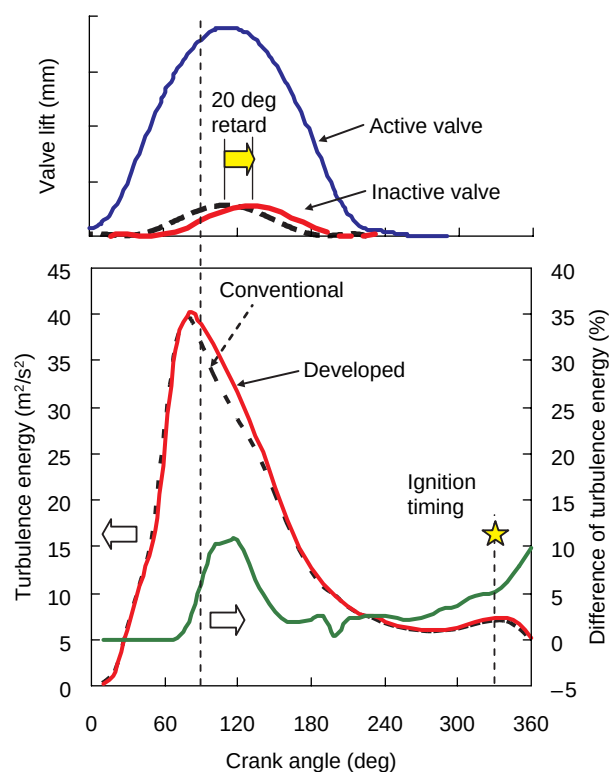


Fig. 7 Effect of inactive valve timing on turbulence energy in combustion chamber

- Pattern coating of molybdenum disulfide on the piston skirts
- Optimization of the piston skirt shape
- Reduction of piston ring tension
- Crank journal bearing metal treated by shot peening and application of molybdenum disulfide
- Plateau honing of cylinder liners
- Cam chain width made narrower
- Cam journal surface roughness reduced
- Accessory belt auto-tensioner

Figure 9 shows the side view of a piston that has had pattern coating applied to the piston skirt portion. Pattern coating is a technique for creating circular pits and bumps in a lattice pattern when applying a molybdenum disulfide coating to the piston skirt. This increases oil retention and reduces piston sliding resistance. The pits are distributed with reference to pit diameter and intervals in order to reduce the coefficient of friction. Figure 10 shows the results of friction testing with the engine operating at 1500 rpm and intake manifold pressure of -45 kPa. A friction reduction of 2% was obtained relative to molybdenum disulfide coating without patterning, and a friction reduction of 1% relative to shot peening and application of molybdenum disulfide, as used on the previous model.

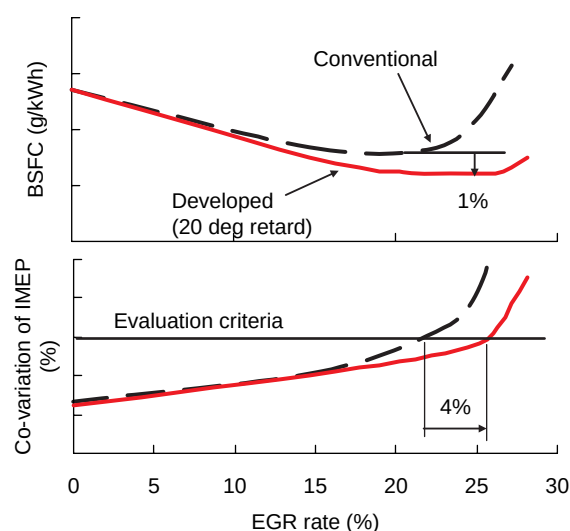


Fig. 8 Effect of inactive valve timing for BSFC and co-variation of IMEP

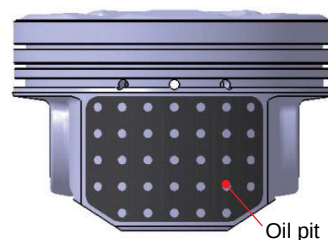


Fig. 9 Pattern coating for piston skirt

3.2.3. Knocking control technology

The frequency of operation in the high-load range becomes higher for smaller displacement engines, for which control of knocking therefore becomes an important concern associated with the reduction of fuel consumption. The previous model used i-DSI with two spark plugs per cylinder to control knocking. With the adoption of four valves, however, the number of spark plugs was reduced to one, so that control of knocking increased in importance. The following knocking control technologies were applied:

- Bowl-type piston
 - Optimization of coolant circulation path
- (1) Piston top shape: The use of a bowl-type shape on pistons to strengthen the in-cylinder flow is also effective for knocking control. Figure 11 shows the calculated results from simulation of turbulence energy inside the cylinder due to differences in the piston top shape with the engine

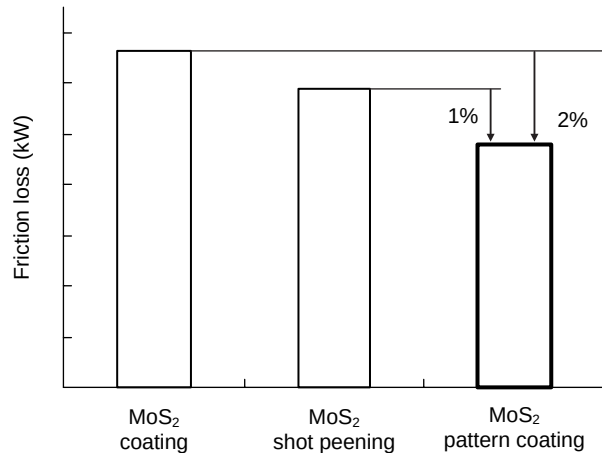


Fig. 10 Effect of pattern coating on friction loss

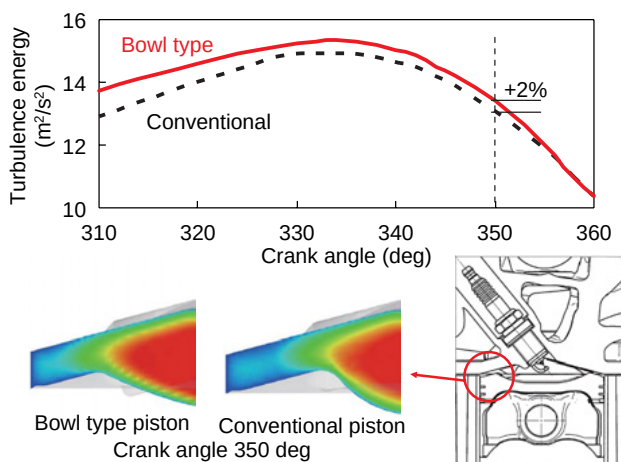


Fig. 11 Effect of piston top form on turbulence energy in combustion chamber

operating at 6000 rpm, or wide open throttle (WOT). This indicates that turbulence energy inside the combustion chamber as a whole has been strengthened by approximately 2%, with a strengthening of the flow in the end gas zone, which is a location particularly associated with knocking. Figure 12 shows the amount of knock retard resulting from differences in piston top shape. The vertical axis of the graph shows the ignition timing for knocking with the MBT at 0°. The amount of ignition retard from knocking is reduced by 1–3° across the entire range of engine speed for the “bowl-in” type relative to the previous model.

- (2) Coolant circulation system: Optimization of the coolant circulation path increased the flow velocity in every part, enhanced the cooling effect in the combustion chamber, and acted to control knocking. Figure 13 shows the coolant circulation path in comparison with the previous model. In the previous model, the coolant went from the water pump into the cylinder head, where the main flow divided into two parts, one going through the cylinder head and the other through the cylinder block. The coolant then followed a path taking it along the cylinder sides on the intake side and the exhaust side, following the same direction in both. This system limited the flow into the cylinder block when the engine was cold, thus enhancing the quick warming effect. When the engine was warm, coolant that had been warmed in the cylinder head could be directed to the cylinder block to maintain the high temperature there and reduce friction. Since the

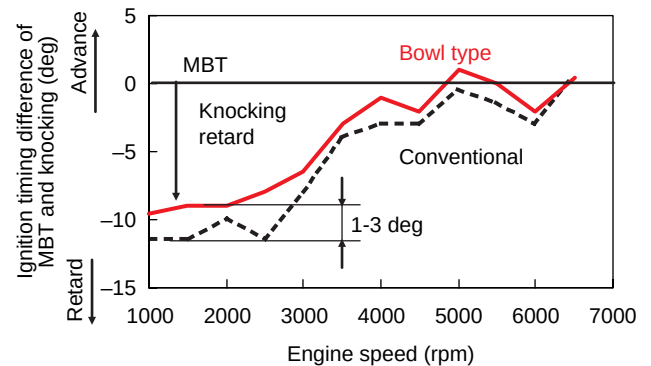


Fig. 12 Effect of piston top shape on ignition timing

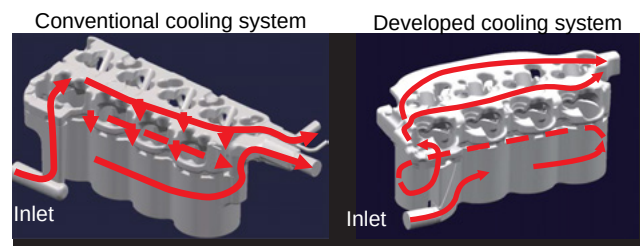


Fig. 13 Cooling circulation system

coolant followed multiple paths, however, the flow velocity in each part tended to decrease. Therefore, a method was adopted to keep the main flow of coolant entering the cylinder block from the water pump in a single flow, as though drawn in a single stroke, thereby raising the flow velocity in the various parts. Figure 14 shows the results from a simulation of the coolant flow velocity distribution with the engine operating at 6000 rpm. Figure 15 shows the results from testing the knocking ignition timing at WOT using the coolant circulation system. The change in the circulation system increased the flow velocity around the combustion chamber and through the upper part of the cylinder block, enabling enhancement of the cooling effect and control of knocking at high speeds.

3.3. Full Throttle Output Characteristics

Figure 16 shows the engine performance curve at wide open throttle. Adoption of the below intake efficiency enhancement technology and knocking reduction technology achieved 73 kW of maximum output and 127 Nm of maximum torque. This yielded an

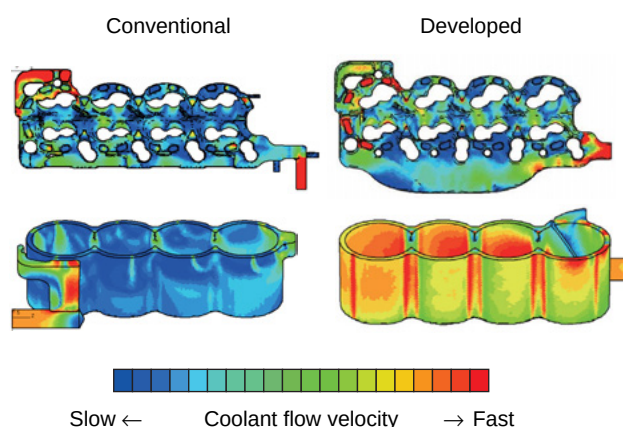


Fig. 14 Comparison of coolant flow velocity between conventional and developed flow

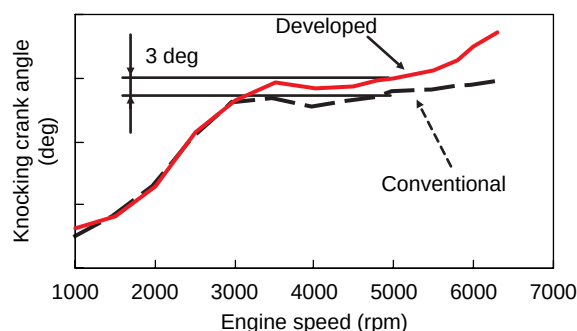


Fig. 15 Comparison of knocking between conventional cooling system and modified cooling system

enhancement of approximately 20% in maximum output and approximately 7% in maximum torque, relative to the previous model.

Intake efficiency enhancement

- 4-valve cylinder head and optimization of port shape
- Reduction in air cleaner air-flow resistance
- Reduction in knocking by means of intake manifold with integrated torque-up resonator
- “Bowl-in” piston
- Optimization of coolant circulation path

3.4. Noise and Vibration Reduction Technology

3.4.1. Engine sound radiation

Measures were taken to reduce engine noise radiation in the 770–2000-Hz range for the developed engine in order to reduce engine noise transmission from the engine compartment at wide open throttle. The method of transfer path analysis was applied to the engine as a standalone unit in the course of implementing efficient measures to

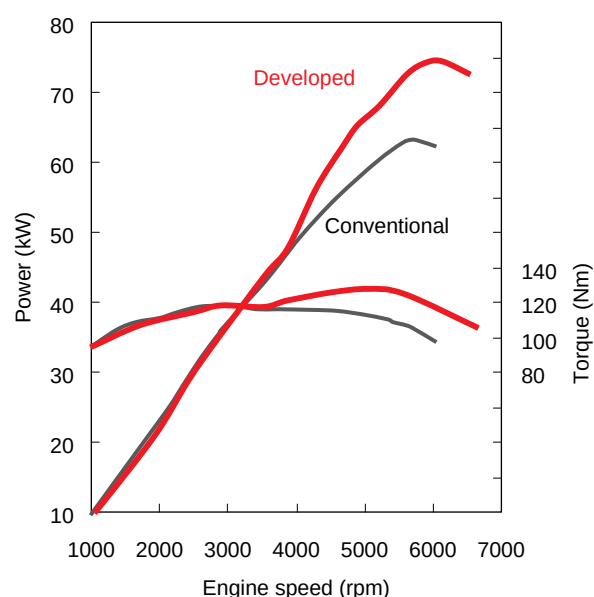


Fig. 16 Engine performance of 1.3L engine

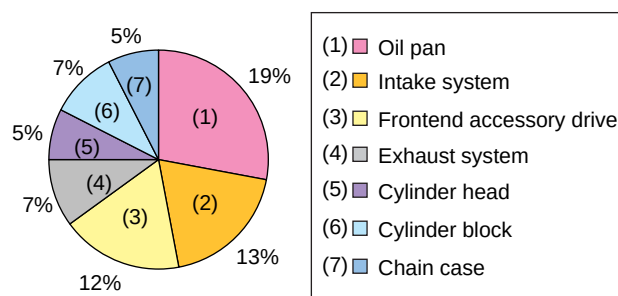


Fig. 17 Contribution to powertrain noise

counter engine noise radiation.⁽³⁾ The results were used to calculate the energy contribution to noise generation by part (Fig. 17). It was found, as a result, that the largest contribution was from the oil pan. Computer-aided engineering (CAE) was utilized to examine the possibility of increasing the rigidity of the oil pan, and the results were applied to the actual engine. A 2.5-dB reduction in engine noise radiation was achieved as a result. Figure 18 shows engine noise radiation with the throttle wide open and on a sweep of engine speeds gradually rising from idle. The adoption of a head cover made of plastic, and other such measures, achieved a reduction of 2–6 dB relative to the previous engine.

3.4.2. Piston slap noise

Figure 19 shows cylinder liner vibration with the engine operating with no load and on a sweep of engine speeds gradually rising from idle. A piston behavior simulation was utilized to achieve a balance in the reduction of piston slap noise and friction.^{(4),(5)} Optimization of the piston offset and of the piston skirt shape realized a 13-dB reduction in cylinder liner vibration, compared to the previous engine, while at the same time enabling a 0.3% reduction in friction.

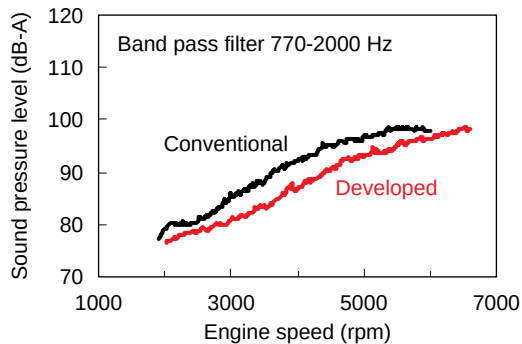


Fig. 18 Comparison of engine noise

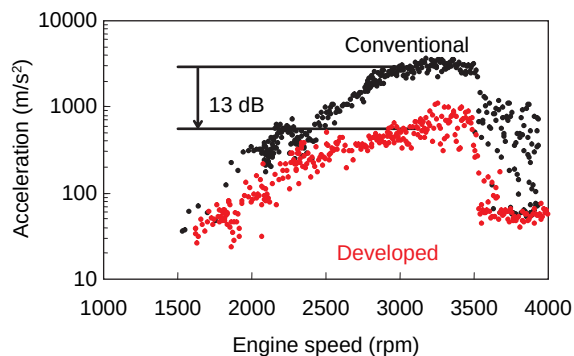


Fig. 19 Comparison of piston shape for cylinder liner acceleration

Table 2 1.5L engine specification

	2008 model FIT	2003 model Fit
Engine code	L15A (Developed)	L15A (Conventional)
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	73 × 89.4	73 × 89.4
Displacement (cm³)	1497	1497
Compression ratio	10.4 : 1	10.4 : 1
Valve train	SOHC i-VTEC High-output VTEC	SOHC VTEC 1 intake valve inactive
Number of valves	4 per cylinder	4 per cylinder
Valve diameter (mm)	In. 28 × 2	27.5 × 1
	Ex. 23 × 2	23 × 1
Gasoline	Regular (RON91)	Regular (RON91)
Max. power (kW/rpm)	88 / 6500	81 / 5800
Max. torque (Nm/rpm)	145 / 4800	143 / 4800

4. 1.5-L i-VTEC

4.1. Overview of Engine and Major Specifications

Table 2 shows the major specifications of the 1.5-L engine compared with the previous model engine. Where the previous 1.5-L model employed VTEC that operates with one intake valve inactive, the new model employs high-output VTEC that is intended to enhance driving performance. The major point of difference from the new 1.3-L model is utilization of the high-output VTEC. Otherwise, the two versions share the same basic configuration. There are two valve assembly types, one in the VTEC that operates with one intake valve inactive, utilized in the 1.3-L engine, and the other in the high-output VTEC. However, the two share the same cylinder head, and the differences were addressed by changes in the rocker arm, cam shaft, and rocker shaft holder. Figure 20 shows the rocker arm shapes. The valve assembly is discussed in detail below.

The output enhancement technology, other than the valve assembly, and the friction reduction technology are shared with the 1.3-L version. They yielded a maximum output approximately 9% higher than that of the previous model, with maximum torque approximately 1% greater.

4.2. Full Throttle Output Characteristics

Figure 21 shows a conceptual view of the high-output VTEC operation in comparison with the previous system. The high-output VTEC constitutes technology for opening the intake valves wider at high speed and increasing the amount of valve lift. When the previous model of high-

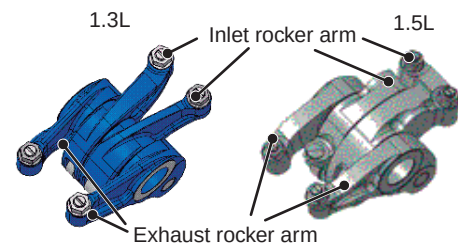


Fig. 20 Comparison of rocker arm shape

output VTEC utilized four valves, it used three rocker arms on the intake side. The new model engine has L-shaped rocker arms that enable one rocker arm to lift two intake valves. This has enabled the engine to realize functionality equivalent to the previous system with a total of just two rocker arms while making the valve assembly compact. The determination of when to switch between the low-speed cam and high-output cam is made according to the engine speed.

Figure 22 shows the performance curve. By adopting high-output VTEC and output enhancement technology held in common with the 1.3-L version, this engine achieves 88 kW of maximum output and 145 Nm of maximum torque. This maximum output is approximately 9% higher than that of the previous model, with maximum torque approximately 1% greater.

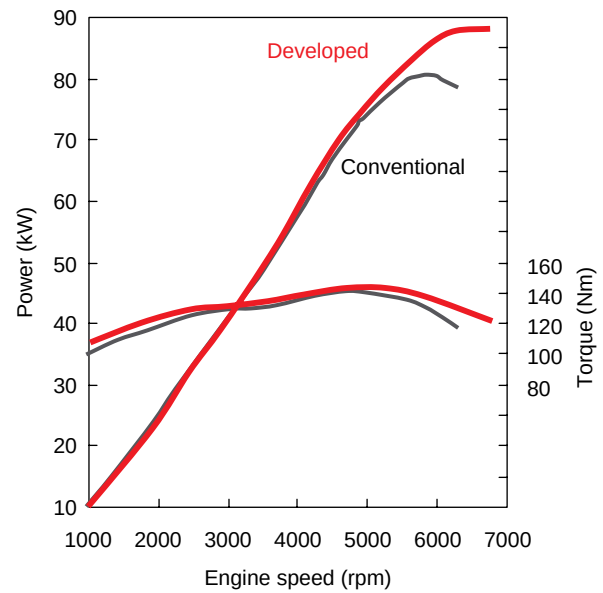


Fig. 22 Engine performance of 1.5 L engine

5. Completed Vehicle Fuel Consumption

Vehicles with the new model i-VTEC engine installed also utilize a newly developed highly efficient continuous variable automatic transmission (CVT) equipped with torque converter that achieve 10-15 mode fuel consumption of 24 km/L for the 1.3-L version and 19.6 km/L for the 1.5-L version. At the same time, they have also successfully realized higher dynamic performance by means of higher output. Figure 23 shows the positioning of mid-range acceleration performance and 10-15 mode fuel consumption for the previous model engine, the new engine, and vehicles sold in Japan.

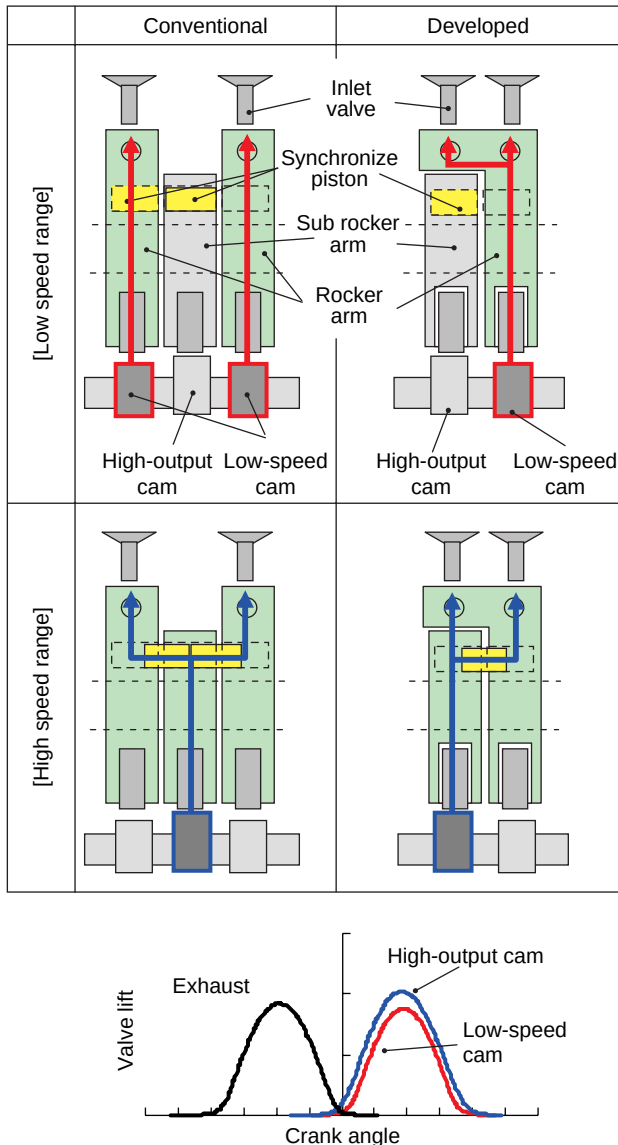


Fig. 21 Valve system operation image and cam profile

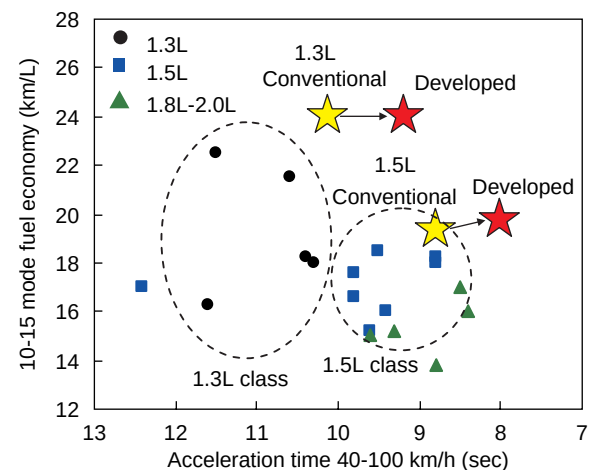


Fig. 23 Positioning of 10-15 mode fuel economy and dynamic performance

6. Low Exhaust Emissions Technology

Technologies adopted for low exhaust emissions include faster light-off of the catalyst by the utilization of a cylinder head with integrated exhaust manifold and a close-coupled catalyst, placement of a UEGO sensor upstream from the close-coupled catalyst and a HEGO sensor upstream from the under-floor catalytic converter, utilization of DBW and AFM for highly precise adaptive control of the air-fuel ratio, and the like. These technologies have achieved a 70% or greater reduction in the amount of precious metal used relative to the previous model engine, while also realizing exhaust emissions at a level 75% lower than required by fiscal year 2005 exhaust emissions regulations.

7. Conclusion

The development of an engine that utilizes 4-valve i-VTEC technology, friction reduction technology, and combustion enhancement technology has realized a balance between lower fuel consumption and high output. The results obtained were as follows:

- (1) The 1.3-L engine achieved maximum output approximately 20% higher and maximum torque approximately 7% greater than those of the previous model, and its use in vehicles incorporating the highly efficient CVT has realized 10-15 mode fuel consumption of 24 km/L.
- (2) The 1.5-L engine achieved maximum output approximately 9% higher and maximum torque approximately 1% greater than those of the previous model while also realizing 10-15 mode fuel consumption of 19.6 km/L.
- (3) Through utilization of the exhaust manifold-integrated cylinder head, close-coupled catalyst, and high-accuracy adaptive air-fuel control, both the 1.3-L and 1.5-L engines have achieved an emissions level 75% below the level required by Japanese 2005 regulations in 10-15 and JC08C mode.

References

- (1) Nakayama, Y., Suzuki, M., Iwata, Y., Yamano, J.: Development of a 1.5L 2PLUG Engine for the 2002 year Model Fit, Honda R&D Technical Review, Vol. 13, No. 2, p. 43-52
- (2) Seko, K., Taga, W., Torii, K., Nakamura, S., Akima, K., Sekiya, N.: Development of 1.8L i-VTEC Gasoline Engine for 2006 Model Year Honda CIVIC, Honda R&D Technical Review, Vol. 18, No. 1, p. 8-15
- (3) Noumura, K., Yoshida, J.: Method of Transfer Path Analysis for Interior Vehicle Sound Using Principal Component Regression Method, Honda R&D Technical Review, Vol. 18, No. 1, p. 136-141
- (4) Kobayashi, T., Take, K., Kamiya, M., Takahashi, Y.:

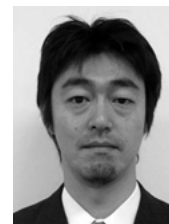
Piston Slap-noise Prediction Using 3-dimensional Piston Secondary Motion Simulation, Honda R&D Technical Review, April 2007, p. 163-169

- (5) Sato, K., Fujii, K., Ito, M., Koda, S.: Friction Analysis by Piston Secondary Motion Simulation in Consideration of Cylinder Block Bore Distortion, Honda R&D Technical Review, Vol. 18, No. 1, p. 94-100

■ Author ■



Ryutaro TAGISHI



Tsutomu SATO



Hiroshi KAWAGUCHI



Yoshiharu HAGIWARA

Metal Pushing V-belt for Torque Converter-type CVT for 1.5-Liter Class Vehicles

Tooru YAGASAKI*

Hideaki AOYAMA*

Masamichi HARADA*

Kenji HARUE*

Kenta UMETU*

ABSTRACT

A metal pushing V-belt for use in a new 1.5 L class torque converter-type CVT (TC-CVT) has been developed.

Because torque is amplified by the torque converter, a TC-CVT places a greater load on the belt than a conventional starting clutch-type CVT (SC-CVT), and the new V-belt therefore had to be able to cope with this increased load.

In order to fit the developed belt for this more severe use environment, the shape of the elements was modified to increase strength, and the accuracy of the shape of the rings was increased by reducing the high order of curvature component, resulting in more stable dynamic behavior. In addition, the hardness of the surfaces of the rings was increased in order to enhance wear resistance.

A noteworthy feature of the developed metal pushing V-belt is the fact that specifications enabling use in a 1.5 L class TC-CVT were achieved using only nine layers of rings.

1. Introduction

In 2001, Honda became the first automaker to internally manufacture a metal pushing V-belt⁽¹⁾. As of March 2007, the company had produced a total of 1 million belts for 1.5 L class SC-CVTs.

The newly developed 1.5 L class TC-CVT employs a torque converter, increasing torque in comparison to the SC-CVT at take-off and when the engine stalls. The metal pushing V-belt should therefore transmit more torque. The clamping force necessary to achieve torque transmission without slipping at the contact surfaces between the belt and the pulleys will therefore be higher than it was in the case of the SC-CVT, necessitating the development of a belt able to tolerate the new load.

This paper will provide an overview of the developed metal pushing V-belt, and will discuss the main technologies that it employs.

2. Development Goals

An increase in the clamping force applied to the belt by the pulleys will affect the elements and rings that make up the belt. The distortion of the elements when the belt is clamped by the pulley will increase, and the tensile

stress on the rings will increase. Tensile stress can be reduced by increasing the number of layers of rings, but this would increase costs. Twelve layers of rings is currently standard, but it was considered that cost competitiveness would be increased if the 1.5 L class TC-CVT could be developed using nine layers of rings.

This consideration led to the development of a metal pushing V-belt using nine layers of rings for the 1.5 L class TC-CVT being set as the development goal.

3. Configuration and Specifications of Metal Pushing V-belt

Metal pushing V-belts are made up of several hundred elements and two sets of layered rings. Figure 1 shows a photograph of the developed belt and Table 1 compares the main specifications of the current and the developed belts. The width of the developed belt is 24 mm, the standard width for a 1.5 L class CVT.

The names of the components making up the belt are shown in Fig. 2. The areas shaded over in Fig. 2 represent changes that have been made to the shape of the current SC-CVT element to increase strength and reduce surface pressure.

* Automobile R&D Center

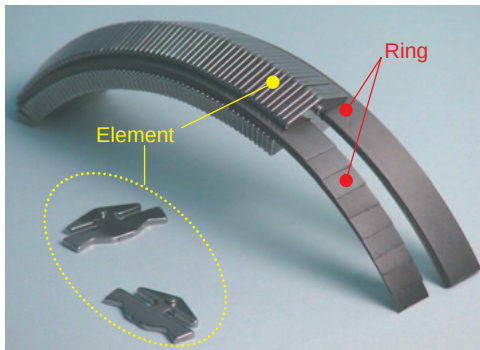


Fig. 1 Newly developed metal pushing V-belt

Table 1 Steel belt specifications

		Current	Developed
CVT type		SC-CVT	TC-CVT
Shaft distance (mm)		143	156
Ring	Width (mm)	a	9.15
	Thickness (mm)	b	0.184
	Diameter (mm)	c	191.7
	Number of rings	9 /Each side	9 /Each side
Element	Rocking edge width (mm)	d	24
	Thickness (mm)	e	1.5
	Body height (mm)	f	5.75
	Mass (g)	1.79	1.97

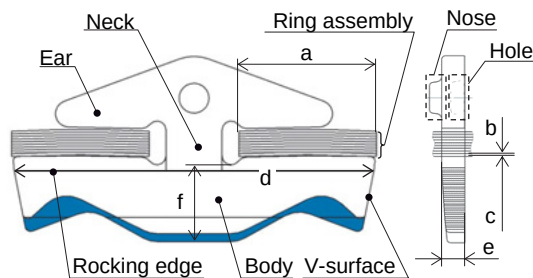


Fig. 2 Configuration of elements and ring assembly

4. Element Strength

The increase in the clamping force in the new belt would generate increased stress due to element distortion and would cause a decline in the wear characteristic of the belt due to increased pressure on the contact surfaces between the pulleys and the elements. These factors had to be taken into consideration. A reduction of 30% in stress was achieved by increasing the height of the element bodies in order to give them a larger cross-sectional shape (Fig. 3).

In addition, the length of the element V-surfaces was increased in order to reduce contact pressure. CAE strength analyses were conducted to design the bottom of the element bodies to allow the contact pressure on the V-surfaces generated by the clamping force to be evenly

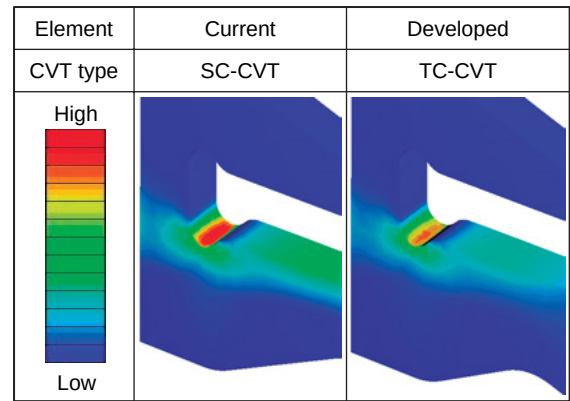


Fig. 3 Stress on element

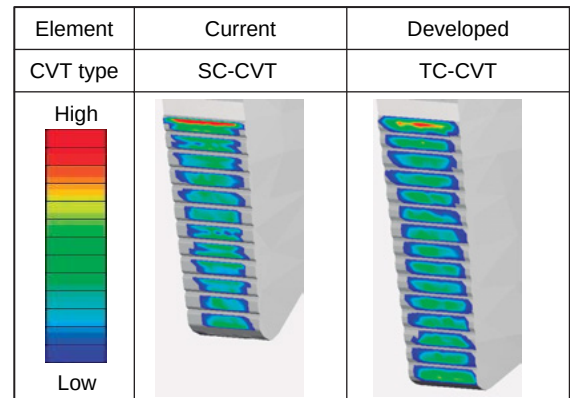


Fig. 4 Contact pressure at V-surface

distributed despite the high rigidity achieved by increasing the height of the bodies and the length of the V-surfaces. This enabled the achievement of a maximum level of contact pressure on the V-surfaces during operation equivalent to or lower than that recorded in the SC-CVT (Fig. 4), and minimized the increase in mass.

5. Wear Resistance of Rings

In the range in which torque is amplified by the torque converter in the TC-CVT, the tensile stress on the rings becomes greater than the tensile stress on the rings in the SC-CVT belt. In order to stabilize the dynamic behavior of the rings when this greater stress is generated, it was necessary to increase the accuracy of the shape of the rings. If the dynamic behavior of the rings became unstable, there would be interference with the sides of the element necks, and the edges of the rings would be subject to wear.

In order to increase the friction resistance of the rings, the development discussed here conducted measurements of the dynamic behavior of the rings, evaluated the accuracy of their shape, and optimized the difference in surface hardness of the rings and the sides of the element necks.

5.1. Measurement of Ring Dynamic behavior

Figure 5(a) shows the string between the drive and the driven pulleys where measurements of ring dynamic behavior were conducted at LOW ratio. Figure 5(b) shows a schematic of the sensor used in the measurements.

Figure 6 shows the results of measurements of ring displacement in the direction of width during operation based on signals from this sensor. In the current rings, right-left displacement of the rings in the string in which measurements were taken increased with increasing tensile stress. The developed rings, by contrast, demonstrated stable dynamic behavior, with no increase in left-right displacement despite increased tensile stress.

5.2. High Order of Curvature of Rings

Conventionally, when the accuracy of the shape of the rings is evaluated, the shape shown in Fig. 7(a) is termed “curve.” A measurement method that does not involve cutting of the ring is used in mass production to enable production control⁽²⁾.

It was shown that in the rings in which displacement in a left-right direction increased in the string used for measurements as tensile stress increased, a curved form of the type shown in Fig. 7(b), on the microscopic level

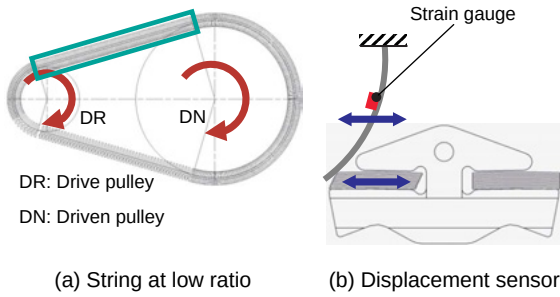


Fig. 5 Measurement of ring displacement

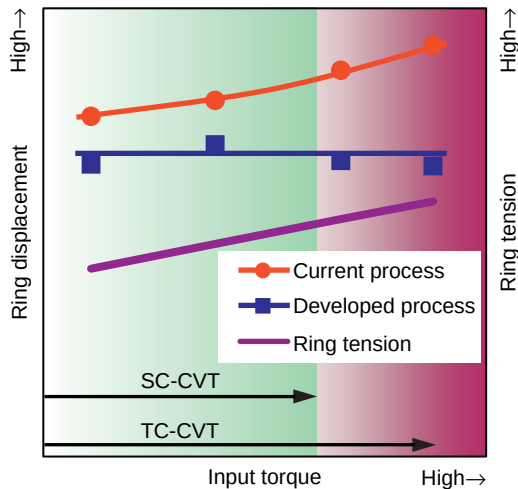


Fig. 6 Comparison of ring displacement

of micrometers and possessing a high degree of periodicity, also exists in addition to the curved form made up of low-order components shown in Fig. 7(a).

The high-order component of this curvature was highlighted by the application of Fourier analysis following the removal of low-order components from the automatically measured curvature data. Because this method can quantify the periodicity of specific orders across the entire length of the rings, it is able to identify the causes of curvature in the production process.

Figure 8 shows the results of Fourier analysis of measurements taken using 18 layers of rings, with Fig. 8(a) showing results for the current rings, and Fig. 8(b) showing results for the developed rings.

The amplitude of the sixth-order component is conspicuous in the results for the current rings. A procedure related to the sixth order component was therefore sought in the production process of the rings. It was found that the outer diameter of the roller used in the rolling process was approximately one-sixth the diameter of the rings, and that the accuracy of this roller was affecting the curvature of the rings. The accuracy of the

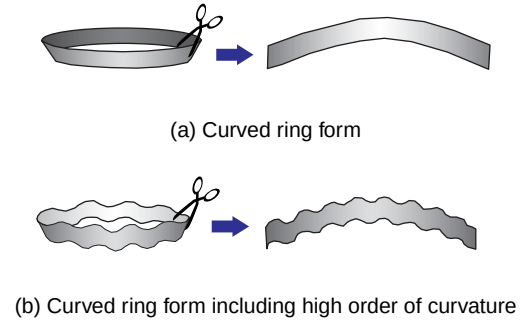
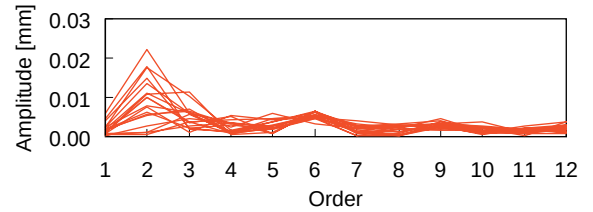
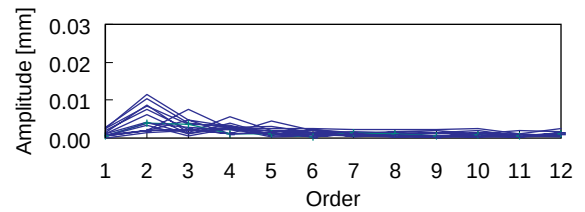


Fig. 7 Schematic of curved ring form



(a) Current



(b) Developed

Fig. 8 Comparison of frequency component

roller was increased, resulting in a reduction in the amplitude of all orders, in particular the sixth-order component.

5.3. Optimization of Difference in Surface Hardness

In order to help prevent wear from progressing through temporary contact between the rings and the sides of the element necks, the surface hardness of the developed rings was increased to a higher level than the surface hardness of the sides of the element necks.

5.3.1. Comparison of surface hardness of rings and sides of element necks

Figure 9 shows the hardness of the developed rings and element necks in the direction of depth from the surface.

The hardness of the surface of the rings is higher than that of the sides of the element necks, and the gradients for the element necks show that they become harder from the upper section to the lower section. This allows the edges of the rings on the outer circumference side, where the change in dynamic behavior is greater in the layered rings, even if they make contact with the sides of the element necks, to have the high degree of difference in surface hardness that will help prevent wear from progressing in the rings.

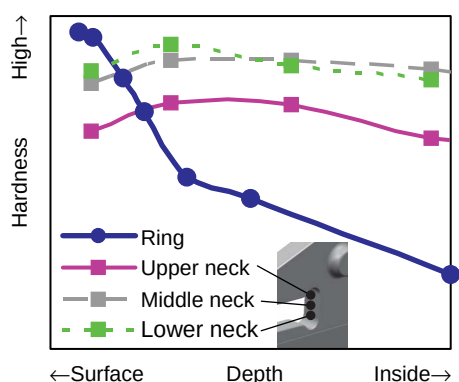


Fig. 9 Hardness of element neck and ring

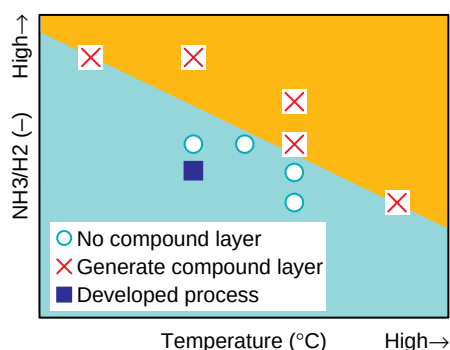


Fig. 10 Compound layer generation at nitriding

5.3.2. Ring hardness

Figure 10 shows whether a compound layer was or was not generated on the surfaces of the rings when the temperature and the ratio of the gases were varied during the nitriding process. Hardness increases as the nitrogen gas ratio increases, but if a compound layer forms, durability can decline.

Optimization of conditions during nitriding of the developed rings has increased the concentration of nitrogen on the surface, resulting in increased surface hardness. In addition, the internal hardness of the rings does not reduce the toughness that is a characteristic of the maraging steel used in the rings.

5.3.3. Hardness of element neck

Compressive residual stress is conventionally imparted to the surface of the sides of the neck section by means of water jet peening, in order to increase strength. New conditions were set for the developed elements so as to allow the surface hardness of the sides of the element necks not to exceed that of the rings, while still imparting sufficient compressive residual stress to help prevent a decline in strength.

6. Strength and Durability

6.1. Element Strength

To verify the strength of the developed elements, their performance in unit fatigue strength tests was compared with that of the current elements (Fig. 11). The results of strength tests and strength calculations correspond almost exactly, with both showing a strength increase of 30% in the developed elements.

6.2. Wear Resistance of Rings

The current belt and the developed belt were subjected to a durability test using a high level of tensile stress, as would be generated at take-off in a TC-CVT. Wear at the edges of the rings was reduced by 64% in the developed belt in comparison to the current belt.

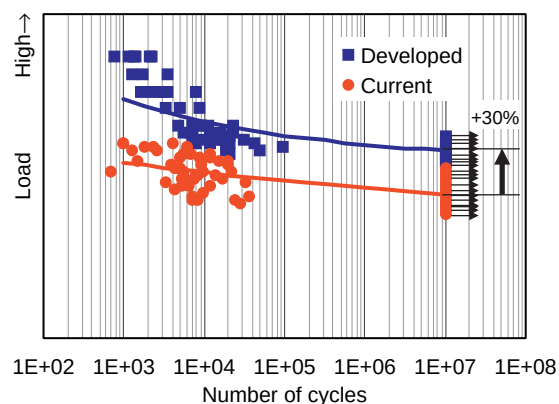


Fig. 11 Fatigue strength properties of simple element

7. Maximum Transmitted Power

Figure 12 shows a comparison of the maximum transmitted power and the maximum allowable torque of the current belt and the developed belt. The new metal pushing V-belt is able to cope with the increased torque produced by the use of a torque converter in addition to the higher levels of power and torque resulting from the evolution of the engine, with only nine layers of rings.

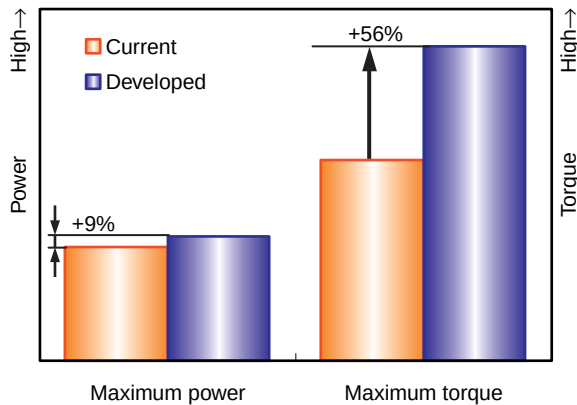


Fig. 12 Potential of newly developed V-belt

8. Conclusion

A metal pushing V-belt using nine layers of rings that can be employed in a TC-CVT has been developed. The major points of this development are as follows:

- (1) The height of the element bodies and the length of the element V-surfaces were increased, resulting in increased strength and an enhanced wear characteristic.
- (2) The high order of curvature component of the rings was reduced and the accuracy of the shape of the rings was increased, resulting in more stable ring dynamic behavior.
- (3) The hardness of the surface of the rings was increased and the difference in hardness between the surface of the rings and the surface of the sides of the element necks was optimized, increasing the wear resistance of the rings.

9. Afterword

The development of a metal pushing V-belt for a TC-CVT discussed in this paper can be characterized as a project focusing on small details. In seeking further performance enhancements even from a specification that had been considered completed, such a focus on details involves identifying further points that can be modified and ceaselessly making modifications in order to achieve further evolution.

Guided by Mies van der Rohe's phrase "God is in the details," Honda will seek to achieve further evolution of

the parts discussed in this paper in future through theoretical study of form and the development of innovative production technologies, while maintaining a close focus on the details.

References

- (1) Yagasaki, T., Aoyama, H., Saito, T., Ishii, K., Okada, Y., Arikawa, M.: Development of Metal Pushing V-Belt for Continuously Variable Transmission, Honda R&D Technical Review, Vol. 14, No. 1, p. 181-190
- (2) Arikawa, M., Shima, H.: The Configuration Evaluation Technique for CVT Steel Belt Rings, Honda R&D Technical Review, Vol. 14, No. 2, p. 57-62

■ Author ■



Tooru YAGASAKI



Hideaki AOYAMA



Masamichi HARADA



Kenji HARUE



Kenta UMETU

Development of High-performance Diesel Engine Compliant with Euro-V

Ryuta MATSUI*
Shoshi HIDAKA*

Kazuaki SHIMOYAMA*
Shigeji NONAKA*

Isao CHIBA*

ABSTRACT

Honda has developed a 2.2 L 4-cylinder turbocharged diesel engine that has achieved high power, low fuel consumption, and ultra low emissions. This is a second-generation diesel engine, following Honda's first diesel power plant for automobiles launched in 2004. The newly developed engine has realized larger reductions in exhaust emissions, enabling compliance with Euro-V standards, as well as enhancements in output and in noise and vibration (NV) reduction, while also maintaining fuel economy equivalent to that of the previous engine. A 180 MPa common-rail system was adopted and the shape of the combustion chamber was optimized for even lower exhaust emission performance. A recently developed, highly efficient variable nozzle turbine (VNT) was adopted and intake and exhaust system performance has been upgraded for enhanced output. Where the maximum output and torque of the previous model engine were 103 kW/340 Nm, these figures have been raised to 132 kW/380 Nm, signifying a larger increase. NV performance has become a concern for diesel-powered passenger vehicles. The structural response of the cylinder block has been bettered by optimizing the cylinder block structure, and a new chain drive-line layout and chain cover structure capable of reducing vibration and noise have been developed. As a result, the NV performance of this engine is better than that of previous diesel engines.

1. Introduction

Within the context of growing worldwide concern for environmental issues, the demand for diesel engines that have a large impact in CO₂ reduction and high power performance has been expanding rapidly, particularly in Europe. Diesel power performance has been rising to that on par with gasoline engines. Meanwhile, however, the European exhaust emissions standards that are scheduled to take effect in 2009 (EURO-V) will be much more rigorous than the current EURO-IV standards.

The first diesel engine Honda developed to be manufactured in-house was developed for use in the ACCORD in 2003, and it complied with EURO-IV at that time, before those standards were enforced.^{(1) - (3)} This model subsequently saw wider use in the CR-V, CIVIC, and FR-V, as well, and was well received by the market. During that time, a diesel particulate filter (DPF) system capable of reducing emissions of particulate matter (PM) to lower levels was also developed and put into use.⁽⁶⁾ Following those developments, Honda has developed a second-generation diesel engine that achieves greatly

enhanced power performance and reduced exhaust emissions as well as reduced noise and vibration. This paper reports on the development concept, the achieved performance, and the technology that was applied to that end.

2. Development Concept

The concept for the present engine was to maintain the fuel economy characteristics of previous models while also achieving top-class power performance and EURO-V compliance. Controls on exhaust emissions have become particularly rigorous in recent years, and the new standards will require NO_x approximately 28% lower and PM 80% lower than EURO-IV. Achieving these levels called for the development of NO_x reduction technology using highly precise combustion control as well as the enhancement of PM reduction technology through use of the DPF developed in 2005. Figure 1 shows recent trends in exhaust emission regulations. Previous models had already earned good reputations for their handling of the noise and vibration typical of diesel engines, and the goal

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for this model was to attain performance that was still one rank higher. One of the issues was combustion noise, which had to be reduced in balance with the reduction in exhaust emissions. This necessitated still more advanced control technology. In structural systems, vibration control and noise prevention also became necessary in the cylinder block and chain case in particular.

The following three items were pursued as the core technologies for achieving the above objectives.

- (1) Lightweight, highly rigid, quiet engine frame
- (2) Highly precise combustion control
- (3) Highly efficient exhaust processing system

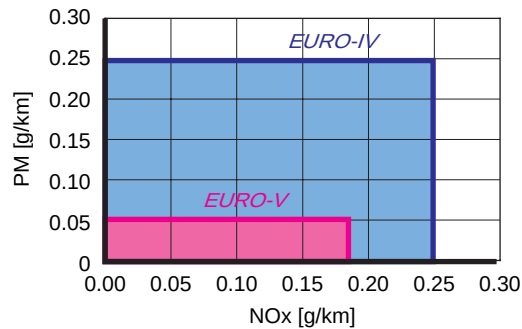


Fig. 1 Exhaust emission regulations

3. Overview of Engine

3.1. Overview of Engine and Major Specifications

The maximum power and maximum torque of this engine have been increased to 132 kW and 380 Nm, compared to 103 kW and 340 Nm in the previous model. The increased maximum combustion pressure that accompanied the upgraded power output was handled by reinforcing the strength of the cylinder block, the cylinder head, and other engine frame parts.

A third-generation common-rail system, manufactured by Bosch, that has a piezoelectric injector with a maximum injection pressure of 180 MPa were adopted for the fuel injection system in order to balance the requirements of increased power output and compliance with EURO-V regulations.

The DPF system developed and put on the market in 2005 was further enhanced and included as standard equipment to make the exhaust after-treatment system comply with EURO-V regulations. A layout was adopted that places the DPF directly under the turbocharger with the oxidation catalyst. This enabled enhancement of DPF regeneration performance. The engine also incorporates a new front exhaust with a view to packaging, including for installation on other vehicle models. An external view of the engine is shown in Fig. 2, and the main specifications are in Table 1.

Table 1 Main specifications of i-DTEC diesel engine

Engine	Developed model	Previous model
Cylinder configuration	In-line 4-cylinder	In-line 4-cylinder
Bore × stroke (mm)	85 × 96.8	85 × 97.1
Displacement (cm ³)	2197	2204
Compression ratio	16.3	16.7
Valve Train	DOHC 4 valves	DOHC 4 valves
Fuel injection system	180 MPa common rail	160 MPa common rail
Maximum power [kW/rpm]	132/4000	103/4000
Maximum torque [Nm/rpm]	380/2000	340/2000

3.2. Main Elements of Engine Structure

The same advanced semisolid casting technology (ASCT) used to fabricate the cylinder block for the previous model was adopted and closed-deck block structure for the offset cylinder layout was realized in this engine. The rise in combustion pressure from the higher power was handled by developing cylinder head gaskets with a new structure and upgrading the strength of the area around the bearing caps.

The basic design for the cylinder heads is like the previous model in that it has a layout of in-line valves and center injection. As shown in Fig. 3, it was also made lighter and more compact by lowering the height of the cylinder head while also enhancing productivity and assuring strength. In order to support the increased combustion pressure, the thickness of the gasket was increased and particular efforts were made to assure that

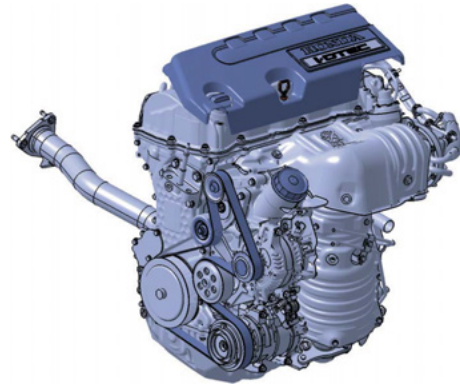


Fig. 2 External view of i-DTEC diesel engine

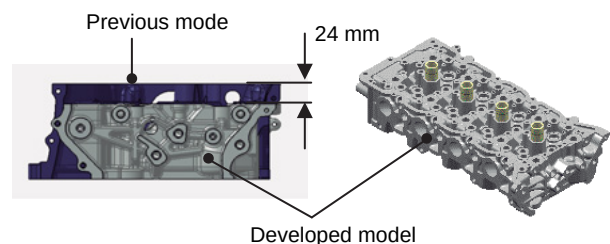


Fig. 3 Comparison of cylinder head configuration

the interior structure of the water jacket would have adequate strength to sustain high power output by conducting structural analysis using computer-aided engineering (CAE) to find ways of reducing stresses.

Figure 4 shows this engine valve assembly layout and vacuum pump location, compared to the previous model. As will be explained below, this design seeks to reduce chain meshing noise and achieve greater compactness by adopting a two-axis layout for the valve drive assembly in which the vacuum pump is driven by an Oldham coupling from the transmission end of the exhaust cam shaft, instead of the three-axis layout for the vacuum pump drive in the previous engine.

3.3. Fuel Injection System

The fuel injection system uses a piezo-electric injector with a maximum injection pressure of 180 MPa in order to reduce exhaust emissions by achieving a balance between enhancement of spray characteristics and greater power output. The injector body contains an integrated actuator formed by alternating layers of piezo-electric elements and electrodes. The moving parts that operate during injection are therefore more compact than in a solenoid type injector, enabling reduction of the total height of the cylinder head. Figure 5 shows a general view of the piezo-electric injector.

The higher responsivity of the actuator is reflected

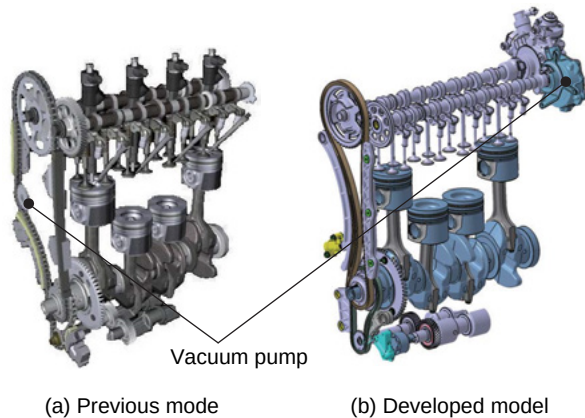


Fig. 4 Schematic diagram of drive train system

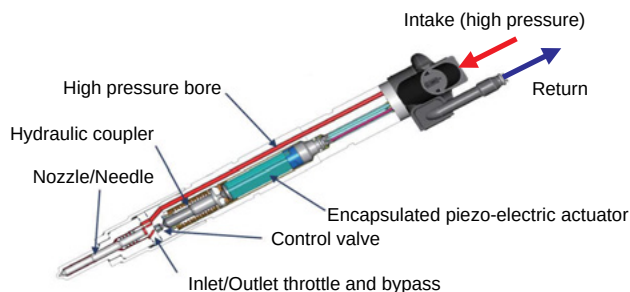


Fig. 5 Drawing of Bosch piezo-electric injector

more efficiently in the injection characteristics, yielding a nearly rectangular injection rate waveform. The time needed to activate the actuator and reach maximum injection volume has been shortened approximately 40% compared to the previous model. This has increased the possible range for microinjection fuel volume and interval settings during multiple injection, which is important for the reduction of both exhaust emissions and NV. These measures have enabled higher precision combustion control.

4. Main Technical Details

4.1. Combustion Technology

Figure 6 shows an overview of the exhaust emissions objectives achieved.

The EURO-V regulations apply more rigorous controls, particularly on PM and NOx emissions. Reduction of PM calls for the air utilization rate to be enhanced, and reducing NOx emissions calls for combustion temperatures to be lowered. In order to reduce PM emissions, therefore, the combustion chamber was made the reentrant type, which has a shallower, more dish-like shape than the previous model.^{(4),(5)} This is intended to achieve a uniform air-fuel mixture by spreading the fuel spray, and to limit the dispersion of fuel outside the combustion chamber might cause by the longer period of fuel injection occasioned by higher power output. A balance between higher power output and NOx reduction was also sought by reducing the compression ratio to 16.3 from 16.7 for the previous model and by lowering the combustion temperature. Figure 7 shows the shape of the combustion chamber.

The injector nozzle was positioned at the center of the combustion chamber. The number of nozzle holes was

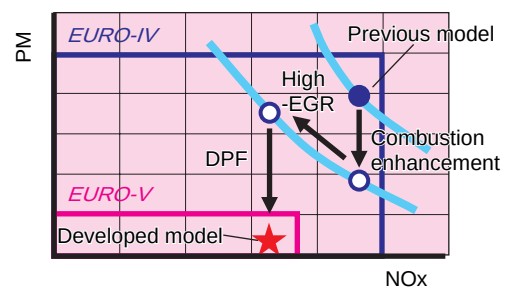


Fig. 6 Enhancement of exhaust emissions

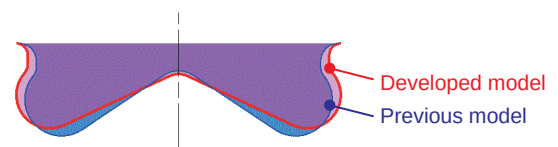


Fig. 7 Shape of combustion chamber

Table 2 Specifications of injection system

Specification	Developed model	Previous model
Injector specification		
Type	Piezo-electric	Solenoid
Max. injection pressure [MPa]	180	160
Number of holes	7	6
Hole Dia. [mm]	$\phi 0.12$	$\phi 0.13$
Spray angle [deg]	156	153
Type of sac	Micro sac	Micro sac
HP-pump specification		
Type	V	Radial
Number of plungers	2	3
Bore $\times$ stroke [mm]	$\phi 6.5 \times 6.0$	$\phi 6.5 \times 6.8$
Type of cam	2-lobe	Eccentric
Driving speed	1/2 crank speed	5/6 crank speed
Flow control	Suction control	Suction control

increased from 6 in the previous model to 7 holes, and the spray cone angle was broadened. This served to enhance the spray atomization and the air utilization rate, achieving reductions in PM and HC emissions. The nozzle hole diameter was decreased while the number of nozzle holes was increased in order to keep the total nozzle hole area generally equivalent to the previous model. This achieved a balance between enhancement of power output and reduction of engine-out exhaust emissions. Table 2 shows the injector nozzle and fuel pump specifications of the developed model in comparison with the previous model.

A key factor in achieving reduction of exhaust emissions and enhancement of fuel consumption, and further in achieving reduction of combustion noise, is setting the optimum in-cylinder flow according to engine operating conditions. The intake manifold has been fitted with a continuously variable swirl control valve (SCV) as in the previous model in order to generate an optimum swirl under various conditions. For the present SCV control system, the vacuum control used previously was changed to electrical control in order to support combustion control with greater response and higher precision.

The exhaust gas recirculation (EGR) system, which is important for NO_x reduction, has been combined with a highly efficient EGR cooler in order to raise the EGR rate. It also employs an EGR cooler bypass system that has a switchover mechanism to realize stable combustion at lower EGR gas temperatures. The adoption of an electrically operated EGR valve and a tournament-type arrangement of ports for EGR gas distribution also support enhanced control response and decreased inter-cylinder variation. The increase in PM emissions brought on by enhancement of the EGR rate was addressed through adoption of the DPF system.

The use of these technologies achieved compliance with the EURO-V exhaust emissions regulations.

The distinctive combustion noise of the diesel engine was addressed using multiple injection, which is the

advantage of the common rail system. This approach varies the number and pattern of pilot injections in accordance with operating conditions and environmental conditions.

Figure 8 shows the engine power curve at full load power. Increasing the intercooler size and placing the radiator at the front enhanced fresh air cooling performance. In combination with the higher injection rate resulting from the increase in fuel injection pressure noted above, this has enabled greater power output. A newly developed VNT was adopted for the exhaust system in order to perform highly efficient conversion to supercharged energy. This realizes high-level supercharging and response while also enabling balanced distribution of EGR volume and optimum fresh air volume according to operating conditions in the partial load range, thus enabling reduction of exhaust emissions. Figure 9 shows a general view of the VNT. The DPF diameter was also increased for the purpose of reducing pressure drop.

4.2. Exhaust Gas After-treatment Technology

In order to reduce exhaust emissions, it is important to enhance the performance of the exhaust gas after-

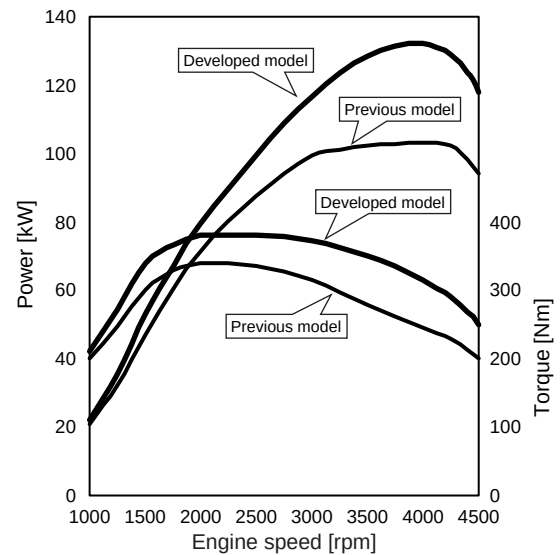


Fig. 8 Power curve of i-DTEC engine

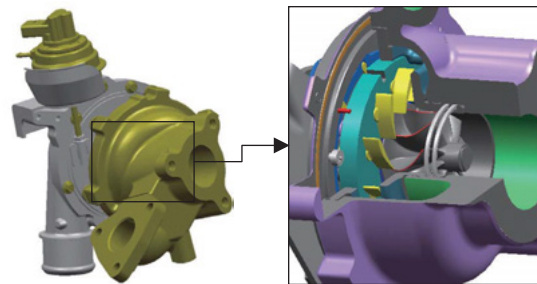


Fig. 9 Variable nozzle turbocharger

treatment system and to do so in conjunction with development of the combustion technology described above. It is important to enhance the PM regeneration performance of the DPF and have faster light-off of the catalyst during cold starts of the diesel engine, which has particularly low exhaust gas temperatures.

The layout of the exhaust after-treatment system for this engine has a diesel oxidation catalyst (DOC) with an air gap in the low heat-mass structure located directly beneath the turbocharger. Immediately behind it is the DPF. This realizes a balance between shortening the time to light-off of the catalyst during the air-warming process and enhancing DPF regeneration performance.

4.2.1. Air gap oxidation catalyst

The oxidation catalyst has a two-layered structure with an air gap in between. This achieves fast, stable catalyst light-off by limiting the drop in catalyst temperature while the air is cool immediately after starting the engine. Figure 10 shows a general view of the air gap structure.

4.2.2. DPF system

Figure 11 shows a layout diagram of the exhaust system.

This engine has the DPF placed immediately behind the DOC so as to limit the cooling of exhaust gases on their way to the DPF during regeneration. This enabled a temperature reduction of nearly 100°C in the DOC with

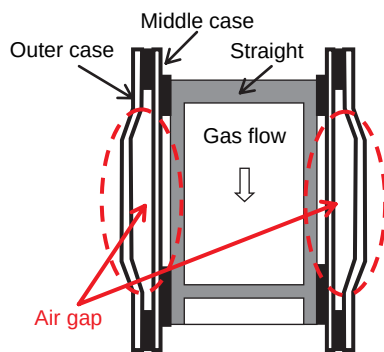


Fig. 10 Close coupled DOC with air gap

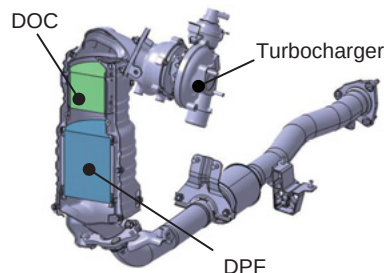


Fig. 11 Close coupled DOC and DPF

the DPF temperature remaining the same. Figure 12 shows the DPF temperature characteristics during regeneration. Taking advantage of the impact of this DOC temperature reduction enabled the DPF temperature to be raised nearly 30°C while limiting the rise in DOC temperature during regeneration. Greater PM combustion speed, reduction in the amount of precious metal, and limitation of deterioration in exhaust gas purification performance have been achieved as a result. Lowering of the exhaust system heat mass before the DPF has also enabled shortening of the warm-up period during regeneration.

Figure 13 shows the time required for regeneration and the impact of reduction in total post injection quantity. Compared to the previous model, this engine has achieved a 19% shortening of regeneration time and 37% reduction in total post injection quantity.

4.2.3. Enhancement of DPF control

The system utilizes post injection in DPF regeneration. During regeneration, the diesel oil component of the fuel mixes with the engine oil (referred to below as “oil dilution”), may be causing concern about reliable

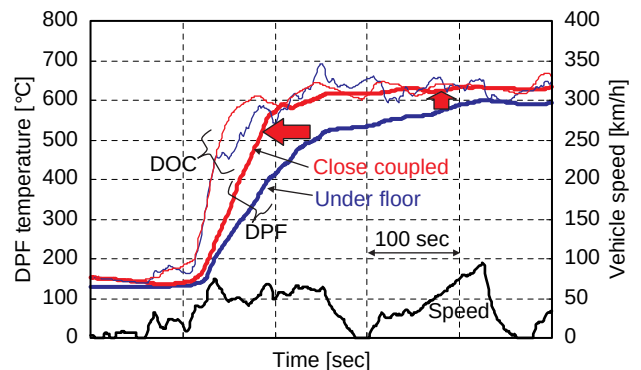


Fig. 12 Effect of close coupled DPF for DOC and DPF temperature

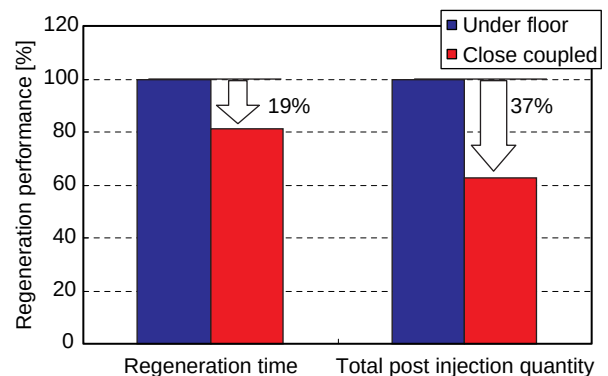


Fig. 13 Effect of close coupled DPF for regeneration performance

durability. With the previous model it was necessary to assume the worst case for conditions of use and limit post injection quantity. With the present engine, however, the cause of dilution and the evaporation mechanism have been understood so that the level of dilution can be computed in the ECU, enabling enhancement of regeneration performance while maintaining reliability. This has yielded regeneration performance in the top class.

4.3. Noise and Vibration (NV) Reduction Technology

With the roller chain generally employed in diesel engines, the reduction of chain meshing noise is important for assuring quietness. Measures taken in the developed engine, including the layout change, have reduced this chain meshing noise. The increase in noise that occurs with increased power output has also been addressed by means of structural systems, as detailed in the following.

4.3.1. Reduction of chain noise

The cam drive chain formerly had a three-axis layout with a sprocket-driven vacuum pump. This was changed to a two-axis layout driven by an Oldham coupling from the exhaust cam shaft. As a result, the large vibrating force generated when the small-diameter sprocket wheel meshed with the chain no longer acted on the vacuum pump shaft, and this reduced the meshing noise from the cam drive chain.

The noise radiating characteristics of the chain case are a major factor influencing the chain noise mechanism. The measures applied to the developed engine include giving the case a dimpled shape and increasing the number of layers in the vibration damper plate in order to enhance its vibration damping performance. This is yielding a reduction effect. Figure 14 shows the shape of the chain case.

Implementation of these measures has resulted in a reduction in chain meshing noise, including on the oil pump drive side, compared to the previous model. Figure 15 shows the levels of chain noise achieved.

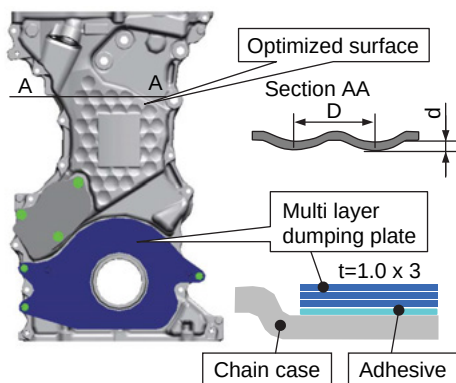


Fig. 14 Optimized chain case

4.3.2. Reduction of noise radiation

The rise in output power is accompanied by increased combustion pressure. This tends to increase combustion excitation force, which is a source of radiant noise, and thus is a factor in worsening noise. These issues were addressed by optimizing the shape of the crankshaft, the cylinder head, the cylinder block, and other such components with the goal of assuring strength and rigidity as well as enhancing structural damping. Measures were also taken, as described above, to optimize the surface shape of the chain case and the oil pan. In combination with the combustion noise reduction effect from multiple injection, these measures achieved noise levels equivalent to those of the previous model even while output power was being raised by 40 Nm. Figure 16 shows the noise radiation levels that were achieved.

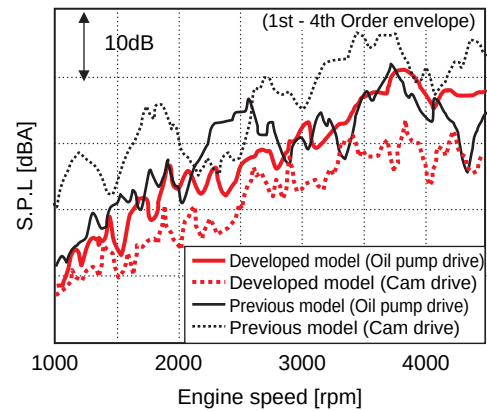


Fig. 15 Effect of developed chain drive system and chain case for chain drive noise reduction

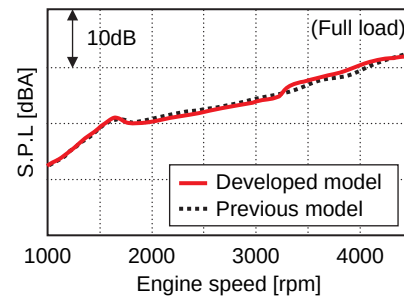


Fig. 16 Comparison of engine radiation noise

5. Conclusion

Honda has developed a second-generation diesel engine that achieves good exhaust emissions performance that both reduces CO₂ emissions and enables compliance with the EURO-V exhaust emissions regulations. In addition to this high level of environmental performance, the engine simultaneously achieves high power

performance and quietness. The developed engine thus is highly capable of providing users with satisfying driving pleasure. Development of this engine yielded the following results:

- (1) A new combustion chamber shape and a 180-MPa common rail system were adopted, and a highly efficient exhaust gas after-treatment system was incorporated. With this combination, the new engine has already achieved compliance with EURO-V emissions standards.
- (2) High power performance has been achieved while reducing exhaust emissions by reducing the compression ratio, employing a highly efficient VNT, and enhancing the exhaust system.
- (3) Performance on the higher level is assured with regard to quietness and fuel consumption.
- (4) Upgraded DPF regeneration performance under cold water and low load operating conditions together with engine oil dilution management have realized an after-treatment system that provides higher performance and higher reliability.

References

- (1) Abe, T., Nagahiro, K., Aoki, T., Minami, H., Kikuchi, M., Hosogai, S.: Development of New 2.2-liter Turbocharged Diesel Engine for the EURO-IV Standards, SAE Paper, No. 2004-01-1316(2004)
- (2) Abe, T., Nagahiro, K., Tsuji, Y., Tsukimura, K., Osaki, K., Ozawa, K.: Development of a New Turbocharged Common Rail Diesel Engine, Honda R&D Technical Review, Vol. 16, No. 1, p. 103-110
- (3) Kikuchi, M., Okawara, K., Miyake, T., Goto, S., Matsui, K., Koide, S.: Development of New Turbocharged Common Rail Diesel Engine, Journal of Society of Automotive Engineers of Japan, Vol. 59, p. 124-127(2005)
- (4) Kanda, T., Kobayashi, S., Matsui, R., Sono, H.: Study on Euro IV Combustion Technologies for Direct Injection Diesel Engine, SAE Paper, No. 2004-01-0113(2004)
- (5) Kanda, T., Kobayashi, S., Matsui, R., Sono, H.: Combustion Technologies for Euro IV-compliant Direct Injection Diesel Engine, Honda R&D Technical Review, Vol. 16, No. 2, p. 139-146
- (6) Chiba, I., Kaneko, I., Matsui, R., Ishihara, Y., Matsukado, R.: Development of DPF System for the EURO-IV-compliant Diesel Engine, Journal of Society of Automotive Engineers of Japan, No. 103-05, p. 15-18(2005)

■ Author ■



Ryuta MATSUI



Kazuaki SHIMOYAMA



Isao CHIBA



Shoshi HIDAKA



Shigeji NONAKA

Development of 2.4 L i-VTEC Gasoline Engine for 2008 Model Year ACCORD

Ryota KAWAGUCHI*	Kazuya YAMAMOTO*	Takashi KAYABA*
Sadao KOJIMA*	Takahiro SHINKAI*	Koichiro ASAME*

ABSTRACT

A 2.4 L in-line 4-cylinder i-VTEC gasoline engine for the 2008 model year ACCORD was developed with the aim of balancing high output with low exhaust emissions.

The VTEC mechanism of this engine with the i-VTEC system was developed to switch between cams on the intake and exhaust valve sides at different engine rpms. On the exhaust side, at low speeds it operates with one exhaust valve inactive to increase the flow motion of the exhaust gas and promote after-burning. This raises the catalyst temperature. Operating with one valve inactive also reduces exhaust interference and increases higher low-speed torque. On the intake side, the variable camshaft phasing mechanism, together with the variable valve timing and lift, enable optimum valve timings to be set for the low-and high-speed engine rpm. In addition to this new VTEC mechanism, the developed engine also adopted a cylinder head with exhaust manifold, a close-coupled catalytic converter, and other new technology. The result is an engine that achieves maximum output of 142 kW, maximum torque of 220 Nm, and power performance at the top level in its class. At the same time, this engine also realizes a balance between low fuel consumption and low exhaust emissions for U.S. LEV II SULEV regulation on par with that of previous models.

1. Introduction

As engine development addresses the needs of global environmental protection and energy conservation, the enhancement of engine drive performance has become an important issue.

Honda has developed a new-generation engine employing such technologies as a variable cylinder management system that makes use of cylinder deactivation mode, a direct-injection lean burn system, a reduction in the total engine displacement through the addition of a turbocharger, and the like.

The previous engine had experienced issues in achieving a balance of high power performance and environmental performance at a high level.

The present engine achieves high engine performance by taking a previous 4-cylinder i-VTEC system⁽¹⁾ with a variable camshaft phasing mechanism (VTC) combined with VTEC as the base, then reducing the intake and exhaust resistance and increasing the compression ratio for

higher engine performance with a maximum output of 142 kW.

Exhaust emissions were reduced by the use of a cylinder head with exhaust manifold, a close-coupled catalytic converter, and high-precision air-fuel ratio control. A new VTEC mechanism, high-ignitability plugs, and a new fuel injector were also developed and the catalyst was enhanced to achieve high engine performance. The engine thus achieved reduced exhaust gas emissions for U.S. LEV II SULEV⁽²⁾ regulation as well as a high-level balance between power performance and environmental performance. This paper provides an overview of the structure and concept of this new model engine and of the technologies applied to it.

2. Development Goals

The aim of the engine for the new model ACCORD is to address advanced emissions requirements as a matter of social responsibility while also achieving outstanding

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Table 1 Engine specifications

Engine code	K24A (Developed model)		K24A (Previous model)	
Cylinder configuration	In-line 4-cylinder		In-line 4-cylinder	
Bore × stroke (mm)	87 × 99		87 × 99	
Displacement (cm ³)	2354		2354	
Compression ratio	10.5 : 1		9.7 : 1	
Valve train	DOHC i-VTEC		DOHC i-VTEC	
VTEC Type	Inlet	Low-speed / High-speed	1-valve operation	
	Exhaust	1-valve operation	N/A	
Number of valves	4 per cylinder		4 per cylinder	
Valve diameter (mm)	Inlet	36	35	
	Exhaust	31	30	
VTC angle (deg)	50		25	
Intake manifold	Resin with glass fiber		Aluminum alloy	
Exhaust manifold	Integrated with cylinder head		Double stainless steel pipe	
Oil pan	Aluminum		Steel plate	
Catalytic converter (L)	Close-coupled (1.0) + under-floor (1.0)		Under-floor (1.0 + 1.0)	
Recommended gas	Unleaded regular (RON 91)		Unleaded regular (RON 91)	
Max. power (kW[PS]/rpm)	142 [193] / 7000		125 [170] / 5800	
Max. torque (Nm[kgm]/rpm)	220 [22.4] / 4400		220 [22.4] / 4000	

power performance. The development concept of “The World’s BEST! Highest Output & Lowest EM L4 Engine” had the following objectives:

- (1) Output of 142 kW with regular gasoline
- (2) Compliance with U.S. LEV II SULEV exhaust emissions regulations
- (3) Fuel consumption at the top level in its class
- (4) Quieter operation

3. Overview of Engine and Major Specifications

Table 1 shows the specifications of the new model engine and the previous model. Figure 1 shows an exterior view of the new engine.

The developed engine was engineered to run at higher speed than the previous model. Various technologies were adopted for the purpose of high engine performance, including optimized valve timing, a higher compression ratio, higher diameter intake and exhaust valves, and the like.

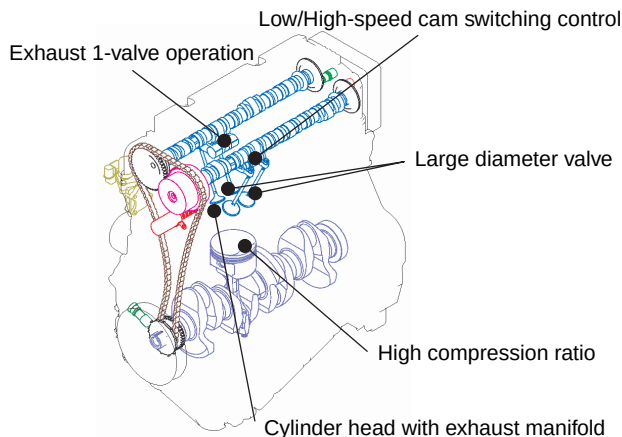


Fig. 1 New application technologies for developed K24A engine

4. Power Performance

4.1. Power Performance

The power characteristics of the new model engine are shown in Fig. 2.

Measures employed to give this engine enhanced performance include higher speed, optimized valve timing, a higher compression ratio, higher diameter intake and exhaust valves, and the like. The adoption of M12 long reach spark plugs and a piston oil jet also reduce knocking to enable 142 kW of output and 220 Nm of torque.

4.2. Technology for Higher Engine Performance

The previous 4-cylinder engines that used a cylinder head with exhaust manifold encountered obstacles to higher engine performance because of exhaust interference. Figure 3 shows the results of simulation analysis. The results from simulation of pressure distribution in the exhaust ports from the commencement of exhaust to intake in the No. 1 cylinder show that the pressure in the No. 1 cylinder ports increases again in the area of overlap between exhaust and intake strokes in that cylinder. An exhaust gas simulation conducted to analyze the causes of this showed that the exhaust from cylinder No. 3 moves to the side of cylinder No. 1. As a result, the pressure in the cylinder No. 1 exhaust port increases so that a scavenging effect is not obtained. A similar phenomenon was occurring in cylinder No. 4. This showed it would be necessary to give the exhaust ports shapes that would prevent the exhaust gas from cylinder Nos. 2 and 3 from interfering with the scavenging effect in cylinder Nos. 1 and 4.

The shape of the ports was optimized to help prevent interference with scavenging in cylinder Nos. 1 and 4 as

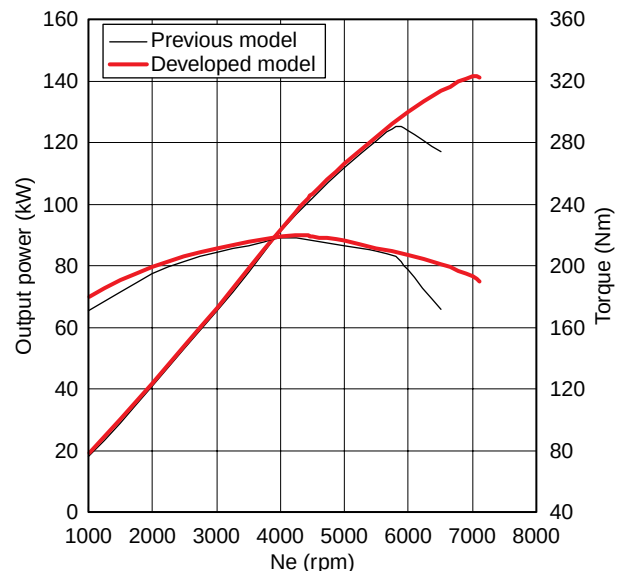


Fig. 2 Engine performance

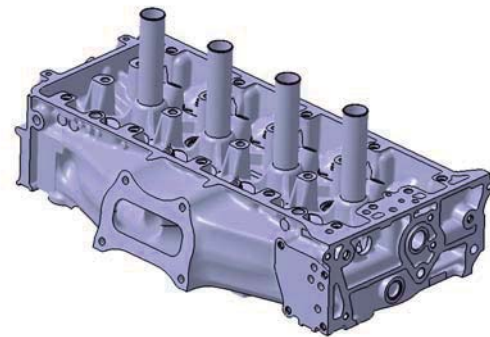
shown in Fig. 4. The angle θ was increased, L was reduced, and S was increased. Adoption of this shape achieved high engine performance.

The valve timing was handled in a similar manner so that the exhaust valves would close before the exhaust gas could move to the other side. This yielded higher engine performance even when a cylinder head with integrated exhaust manifold was used.

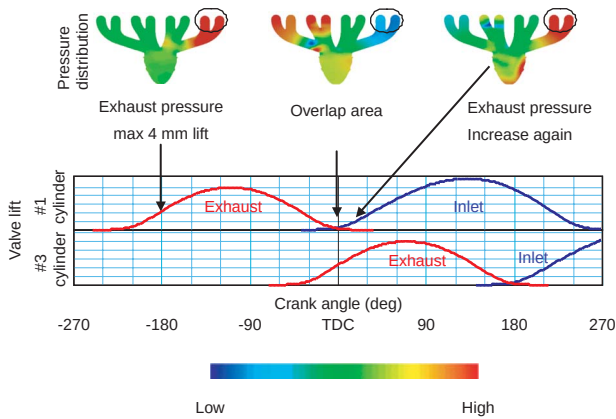
Previous measures to reduce exhaust emissions involved issues with passageway resistance in the exhaust system.

In order to support higher engine performance in this engine, however, a new catalyst that enables reduction of exhaust emissions with fewer cells was developed. The reduction in number of cells resulted in a reduction in the geometrical surface area, while the reduction in the amount of precious metals lowered the catalyst function. This was addressed by reducing the catalyst washcoat to increase the geometric surface area and controlling the pores in the catalyst layers to achieve greater dispersion of the reaction gases to the deep layers of the catalyst. Reduction of the catalyst washcoat reduced the heat mass

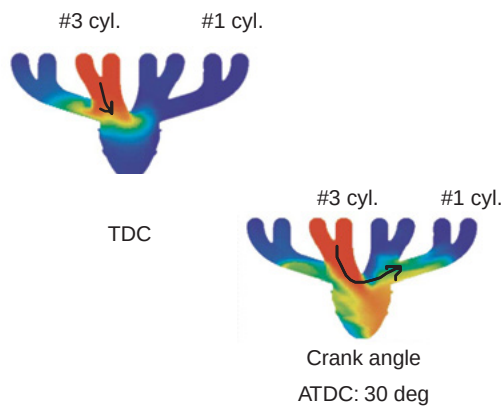
and enhanced catalyst light-off performance. As this introduces a possibility of reduced OSC performance by the catalyst, however, the Ce/Zr composite oxides were optimized, thus enhancing the heat resistance of the OSC material and raising OSC performance by the catalyst. The adoption of these technologies enabled the achievement of a high-level balance between reduced exhaust emissions and higher engine performance, and additionally enabled a 50% reduction in the amount of precious metals used compared to the previous catalyst.



(a) Overview

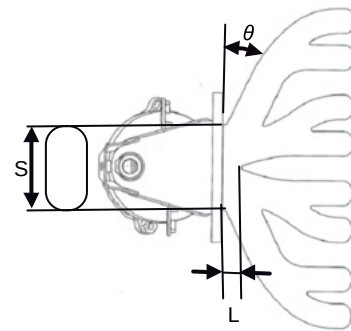


(a) Exhaust gas pressure distribution



(b) #3 Cylinder exhaust gas flow

Fig. 3 Exhaust gas flow and pressure distribution in exhaust port



(b) Section view

Fig. 4 Cylinder head exhaust port shape

5. i-VTEC System

This engine adopted the former low/high valve timing lift switching mechanism on the intake side and 1-valve operation on the exhaust side.

Figure 5 shows this engine's VTEC switching mechanism. The system needs to be able to switch between different engine speeds, with high-speed operation on the intake side and low-speed operation on the exhaust side. Their respective oil channels were therefore made independent and a new dual system of spool valves was developed to achieve three-stage switching.

For the low/high switch on the intake side, which is similar to the switch used in the previous model, Honda has for the first time employed aluminum for the three

rocker arms. A new high-strength material was developed in order to use aluminum for the three rocker arms. The newly developed material realizes a 0.21-kg weight reduction per vehicle, as well as a cost reduction.

The new engine also uses 1-valve operation on the exhaust side. Operating with one valve inactive causes a cross-flow in the exhaust gas, generating a powerful swirl. Figure 6 shows the results from exhaust gas simulation.

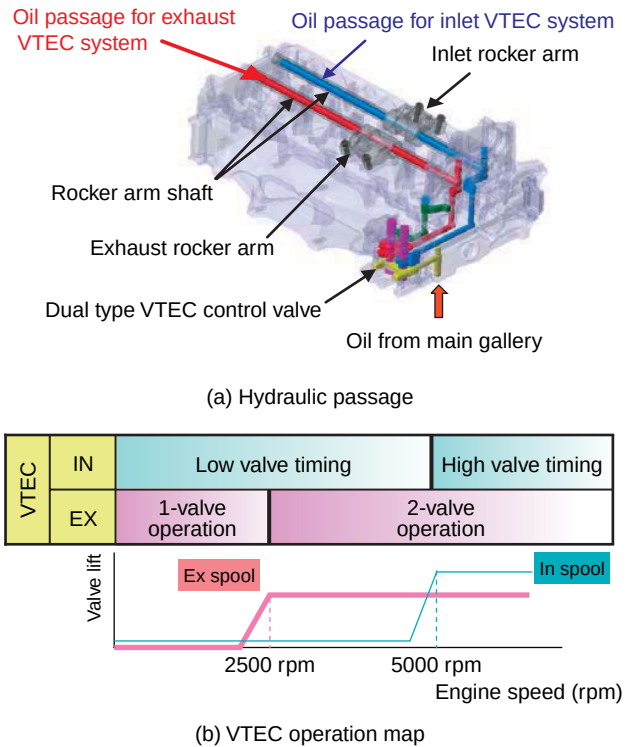


Fig. 5 VTEC unit and operation map

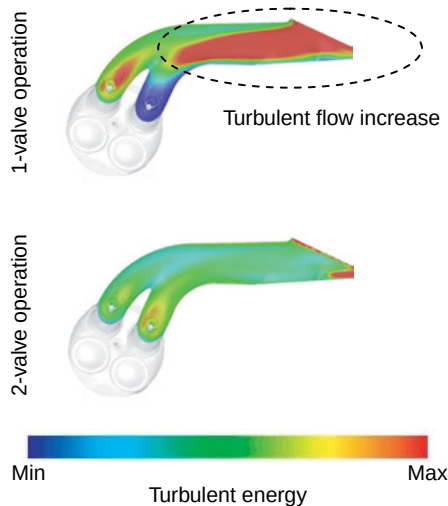


Fig. 6 Comparison of exhaust gas flow between 1-valve operation and 2-valve operation

These results indicate an increase in turbulent flow.

The results from verification of cold starting with an actual engine are shown in Fig. 7. There is an increase in the turbulent flow inside the port, promoting the oxidation reaction in the feed gases. As a result, reaction heat is generated for faster light-off of the catalyst, enabling a reduction in HC emissions.

One other effect of 1-valve operation on the exhaust side is an enhancement of volumetric efficiency in the low-speed range. Figure 8 shows a comparison of output characteristics with 2-valve operation. Operating with one valve inactive in the low-speed range reduces blowback of exhaust into the cylinder and enhances low-speed torque.

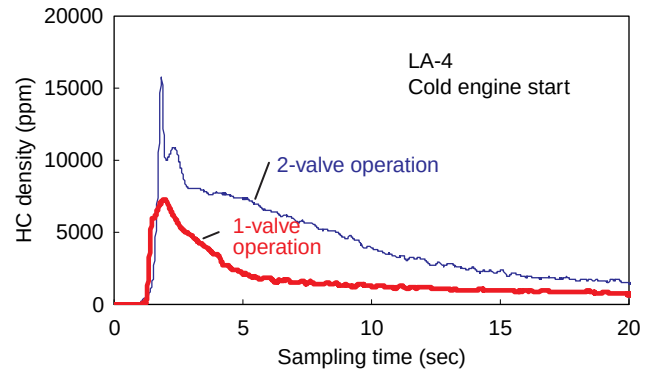


Fig. 7 Comparison of amount of HC emission between 1-valve operation and 2-valve operation

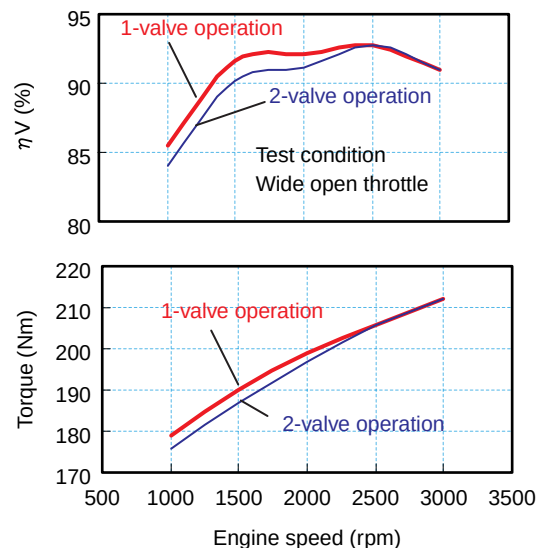


Fig. 8 Comparison of output performance

6. Low Exhaust Emissions

6.1. Exhaust Gas Treatment System

Figure 9 shows the exhaust gas purification system. One close-coupled catalytic converter is installed at the cylinder head with exhaust manifold and connected by the exhaust pipe to an under-floor converter with a three-way catalyst.

6.2. Exhaust Gas Reduction Technology

The exhaust emissions reduction technologies employed in this engine can be generally grouped into the following six categories:

(1) Reduction of heat mass for faster light-off of the catalyst

Use of the cylinder head with exhaust manifold and the close-coupled catalytic converter reduce the heat mass for faster light-off of the catalyst.

(2) More precise control of air-fuel ratio

In order to achieve more precise control of the air-fuel ratio, a universal exhaust gas oxygen (UEGO) sensor is installed upstream from the close-coupled catalytic converter and a heated exhaust gas oxygen (HEGO) sensor downstream from it. The system also employs prediction and identification-type sliding mode (PRISM)⁽²⁾ control like that of the previous model engine, thus realizing greater precision in the air-fuel ratio. The timing for fuel injection immediately after starting the engine was also optimized to reduce the amount of HCs before catalyst light-off takes place.

(3) Use of high-ignitability spark plugs for ignition timing control

This engine uses high-ignitability spark plugs, as shown in Fig. 10, that have a cylinder of precious metal welded onto the outer electrode. The ground electrode is given a needle-like shape to reduce quenching of the

flame core and enhance ignition stability. As shown in Fig. 11, this plug enables ignition retardation by 10° compared to the previous iridium plug, so that the exhaust gas temperature is 150°C higher and HCs are reduced 75%. Use of this spark plug yields a reduction in exhaust emissions amounting to a 13% NMOG reduction in LA-4 mode.

(4) More precise fuel injection

A new model injector was developed to enhance performance more than before in order to achieve a balance of greater output with lower exhaust emissions. The main goals were to enhance atomization performance and expand the possible area of injection (widen the range). Figure 12 shows the structure of this injector.

Effective means for promoting atomization include reducing pressure loss in the fuel passageway and keeping one spray from interfering with another. In order to reduce pressure loss, the fuel passageway shape and area were optimized. In order to reduce interference with the spray, a form control plate was employed and computer-aided engineering (CAE) was employed to optimize the fuel passageway and nozzle hole placement. As a result, the spray particle diameter was reduced 40% compared to the previous model and a particle diameter was achieved

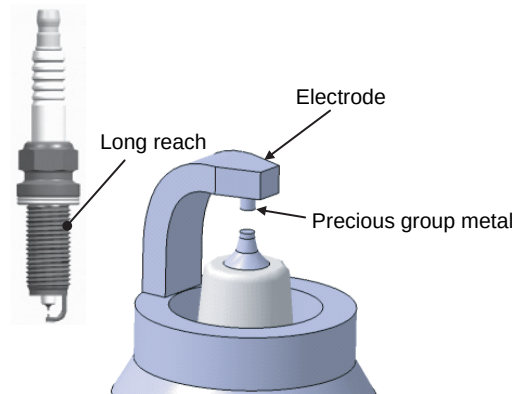


Fig. 10 High ignitability plug

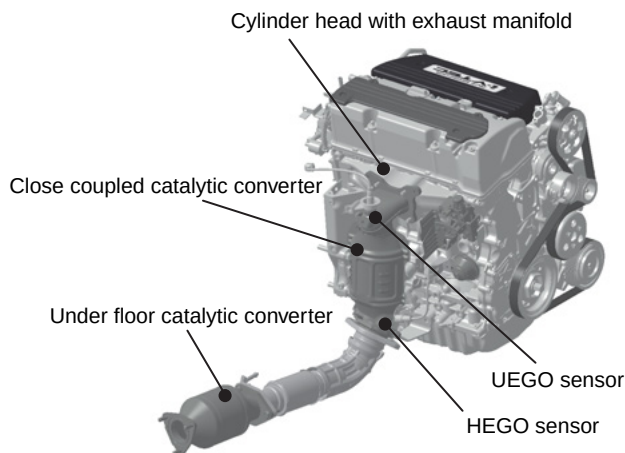


Fig. 9 Exhaust system arrangement

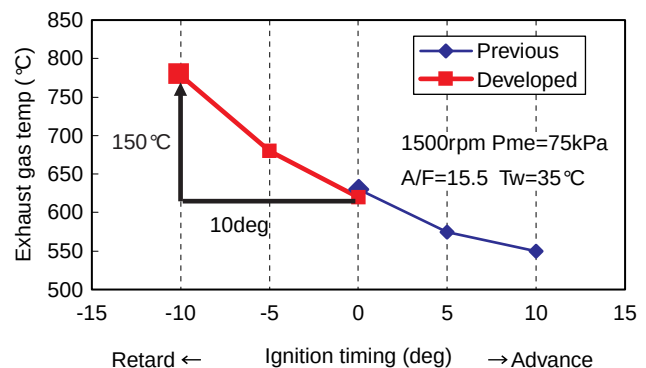


Fig. 11 Comparison of plug performance

equivalent to that formerly achieved by compressed air-assisted mechanisms.

Effective means for achieving a wider range include enhancing the valve opening and closing response. Reducing the weight of the needle valve, optimizing the stroke, and increasing the suction power yielded a 20% wider range compared to the previous model and contributed to higher engine performance.

(5) Exhaust gas flow enhancement effect

In order to maximize the purification performance and limit the deterioration of the catalyst, it is necessary to introduce exhaust gases to the catalyst in an even manner. This is also effective in raising output because it reduces loss of pressure in the exhaust gases. Figure 13 shows the shape of the front cone. The exhaust system of this engine has a catalytic converter placed immediately after the cylinder head with exhaust manifold. This layout produces a bend in the exhaust gases that emerge from the ports, making it more challenging for the exhaust gases to be introduced evenly.

Figure 14 shows an analysis of exhaust gas flow through the front cone. Exhaust gases from the No. 2 and

No. 3 ports tend to flow along the outer wall of the front cone because of an inertia force [Fig. 14 (a)]. Exhaust gases from the No. 1 and No. 4 ports pass through a sharply-angled passageway so that the gases form a spiral flow at the front cone collector section and remain in a spiral flow as they pass on to the outer edge of the converter [Fig. 14(b)].

The gas flow characteristics shown in Fig. 14 were therefore taken into consideration in optimizing the shape of the front cone. As shown in Fig. 15, the exhaust gases

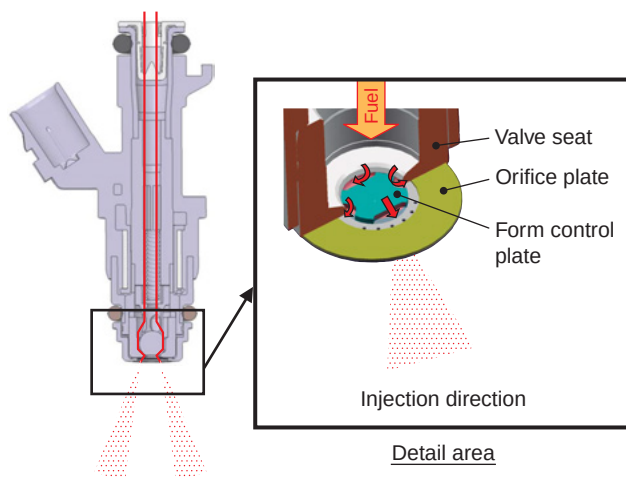


Fig. 12 Detailed structure of injector unit

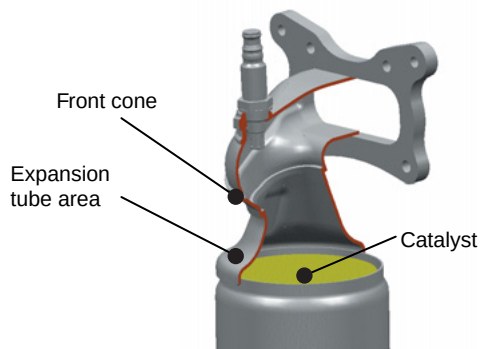
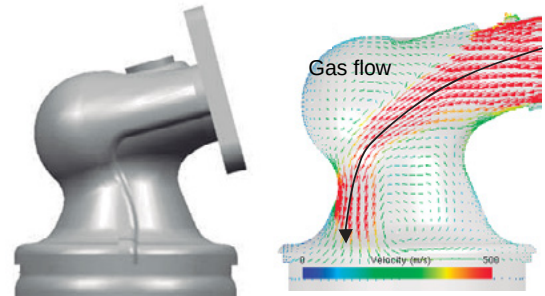
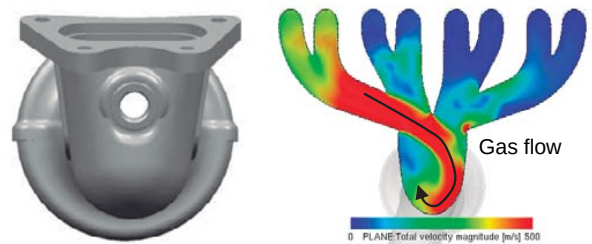


Fig. 13 Front cone section view



(a) #2, #3 port gas flow



(b) #1, #4 port gas flow

Fig. 14 Analysis of exhaust gas flow

	Start specification		Final specification	
Shape				
#1, #4				
#2, #3				

0 70
Velocity (m/sec)

Fig. 15 Optimized exhaust gas feed to catalyst

that had formerly collected at the outer edge now flowed instead through the central area so that the gases could be directed against the catalyst in an even manner.

The cone shape farther down the expansion tube area was also reshaped to be more like a bell mouth in order to reduce eddy loss at the wall surface⁽³⁾.

(6) Enhanced air-fuel ratio controllability

Figure 16 shows the state of gases from all cylinders on their exhaust stroke as they strike the UEGO sensor. It is necessary for the UEGO sensor to be able to detect the exhaust gases from every cylinder uniformly in order to enhance air-fuel ratio controllability. Computational fluid dynamics (CFD) simulations of the exhaust gases from each cylinder were conducted and analyzed in order to optimize the sensor location. The results enabled the sensor to receive exhaust gases from all cylinders uniformly, enabling more precise control of the air-fuel ratio.

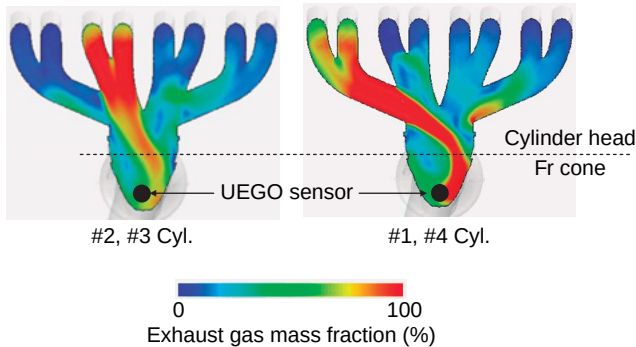


Fig. 16 UEGO Sensor arrangement optimization

7. Fuel Consumption

7.1. Engine Standalone Fuel Consumption

Figure 17 shows the brake specific fuel consumption (BSFC) for the total engine displacement. The VTC was widened from the previous 25° to 50° in order to obtain an internal exhaust gas recirculation (EGR) effect, reduce pumping loss, and enhance BSFC 4.1% in stoichiometric air-fuel ratio combustion, as compared to the previous model engine. This achieved a reduction in the engine's standalone fuel consumption.

7.2. Fuel Consumption Reduction Technology

This engine changed the operating angle of the VTC employed as before from 25° to 50°. The results of the change are shown in Fig. 18. It is apparent that the change from the previous VTC operating angle of 25° to the wider 50° causes an internal EGR effect that reduces pumping loss on the intake stroke.

Optimizing the VTC angle for every engine operating range produced the results shown in Fig. 19. Fuel

consumption was enhanced approximately 1% in U.S. LA-4 mode, which evaluates the low to medium-load operating range, and approximately 3% in highway mode. This places the engine at the top level in its class for fuel

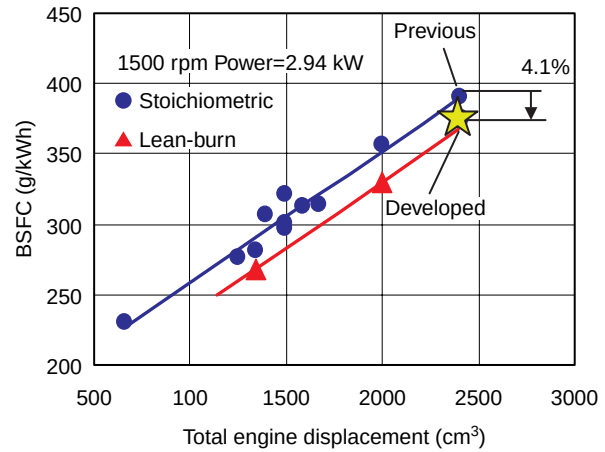


Fig. 17 Effect of BSFC decrease

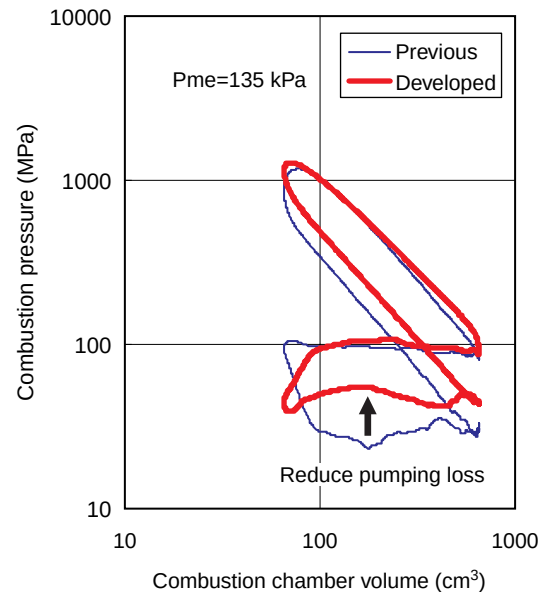


Fig. 18 Effect of new VTC angle

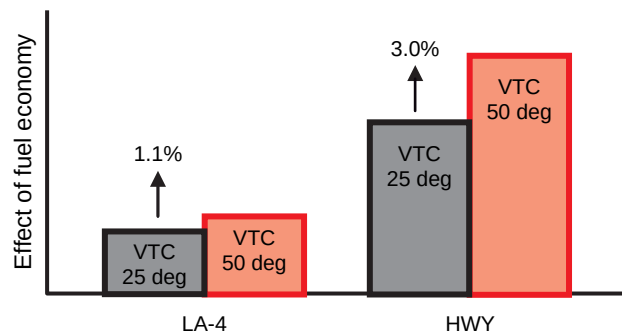


Fig. 19 Effect of fuel economy on VTC angle

consumption. The development of a new highly heat-resistant material for the converter mat in the close-coupled catalytic converter assured a stoichiometric air-fuel ratio combustion range equivalent to that of the previous under-floor converter.

8. Noise and Vibration Reduction Technology

Noise and vibration (NV) performance is a key factor in achieving enhanced comfort. Figure 20 shows how increasing single part sound radiation becomes a concern when the previous model engine is made to yield higher engine performance.

With this engine, however, an aluminum oil pan is employed and power plant rigidity is increased to achieve NV levels equivalent to those in previous models.

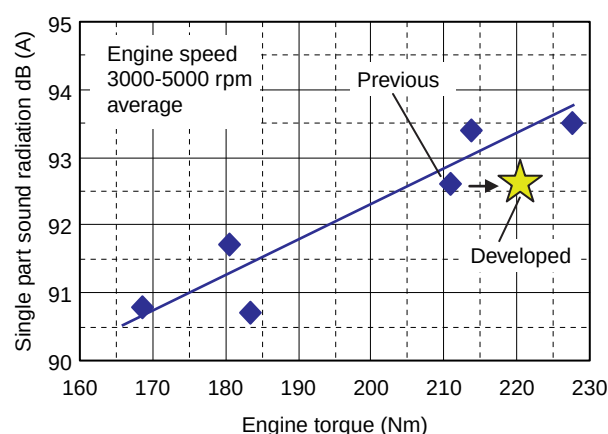


Fig. 20 Positioning of noise vibration

9. Conclusion

The below findings were obtained with the developed engine. The realization of these specific technologies enabled a high-level balance between better levels of emissions and outstanding power performance.

- (1) Analysis of the effects of exhaust interference in an in-line 4-cylinder engine enabled achievement of high power performance even with the cylinder head with exhaust manifold structure. The result was 142 kW of output and 220 Nm of torque, placing the engine at the top level in its class.
- (2) The adoption of operation with one exhaust valve inactive and optimization of the flow of exhaust gases for enhanced purification performance, the use of a high-ignitability plug, and other such technologies yielded higher engine performance than with the previous model, but still achieved U.S. LEV II SULEV regulation and reached low emissions levels equivalent to those of the previous model.
- (3) Changing the operating angle of the VTC from the

previous 25° to 50° enabled the internal EGR effect to function and reduced pumping loss, thus enhancing fuel consumption.

- (4) Increasing power plant rigidity secured quiet operation equivalent to previous levels even though higher engine performance than that of the previous model was achieved.

References

- (1) Niizato, T., Hayashi, A.: Development of New 2.0L Lean-burn Engine, Honda R&D Technical Review, Vol. 12, No. 2, p. 45-54
- (2) Kitagawa, H., Mibe, T., Okamatsu, K., Yasui, Y.: Super Ultra Low Emission System for ACCORD SULEV, HONDA R&D Technical Review, Vol. 12, No. 2, p. 37-44
- (3) Seko, K., Taga, W., Torii, K., Nakamura, S., Akima, K., Sekiya, N.: Development of 1.8L i-VTEC Gasoline Engine for 2006 Model Year Honda CIVIC, Honda R&D Technical Review, Vol. 18, No. 1, p. 8-15

■ Author ■



Ryota KAWAGUCHI



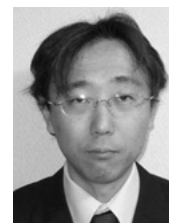
Kazuya YAMAMOTO



Takashi KAYABA



Sadao KOJIMA



Takahiro SHINKAI



Koichiro ASAME

Development of V6 Engine with New Variable Cylinder Management

Makoto SEGAWA* Kazuhide KUMAGAI* Ryuuji SATO*
Yuuichi TAMURA* Mikio FUJIWARA*

ABSTRACT

A new V6 3.5-L i-VTEC variable cylinder management (VCM) engine was developed with the goals of high output, low fuel consumption, and low exhaust emissions. This engine employs a cylinder deactivation mechanism that uses variable valve timing and lift electric control (VTEC) that enable operation with three, four, or six cylinders according to operating conditions. With the addition of 4-cylinder operation, this realizes three-mode control over the number of cylinders, one mode more than previous cylinder deactivation engines. The increase in the number of cylinder deactivation modes was combined with the new development of hydraulic circuits, a hydraulic switching mechanism, and switching control. This has enabled the instantaneous switching of operating cylinders without losses of drivability, as in previous models. This engine is being installed in the new model ACCORD, giving this vehicle output and fuel economy at the top of its class, and at the same time complying with Partial Zero Emission Vehicle (PZEV) regulations in the U.S. state of California.

1. Introduction

Increasing demands for low fuel consumption and low exhaust emissions are being placed on automobiles from the aspects of the environment and economy. An automobile engine should be able to meet these demands while also exhibiting enhanced driving performance. In order to satisfy these demands, Honda announced a V6 engine that uses a variable cylinder management system (hereafter called “VCM” system)⁽¹⁾, which was first installed in the 2003 model INSPIRE. This system is used to switch the engine between the 6-cylinder and the 3-cylinder modes. Recently, a system that has an additional 4-cylinder mode was developed so as to increase the range over which the engine could be used in a cylinder deactivation condition, and thus additionally enhance the fuel economy.

This paper describes the enhanced fuel economy of the newly developed V6 3.5-L i-VTEC VCM engine (hereafter called “VCM engine”) and the method of achieving this enhancement.

2. Development Goals

The development goal of the VCM engine is to realize low fuel consumption and low emissions on a par with

that of a small displacement engine, without impairing the output of the large displacement engine. The goals of developing environmentally friendly technology that can be used throughout the world to make next generation large displacement engines are as follows.

- (1) High output performance that is appropriate for a V6 engine
- (2) Higher fuel economy exceeding the level of this vehicle class
- (3) Compliance with PZEV regulations of the U.S. state of California

3. Engine Outline and Specifications

Table 1 shows the main specifications of this engine.

3.1. Outline of the VCM System

The VCM system employs technology that deactivates the intake and exhaust valves and simultaneously stops the fuel injection process, and, when the intake and exhaust valves are in a closed condition, puts the inside of the cylinders into a hermetically sealed state, thus reducing both pumping losses in the engine and the brake specific fuel consumption. (Fig. 1)

Compared to the conventional 3-cylinder and 6-cylinder modes, the newly developed VCM system has an

* Automobile R&D Center

Table 1 Engine specifications

Engine code		J30A8	J35Z2
Cylinder configuration		60° V-6 cylinder	60° V-6 cylinder
Bore × stroke (mm)		86 × 86	89 × 93
Displacement (cm ³)		2997	3471
Compression ratio		10.0	10.5
Valve train		SOHC VTEC	SOHC i-VTEC VCM
Number of valves		4 per cylinder	4 per cylinder
Valve diameter (mm)	Inlet	35	36
	Exhaust	30	30
Fuel		Regular	Regular
Maximum power (kW/rpm)		182 / 6250	200 / 6200
Maximum torque (Nm/rpm)		286 / 5000	336 / 5000
Fuel economy (CITY/HWY)		18/26	19/29

additional 4-cylinder mode to permit switchover between 3-cylinder, 4-cylinder, and 6-cylinder operation, thus realizing enhanced fuel economy.

The driving conditions for switchover are as follows: When the load on the engine is small, such as when the vehicle is cruising, the 3-cylinder mode is selected. In 3-cylinder mode, if the allowance drive force is insufficient, such as when driving in the gradual acceleration range or in the high vehicle speed range, the 4-cylinder mode is selected. When further drive force is necessary, the 6-cylinder mode is selected. In this way, this system selects the number of cylinders that results in the best fuel economy according to the drive force.

The VCM system utilizes the conventional Variable valve Timing and lift Electric Control (VTEC) technology. In addition, a new hydraulic passage, a hydraulic switchover mechanism, and switchover control were developed to cope with the increased number of cylinder deactivation switchover patterns.

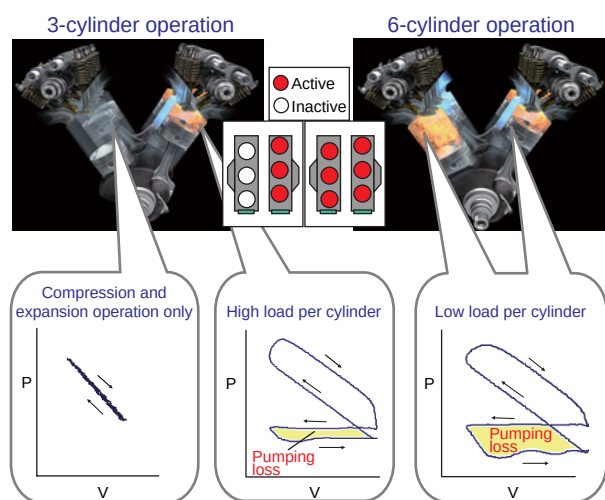


Fig. 1 Pumping loss

3.2. Basic Construction

Figure 2 shows an outline of the valve train mechanism.

The valve operation and deactivation switchover mechanism is the same two-loop hydraulic switching system as that of the conventional VCM system (Fig. 3). Each rocker arm has two hydraulic pistons. When hydraulic pressure is applied to the hydraulic piston A side, the hydraulic pistons are coupled to each other, and when hydraulic pressure is applied to the hydraulic piston B side, the pistons are decoupled.

Figure 4 shows the deactivation condition of the cylinders for each driving mode. At the bank 1 side, only one cylinder needs to be deactivating when the engine is in 4-cylinder mode, and all three cylinders need to be deactivating when the engine is in 3-cylinder mode. Consequently, an independent switching hydraulic passage for each cylinder group is necessary. For this reason, a total of four hydraulic passages, consisting of two sets of two-loop hydraulic switching passages, each consisting of two systems, are used. At the bank 2 side, only one

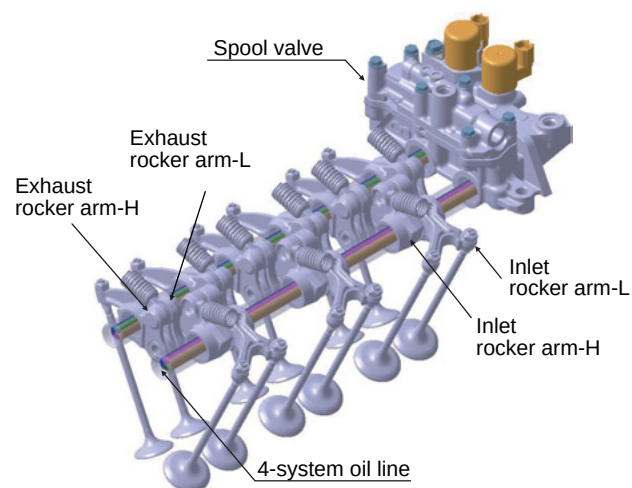


Fig. 2 VTEC VCM valve train

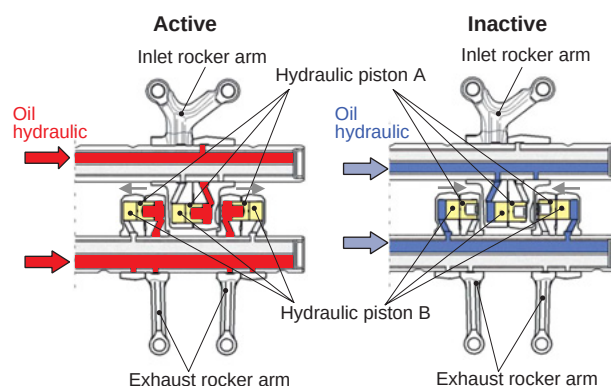


Fig. 3 2-way hydraulic passage VTEC mechanism

cylinder is switched over when the engine is in 4-cylinder mode, hence one 2-system switchover hydraulic passage is used.

In order to configure these switchover hydraulic passages, the inside of the rocker shaft at the bank 1 side is of a 4-chamber construction. Figure 5 shows the hydraulic passage.

The spool valves that controls the hydraulic pressure of this passage is installed on the end of each rocker shaft of banks 1 and 2. The spool valves installed on the bank 1 side consists of two spool valves that independently perform control of the two sets of two-loop hydraulic switching passages. If the concept of the conventional VCM were to have been simply extended, two sets of independent hydraulic passages would have been used. However, in this development, two spool valves were arranged in series as a hydraulic passage. The use of this passage configuration enables a single fault detection hydraulic switch to be used instead of two, which would have been required if independent passages had been used. Also, a 2-way solenoid valve was used as the spool valve on the downstream side. Because the 4-cylinder mode was limited to the high vehicle speed range, it could be used only in the engine speed range in which the hydraulic pressure is high, enabling a 2-way valve of simpler

construction to be used. In addition, efforts are being made toward increased compactness and lightness by partially installing the spool valve into the head cover, integrating the spool valve with the holder, rationalizing the hydraulic passage, and the like.

Furthermore, the shape of the pipes inside the 4-chamber rocker shaft was also changed so that the chambers can be sealed using only two pipes. This reduced the number of parts, which simplified the construction compared to that with four internal pipes, and also reduced the weight and cost.

3.3. Switching Control

The operating conditions of the spool valve at the bank 1 side in 6-cylinder mode, 4-cylinder mode, and 3-cylinder mode are shown in Figs.6 through 8. The passage indicated in red indicates the condition in which hydraulic pressure is applied.

To activate 6-cylinder mode, SPL-A-SOL (spool valve A solenoid) and SPL-B-SOL are switched OFF (Fig. 6).

To switch from 6-cylinder mode to 4-cylinder mode (Fig. 7), SPL-B-SOL is switched ON (1). As a result, hydraulic pressure is applied to SPOOL-VLV-B (spool valve B) (2), initiating movement in SPOOL-VLV-B. SPOOL-VLV-A applies hydraulic pressure to the operating side of the hydraulic piston of the rocker arms of the two cylinders (3). SPOOL-VLV-B applies hydraulic pressure (4), which arrived via SPOOL-VLV-A, to the deactivating side of the rocker arm of the rocker arm hydraulic piston of the remaining cylinder (5). Hydraulic pressure was applied to these cylinders when the engine was in 6-cylinder mode, but the hydraulic oil is discharged from (6). As a result, the rocker arm hydraulic piston moves to the deactivating side, and the valve deactivates. At the same time, the bank 2 side switches SPOOL-VLV-C ON, deactivation cylinder 1, and the engine goes into 4-cylinder mode.

When the engine returns from 4-cylinder mode to 6-cylinder mode (Fig. 6), SPL-B-SOL is switched OFF (1). The application of hydraulic pressure to SPOOL-VLV-B is stopped, and the hydraulic oil is discharged from (2). When the hydraulic pressure in SPOOL-VLV-B decreases, SPOOL-VLV-B is returned by spring force. As a result, the hydraulic passage of SPOOL-VLV-B switches over. Hydraulic pressure is applied to the operating side (3) and the hydraulic pressure on the deactivating side is applied from (4) to SPOOL-VLV-B, then the hydraulic oil flows through (5) and is discharged from SPOOL-VLV-A (6). As a result, the rocker arm hydraulic pressure piston moves to the operating side, and the valve operates. At the same time, the bank 2 side switches SPOOL-VLV-C OFF, and the engine returns to 6-cylinder mode.

To switch over from 6-cylinder to 3-cylinder mode (Fig. 8), SPL-A-SOL is switched ON (1). As a result, hydraulic pressure is applied to SPOOL-VLV-A (2), initiating movement in SPOOL-VLV-A. SPOOL-VLV-A

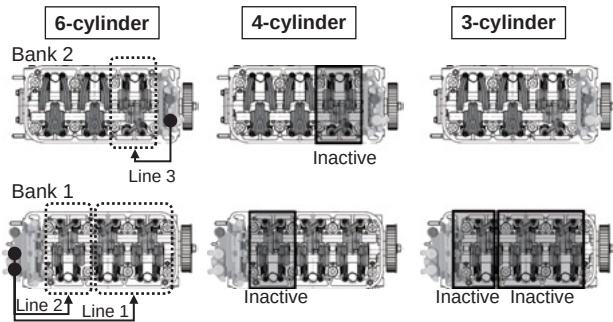


Fig. 4 State in each mode

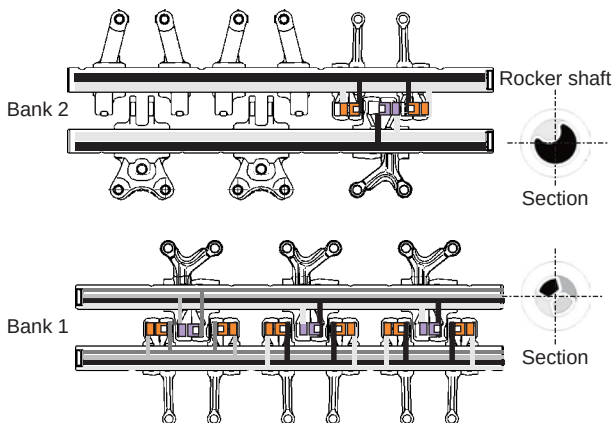


Fig. 5 View of valve train and hydraulic passage

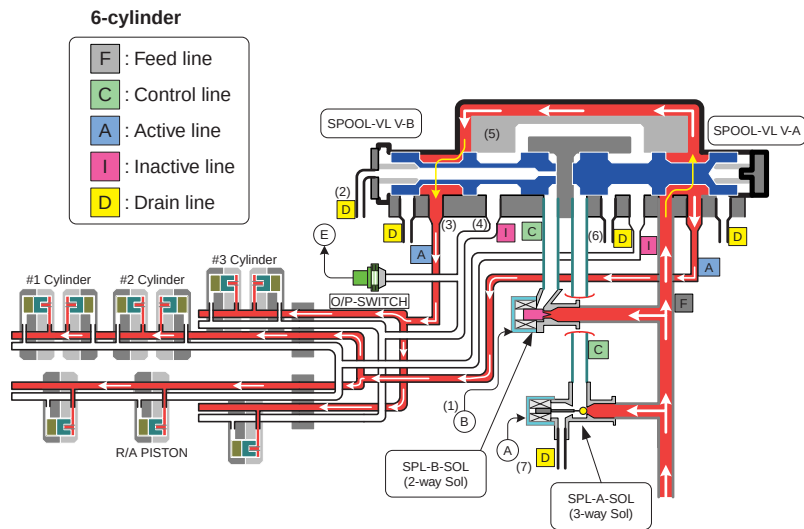


Fig. 6 6-cylinder oil-hydraulics control

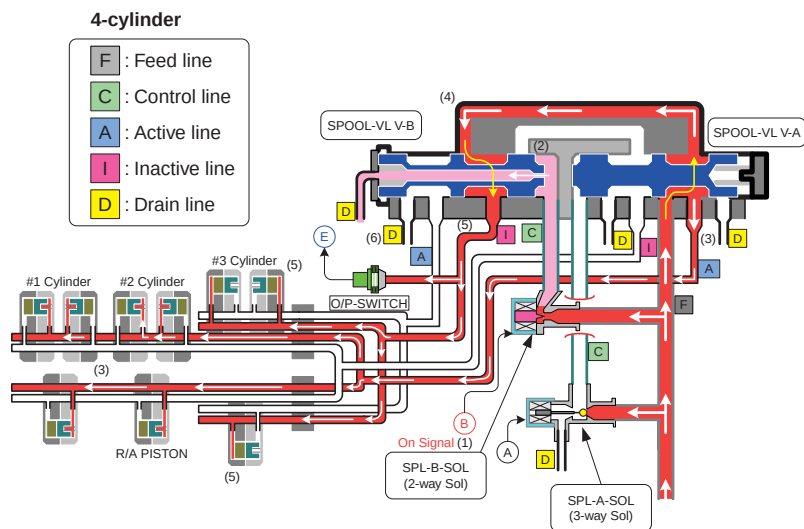


Fig. 7 4-cylinder oil-hydraulics control

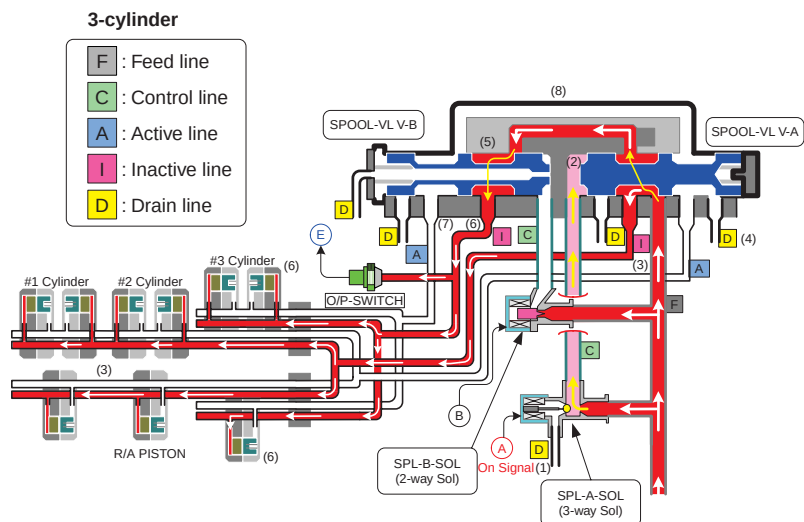


Fig. 8 3-cylinder oil-hydraulics control

applies pressure to the deactivating side of the rocker arm hydraulic piston of the two cylinders (3). The hydraulic pressure applied to the operating side of this cylinder is relieved from (4). As a result, the rocker arm hydraulic piston moves to the deactivating side, and the valve deactivates. SPOOL-VLV-B applies the hydraulic pressure (5) that arrived via SPOOL-VLV-A, to the deactivating side of the hydraulic piston on the remaining cylinder (6). The operating side hydraulic pressure applied to this cylinder enters SPOOL-VLV-B from (7), passes through (8), and is discharged from SPOOL-VLV-A (4). As a result, the rocker arm hydraulic piston moves to the deactivating side, and the valve deactivates.

To switch over from 3-cylinder to 6-cylinder mode (Fig. 6), SPL-A-SOL is switched OFF. The hydraulic pressure applied to SPOOL-VLV-A is stopped, and the hydraulic oil is discharged from SPL-A-SOL (7). When the pressure at SPOOL-VLV-A decreases, SPOOL-VLV-A is returned by spring force. As a result, the hydraulic passage of SPOOL-VLV-A switches over. In this way, SPL-A-SOL, SPL-B-SOL, and SPL-C-SOL, as well as the operation and deactivation of the applicable cylinders are controlled, thus enabling switchover between the three modes.

The functions of SPOOL-VLV-A and SPOOL-VLV-B differ according to whether the discharge of the hydraulic oil in the valve is controlled (SPOOL-VLV-A) or not controlled (SPOOL-VLV-B) by SPL-A-SOL. Controlling the discharge helps eliminate leakage of hydraulic oil when hydraulic pressure is applied, enabling switchover from low pressure to be realized. Because 4-cylinder mode is limited to the high engine speed range, SPOOL-VLV-B, which has a simple construction, can be used. The method of selecting the optimum number of cylinders and the method of controlling the switchover between the different cylinder modes are basically the same as those of the conventional VCM system. Figure 9 shows an outline of engine control.

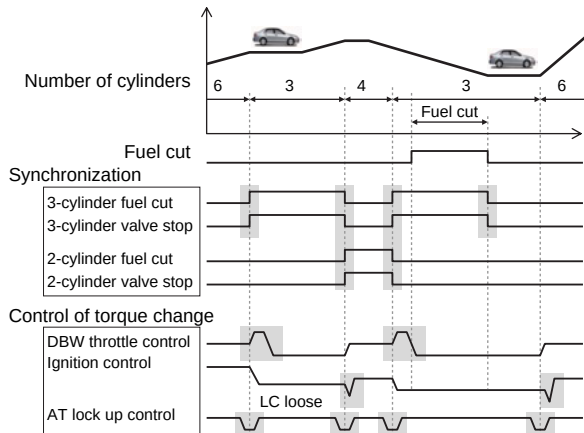


Fig. 9 Pattern of VCM operation

3.4. Output Performance

Figure 10 shows the output characteristics of the new VCM engine. When regular gasoline is specified, the output obtained is 200 kW at 6200 rpm, and 336 Nm at 5000 rpm.

The method of obtaining the above performance is as follows. In order to enhance the cooling performance, the coolant circulation passage between the cylinder block and the cylinder head was modified, and the thread dimensions of the spark plugs were changed from M14 to M12 and long reach plugs were used, enabling the thickness of the water jacket around the combustion chamber to be reduced. Also, a piston oil jet was used to reduce the piston temperature, enabling knocking to be suppressed, and the compression ratio to be set to 10.5. In addition, the valve timing and the shape of the intake system and intake manifold were restudied, the suction efficiency was increased by widening the valve head diameter, for example, and the exhaust efficiency was increased by changing the construction of the exhaust pipe, thus enabling the above performance to be obtained.

3.5. Fuel Economy Performance

With this system, in order to operate the engine on a number of cylinders that conforms to the driving condition, the valve operation of the applicable cylinders is momentarily interrupted, realizing reduced engine friction due to reduced pumping losses and reduced valve operation losses. In addition, the fuel economy is increased due to enhanced thermal efficiency resulting from the use of a load zone in which the combustion form

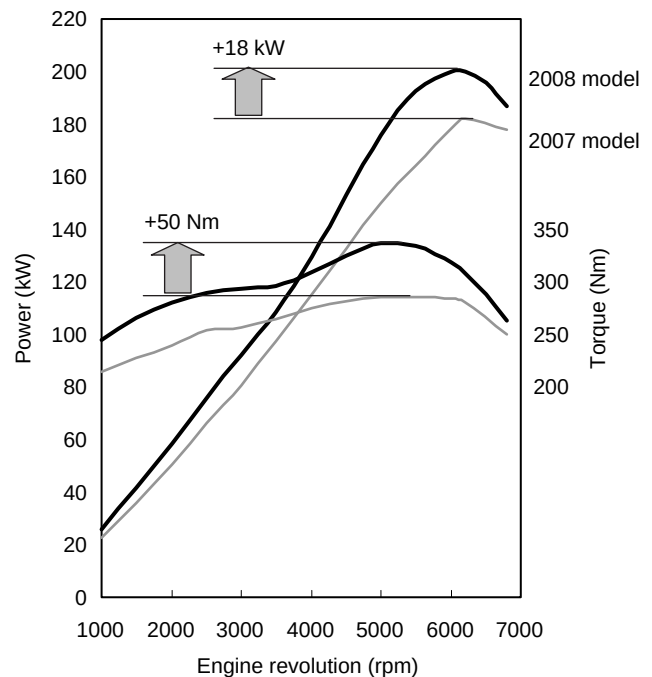


Fig. 10 Output performance

is satisfactory, and by increasing the fuel cut time.

Figure 11 shows the relationship between the total engine displacement and the brake specific fuel consumption (BSFC) when the engine speed is 1500 rpm and the output is 2.94 kW. By switching from 6-cylinder to 3-cylinder mode, BSFC of the stand-alone engine was reduced by about 30%, and despite the fact that the total engine displacement was 3.5 L, the BSFC obtained was equivalent to that of an engine with a total displacement of 2.0 L.

Figure 12 shows the cruising fuel economy effectiveness and the load zone in which cylinder deactivation driving can be performed. A cruising fuel economy exceeding that of the 3.0-L engine of the previous year's model was achieved by driving in 3-cylinder mode in the low-speed range, and in the added 4-cylinder mode in the high-speed range. Figure 13 shows the relationship between the load and the BSFC at

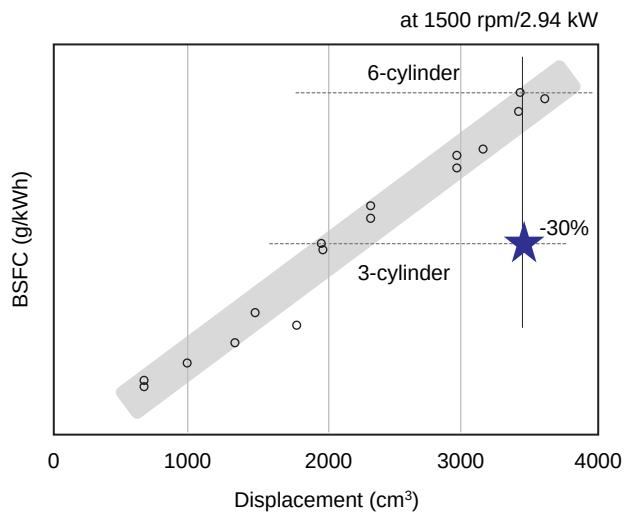


Fig. 11 VCM effect on BSFC

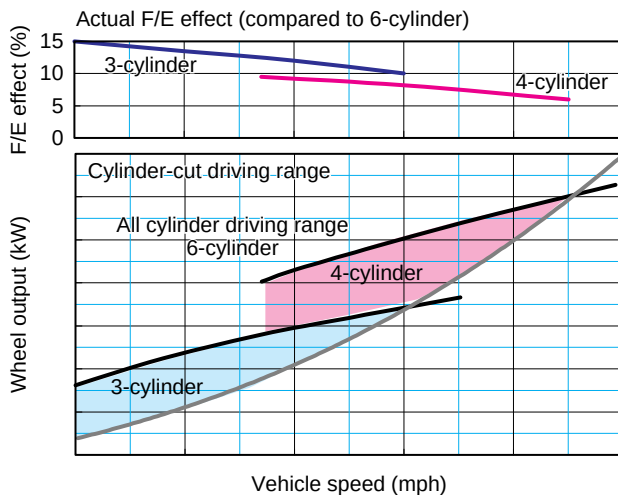


Fig. 12 Effect of VCM on fuel economy

a vehicle speed of 70 mph. The number of cylinders changes according to the required drive force, affecting the fuel economy. While the vehicle is cruising, higher fuel economy can be obtained by selecting the 3-cylinder mode. Under running conditions where additional drive force is needed, higher fuel economy can be obtained by selecting the 4-cylinder mode.

Fuel economy enhancing technology that suppresses knocking, increases the compression ratio, realizes precision control of active lockup in the automatic transmission, and the like, was adopted in addition to the newly developed VCM system. Consequently, as shown in Fig. 14, the fuel economy was higher than that of the 3.0-L engine of the previous year's model despite the fact that the actual engine displacement was 3.5 L. A 10%

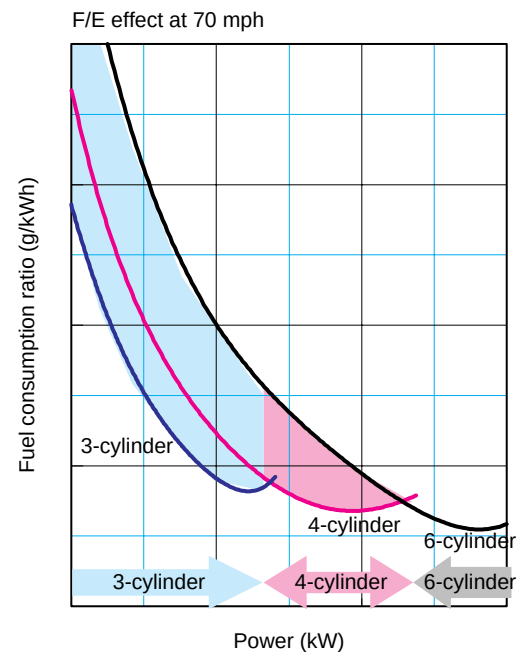


Fig. 13 Fuel consumption comparison

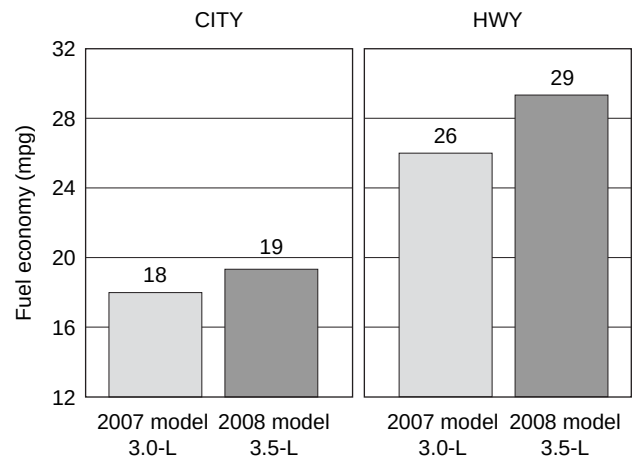


Fig. 14 Fuel economy effect

increase in fuel economy was obtained in EPA highway mode, resulting in top level output and fuel economy for this class of vehicle (Fig. 15).

3.6. Exhaust Gas Performance

The new VCM system complies with the PZEV regulations of the U.S. state of California. Its specifications are shown below.

A high density 900 CPI three-way catalyst was installed immediately behind the cylinder head of each bank. As a result, the thermal capacity was reduced, the temperature rise characteristics in the cold range, for example, were enhanced, and the cleaning performance

was increased. Also, an LAF (linear A/F) sensor and an O_2 sensor were installed at each bank in order to increase the response, and precision feedback control of each bank can be performed. In addition, from the 2008 model, an air flow meter will be used, in order to increase the accuracy of air-fuel ratio control (Fig. 16).

In addition to the abovementioned low emission technology, precision control of the electrically operated EGR valve has been employed, and the starting HC reduced by means of dual probe electrode spark plugs, thus complying with the PZEV regulations of the U.S. state of California and realizing environmental friendliness and low fuel consumption.

4. Comfort

NV (noise and vibration) performance is one important factor for offering comfort worthy of a high-grade automobile. As a result of the addition of 4-cylinder mode, the combustion intervals are unequal, so vibration increases. As a countermeasure, the performance of the NV device used with the conventional VCM was enhanced, and the use of 4-cylinder mode was limited to the high vehicle speed range, thus enabling the NV performance to be satisfied.

The performance enhancements realized by the NV device are as follows.

- (1) Reduction of the long torsion spring constant
As with the conventional VCM system, a long torsion spring is used as the lockup damper. The spring constant of this spring was reduced, resulting in further reduction of vibration in the drive system.
- (2) Increased drive force of the active control engine mount (ACM) and measures for the 4-cylinder order
As with the conventional VCM system, an ACM is used to reduce vibration when the cylinders are deactivating. Four-cylinder order control was added to suppress vibration in 4-cylinder mode, and the drive force was increased in order to suppress vibration when cylinders are deactivating, including when the engine is running in 3-cylinder mode.

5. Conclusion

- (1) A new V6 variable cylinder system to which a 4-cylinder mode was added was developed, with high output, low fuel consumption, and low emissions set as the study objectives.
- (2) Compared to the previous year's model 3.0-L SOHC VETC, a 10% increase in fuel economy was achieved during EPA highway mode driving despite the fact that displacement was increased to 3.5 L.
- (3) While achieving the above level of fuel economy, the output when regular gasoline was used reached 200 kW at 6200 rpm, and 336 Nm at 5000 rpm, which is the top level for this class of vehicle.

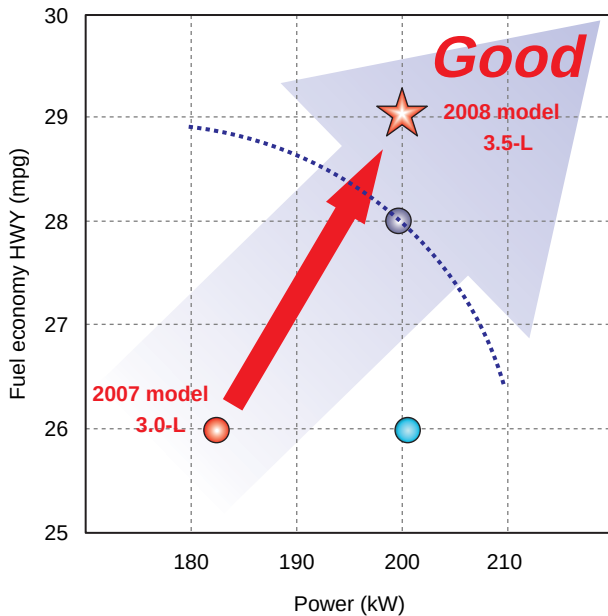


Fig. 15 Performance of 2008 model year ACCORD on fuel economy and power

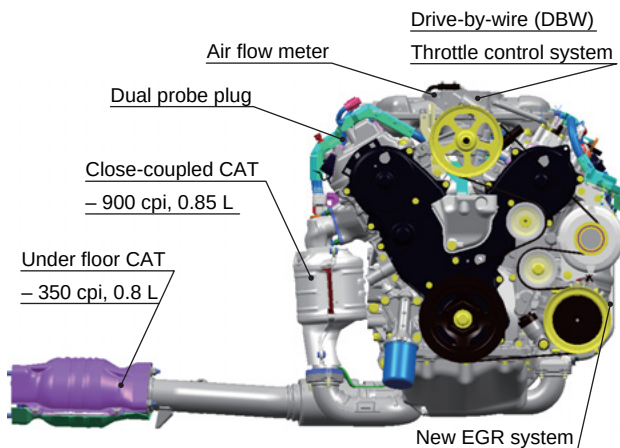


Fig. 16 Engine configuration and control system

Reference

- (1) Noguchi, K., Fujiwara, M., Segawa, M., Sawamura, K., Suzuki, S.: Development of V6 i-VTEC Engine with Variable Cylinder Management, Honda R&D Technical Review, Vol. 16, No. 1, p. 85-92

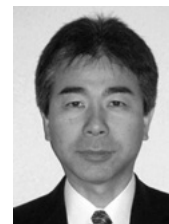
■ Author ■



Makoto SEGAWA



Kazuhide KUMAGAI



Ryuuji SATO



Yuiichi TAMURA



Mikio FUJIWARA

Computational Method to Calculate Flow Rate Distribution through Radiator

Thomas N. Ramsay*

ABSTRACT

In this paper a computational method to calculate the flow rate distribution through a vehicle radiator is outlined. A typical testing method for radiator flow rate distribution is to cover the front grille openings in various combinations and then measure - via anemometers - the change in radiator flow rate to determine the contribution of a specific cooling opening to the overall cooling flow. However, this changes the contribution distribution: a low pressure region will be created behind the covered grille and will draw air from another area. It would be desirable to capture the contribution air flow distribution through the radiator during normal operating modes (e.g. when all the grille openings are clear). This would be challenging in a testing scenario, but relatively straightforward for a computational fluid dynamics (CFD) analysis. Rather than using the typical velocity magnitude or velocity vector visualization techniques, tracing path lines downstream from the cooling openings to the radiator face leads to a method to allow a more realistic description as well as a better way to convey this information. Basically, the intersection points of the path lines are trapped on the face of the radiator, and then triangulated, and the flow distribution is calculated using these triangular elements. Finally, an image is created to visually convey the flow rate distribution.

1. Introduction

In a typical testing scenario, during an engine airflow test, the front grilles would be covered in various combinations and then measure - via anemometers - the change in radiator flow rate to determine the contribution of a specific cooling opening to the overall cooling flow at the front of the radiator. However, this testing scenario does not capture the on-road contribution distribution from each cooling zone: a low pressure region will be created behind a closed grille and will simply be “filled in” by the flow field from another area - thereby potentially creating an unrealistic contribution distribution. A desirable method would be to capture the contribution air flow distribution through the radiator during normal operating modes (e.g. when all the grille openings are clear). This would be challenging in a testing scenario, but relatively straightforward for a CFD analysis. By realizing that path lines will allow downstream tracing of the flow field from the grille openings to the radiator face, a method was developed to allow a more realistic description as well as an imaging technique to convey this information. This method was developed in-house and contains four main steps: (1) path line intersection with

radiator face, (2) triangulation of intersection points, (3) calculation of individual flow rates and edge export, and (4) image creation. It is the concept of employing a triangulation algorithm (Delauney triangulation in this case) to connect the path line intersection points that makes this method novel. To the author’s knowledge, this is the first time this particular technique has been used to make a useful link between the styling-related grille openings and the performance-related cooling flow through the radiator.

2. Path Line Intersection

A full engine compartment CFD model was created and solved at typical US highway speeds, as seen in Figure 1, where the left side identifies the cooling regions and the left side shows the path lines into these cooling regions. Industry standard CFD setup parameters and solution convergence criteria were used.

Figure 2 shows the route the path lines progress from the cooling openings (grilles or bottom breather) to the radiator face. Note that the four colored areas - blue, yellow, green, and pink - represent the nexus of points that the path lines were released from. The large open

* HONDA R&D AMERICAS, INC.

arrows indicate the general direction of the cooling flow path lines from associated cooling region toward the radiator. Keep in mind that the background colors in Figure 2 will be used throughout the rest of the paper to help differentiate the originating cooling region (blue = upper grille, yellow = lower left grille, green = lower right

grille, pink = bottom breather).

Path lines were generated and saved - including the coordinates and the velocity magnitudes - for all four engine cooling zones, the upper grille, the bottom breather or air dam area under the vehicle, and the lower left and right openings. Figure 3 shows the path lines created

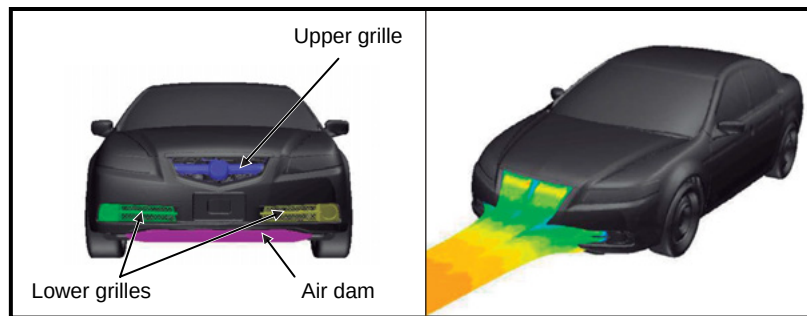


Figure 1 Front end geometry (left) and path lines passing through cooling zones

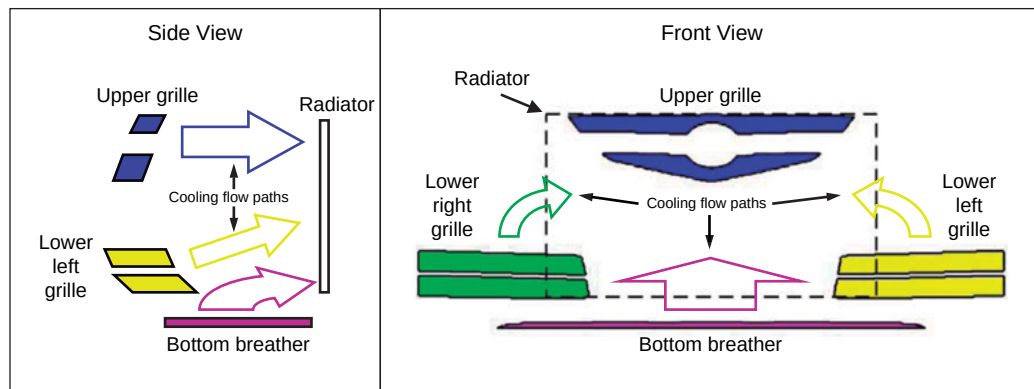


Figure 2 Conceptual path line image

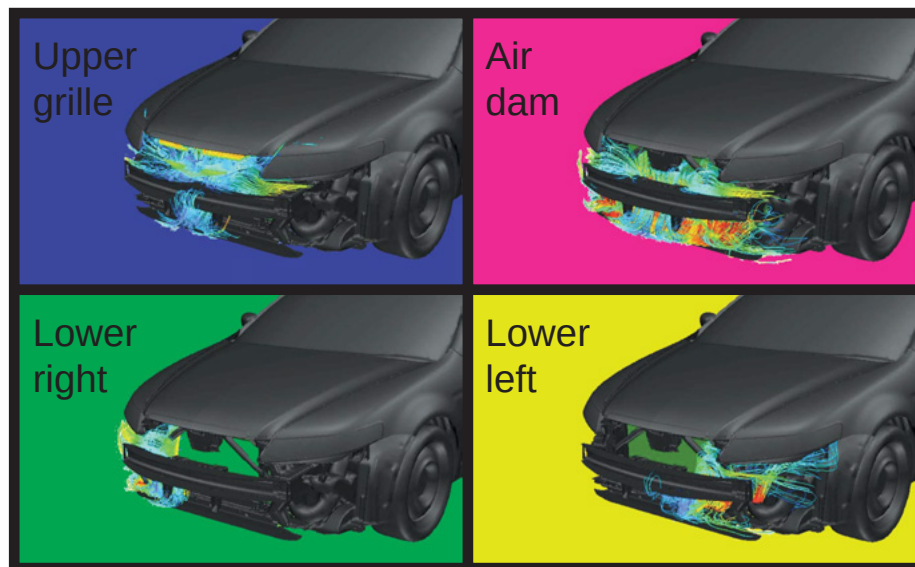


Figure 3 Path line creation

downstream of the four individual cooling zones.

Two custom scripts were written to read in the path line file, intersect those path lines with the radiator face and then to trap all the intersection points that were within the rectangular radiator face, since some path lines would bypass the radiator altogether. Figure 4 shows these intersection points colored by originating cooling zone (blue = upper grille, pink = bottom breather, yellow = lower left grille, and green = lower right grille). Each point represents the intersection of a single path line and the front radiator face.

Upon a close inspection of Figure 4, it is easily seen that there are several intersection points that are considered outliers (e.g. the blue points in the yellow region or the pink points in the green region). These points would then be determined to be outside the core contribution region for that cooling zone. Also note that due to a more direct path, the upper grille intersection points tended to have a higher density than the other three regions; however, this is also a function of the originating number of points, which is dependent on the cooling region area and mesh size.

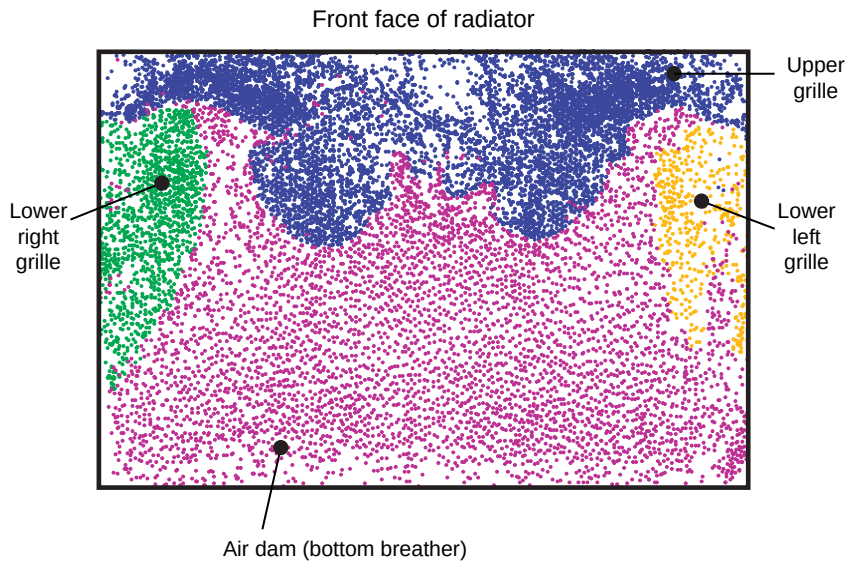


Figure 4 Path line intersection for four radiator cooling areas

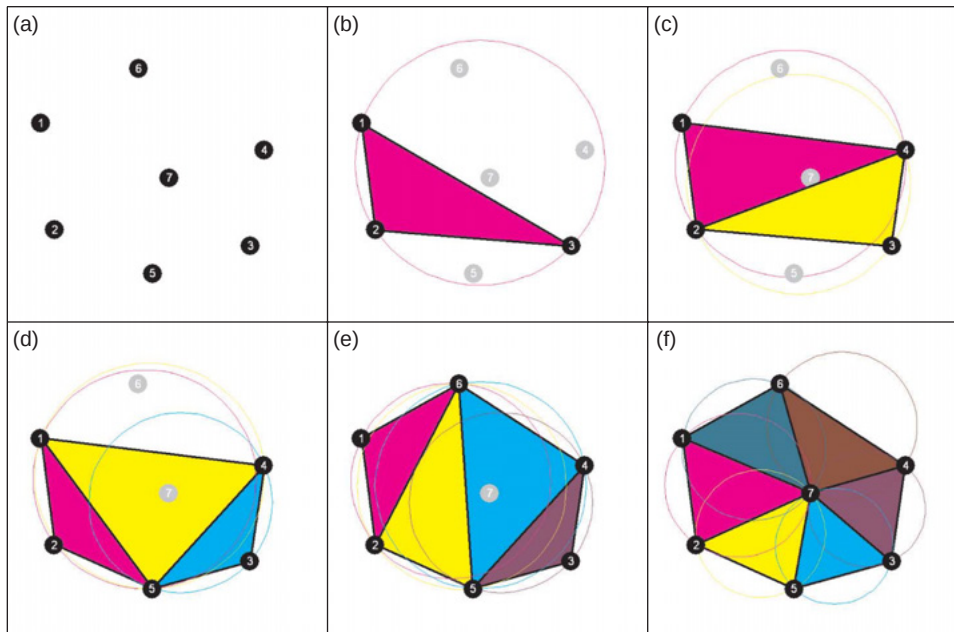


Figure 5 Delauney triangulation, forward progression

3. Point Triangulation

Now that the relevant points on the front face of the radiator have been found, those points must be associated in some way to use them as a basis for flow rate calculation. The best way to do this is Delauney triangulation, which basically connects all the points with a series of triangular elements, in effect meshing the region, but using the pre-existing points as nodes. Figure 5 shows the Delauney triangulation of seven points, where a triangular element is created from the first three points, then as each subsequent point is added, the points are re-triangulated for a best fit of elements. This is accomplished by use of circumscribed circles. If the next point to be added, such as point #4 in Figure 5(b) is within any of the circumscribed circles represented by an element, then those elements will be re-triangulated with

the new point. This is best shown in Figure 5(d), where the point #6 is within the circles of the pink and yellow elements, and thus re-triangulated in Figure 5(e) with the new pink, yellow, and light blue elements. Figure 6 shows the same seven points, but with the addition of triangulated points in reverse order. While the individual triangular elements are created in a different manner, the end result is the same: six triangular elements that contain no grid points within them.

Once the intersection points are triangulated, edge elements are created. In the case of Figure 5 and Figure 6, there are six edge elements (1-2, 2-3, 3-4, 4-5, 5-6, 6-1). These are found by tracking how many elements are associated with each point. Those points with only one or two elements are considered edge points. These edge points are then connected with 1D elements and those elements are sorted to form a closed edge profile.

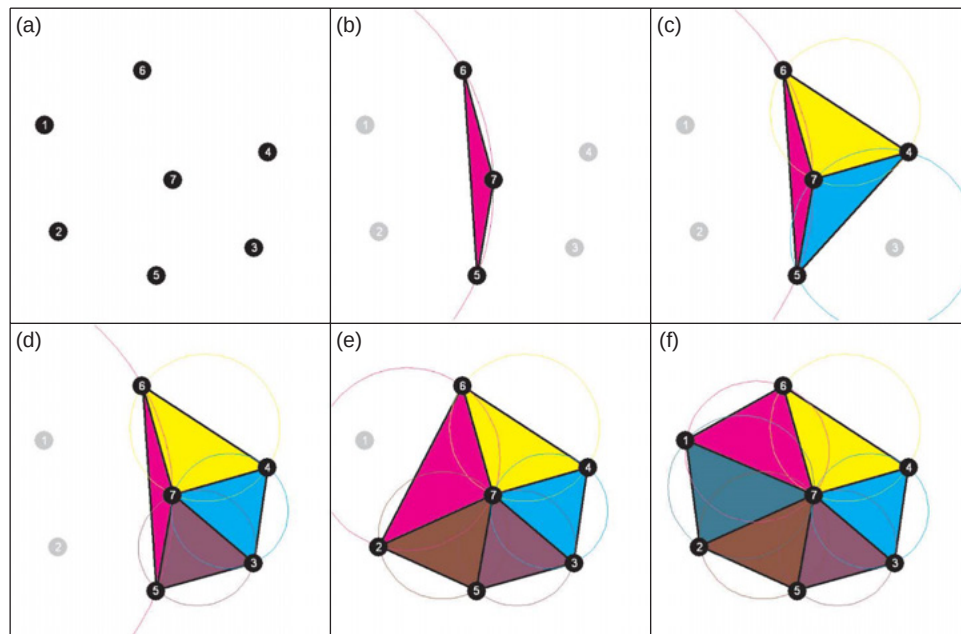


Figure 6 Delauney triangulation, reverse progression

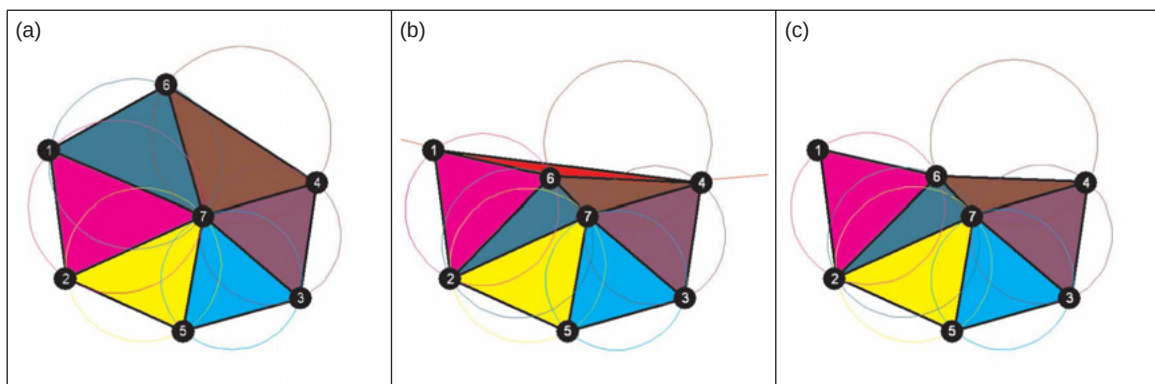


Figure 7 Triangulation for a moved point (#6)

A realistic set of intersection points will not form a well shaped series of triangular elements, so a recursive algorithm that removes highly skewed edge elements was added. Returning to the point set of Figure 5 and Figure 6, Figure 7 shows what happens when point #6 is moved and another element is created (in red). It's pretty clear that the new (red) edge triangular element is ill-formed and would not realistically contribute to the flow rate calculation, thus would be eliminated, as in Figure 7(c).

The typical criterion for ill-formed elements is called skew and is defined based on the following equation:

$$Skew = \frac{Element\ Area}{Ideal\ Area} \quad (1)$$

Where the element area is simply the area of the triangular element, as in Figure 8(a) and the ideal element is the area of a perfect isosceles triangle that lies

within the circumscribed circle of that same element, as in Figure 8(c). The skew limit was set at 0.80.

Additionally, it was also possible that larger concave sections would be present in the point set and then large bridging elements would be created. While most of these elements would be likely eliminated by the edge-skew check, it is sometime necessary to indicate that these bridging elements are again outside the core contribution region for that particular cooling zone. Figure 9 shows the triangulated elements for the four cooling zones on the front face of the radiator. Note that there is some overlap in the regions.

4. Flow Rate Calculation

Now that the individual contribution regions have been triangulated, their flow rates can be calculated. Here is where the wisdom of carrying the velocity magnitude for

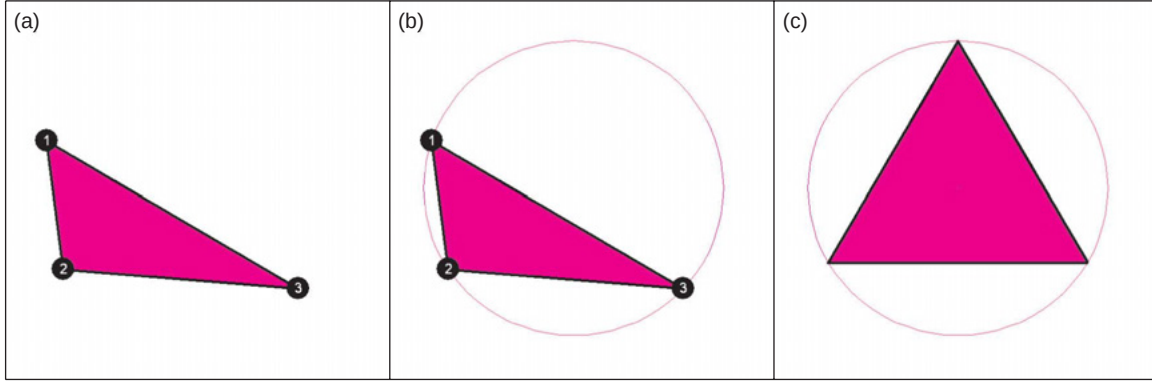


Figure 8 Element skew calculation

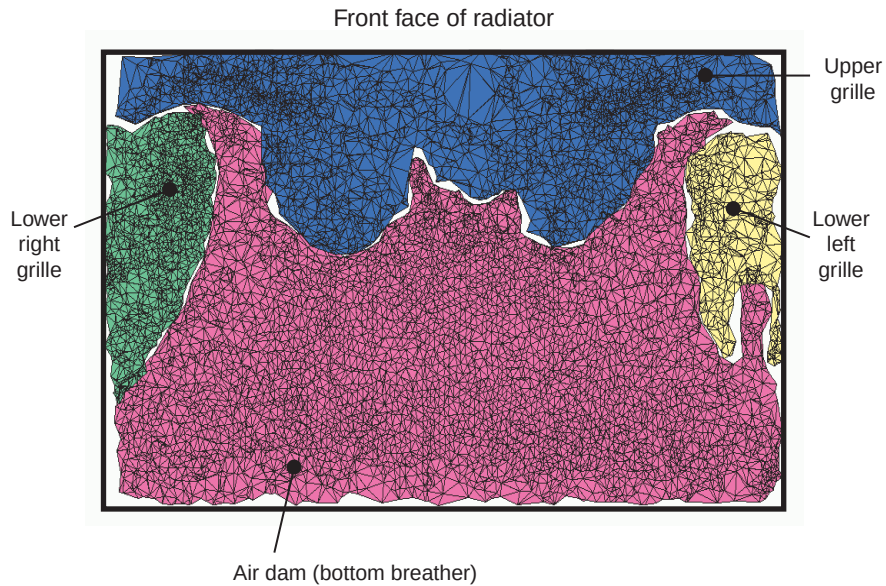


Figure 9 Triangulated contribution regions for candidate radiator

each point comes into play. Realizing that the flow rate of each element can be calculated by:

$$\text{Flow Rate} = \text{Element Area} \times \text{Average Velocity} \quad (2)$$

Where the average velocity is simply computed from the velocity at all three node points. Then all the flow rates are summed up and the total flow rate through the region of interest is computed. Figure 10 shows the total flow rates (in percentages) for the four contribution cooling zones. In addition to the contribution flow rates, the edge elements are exported as well.

5. Image Creation

Now that the contribution flow rates are calculated, this information is sent back to engineering and styling. While bar graphs of the contributions are relatively straightforward and may be created for engineering, styling prefers more visual results. Therefore, the edge elements from Figure 10 are then plotted and filled in via a simple computer drawing package. The final image is shown in Figure 11 and represents a typical contribution image that would then be shown in an analysis of the flow field. By typical image, it has been

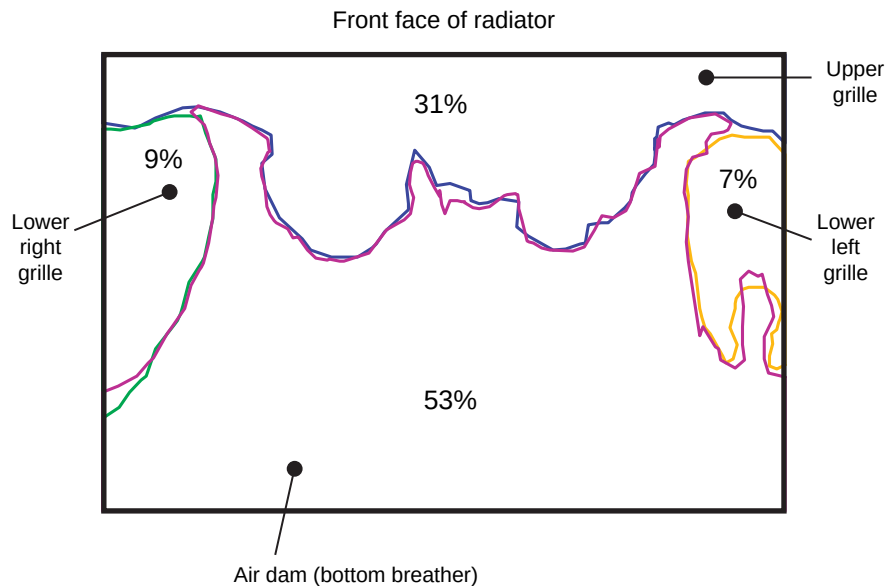


Figure 10 Radiator flow rates for the cooling zones

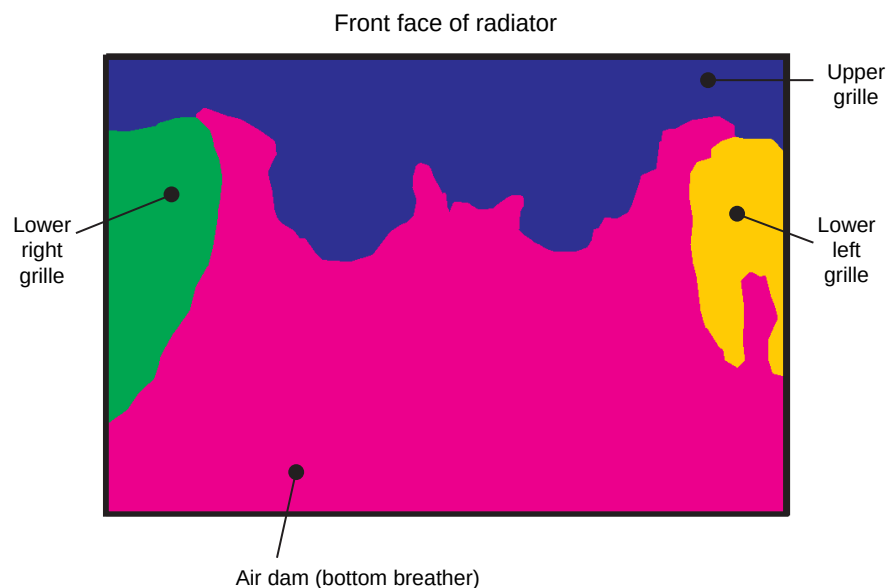


Figure 11 Contribution region final image

shown through past experimental testing that the bottom breather contributes a significant amount of cooling flow, but not how much (for reasons stated in the Introduction). Thus, Figure 11 represents what would be expected from a bottom breather vehicle.

6. Conclusions

A method to both calculate and show the cooling zone distribution on the radiator face has been developed. In developing the proposed method, the initial impetus was to convey complex underhood flow patterns. This was accomplished by connecting CFD results (path lines) with a desired outcome (radiator flow distribution). While at this time it is quite difficult to verify this final image (e.g. Figure 11), this method is another tool that allows greater understanding of the cooling region flow field. This proposed method allows enhanced potential front end design direction to be delivered to engineers and stylists alike and increases the confidence in CFD to deliver unique flow field related results. This better insight into the affects of front fascia design on the flow through the radiator, would, in turn, lead to better styling and performance decisions.

■ Author ■



Thomas N. Ramsay

CAE Analysis for Development of Magnesium Cross Car Beam

Yohei KUWANO*
Tsunehisa HATA*

Yasunori SAKAMOTO*
Takeharu ENDO*

Ayumu UNO*
Sean ATKIN**

ABSTRACT

A magnesium cross car beam has been developed in order to achieve automotive weight savings and thus greater fuel efficiency, while maintaining safety performance.

In the development of a magnesium cross car beam, CAE analysis was used to increase the accuracy of predicting cracks, elongation, and deformation.

This paper will discuss the use of CAE analysis in this development project.

The developed magnesium cross car beam will be employed in the 2008 year model FCX.

1. Introduction

As the auto industry continues to address fuel efficiency through automotive weight savings, cross car beams are increasingly being manufactured from magnesium and aluminum⁽¹⁾⁻⁽⁴⁾, in particular in Europe and the U.S.

Compared to steel and aluminum, magnesium is a brittle material. Thus it is important to address the issues of cracking, elongation, and deformation of magnesium in a collision in instances where a magnesium cross car beam is employed.

To address this issue, CAE analysis was employed to predict cracking during the development of a magnesium cross car beam. This paper discusses the use of CAE analysis in this development project.

The use of CAE analysis resulted in the achievement of a level of performance equivalent to that of a steel cross car beam with a weight saving of approximately 5 kg (40%).

2. Development Using CAE Analysis

The performance of numerous calculations for a CAE

collision analysis at the preliminary examination stage would require an enormous amount of time. For this reason, the CAE collision analysis in the initial examination was replaced by a simple static load CAE analysis that required less calculation time.

The coincident hot spot monitoring approach⁽⁵⁾ developed by Meridian Technologies Inc. was employed to predict cracking in the magnesium cross car beam. In this method, areas of both high strain and high maximum principal stress are defined as “hot spots.” These hot spots indicate that tensile stress is acting on the areas in which they appear, and suggest that there is a potential for fracture. This enables cracks to be predicted.

2.1. Basic Shape of Cross Car Beam and CAE Analysis

Figure 1 shows the structure of a conventional steel cross car beam and the magnesium cross car beam developed in this project.

A conventional steel cross car beam is a welded structure consisting of a pipe that forms the main beam and stamped parts including the steering column and center frame.

In the case of a magnesium cross car beam, parts that can be cast, including the main beam, steering column and

* Automobile R&D Center

** Meridian Technologies Inc.

Table 1 Chemical composition of AM60B (weight %)

Al	Zn	Mn	Si	Cu	Ni	Fe	Others
5.5-6.5	≤ 0.22	0.24-0.6	≤ 0.10	≤ 0.010	≤ 0.002	≤ 0.005	≤ 0.02

Table 2 Mechanical properties of AM60B

Tensile strength [MPa]	Yield stress [MPa]	Elongation [%]
223	124	10

center frame, are integrally formed by die casting. Based on a standard wall thickness of 2.5 mm and a C-section as the basic sectional shape of the main beam, repeated CAE studies were conducted to define the areas that needed extra ribs, increased wall thickness and modification of the corner radii, enabling optimization of the main beam geometry.

Based on the above considerations, a CAD layout was formulated, and mesh models for CAE analysis were created.

2.2. Die Casting Material

AM60B⁽⁶⁾⁻⁽⁸⁾ was employed to cast the magnesium cross car beam. Table 1 shows the chemical composition of AM60B, while Table 2 provides representative values for the mechanical properties of the material.

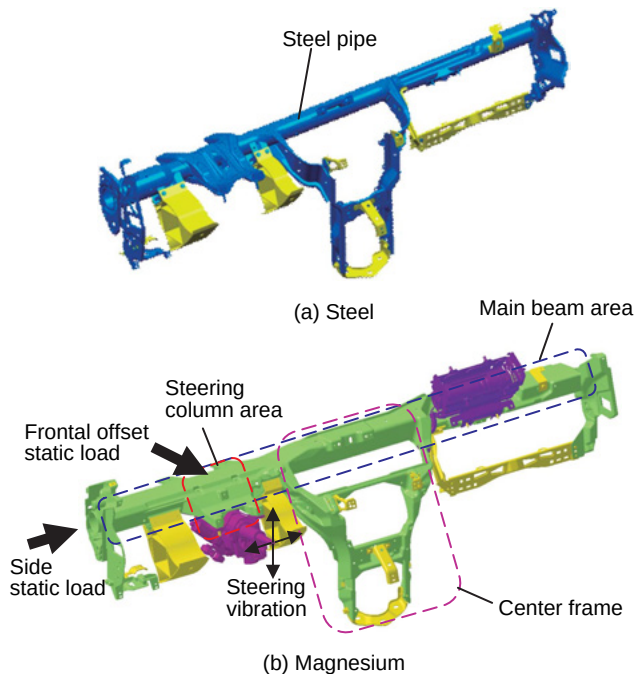


Fig. 1 Cross car beam configuration

3. Results of CAE Analyses

Figure 2 shows the results of CAE analysis of steering vibration as a vertical strain energy distribution diagram. A high level of strain energy indicates a high level of sensitivity in terms of steering vibration. These results indicate that the stiffness of the main beam on the driver side and the center frame are important factors in steering vibration performance.

Figures 3 and 4 show the results of a frontal offset static load CAE analysis and a side static load CAE analysis, respectively. The results indicate that during the application of a frontal offset static load, stress

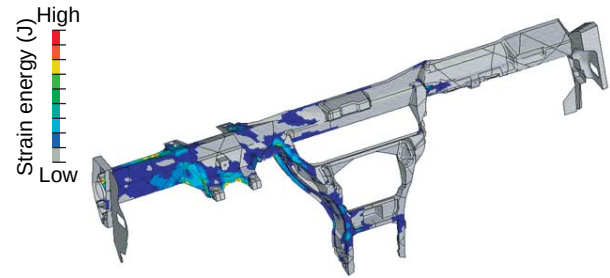


Fig. 2 Steering vibration CAE result (strain energy distribution)



Fig. 3 Frontal offset static load CAE result (Stress distribution)

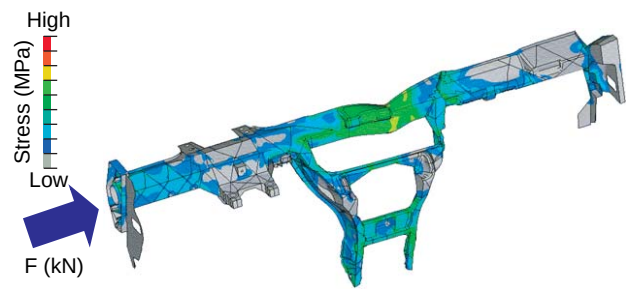


Fig. 4 Side static load CAE result (Stress distribution)

concentrates in the main beam on the driver side, while during the application of a side static load stress concentrates on the main beam from the driver side through to the passenger side.

4. Correlation of CAE Analyses and Test Results

Tests were conducted using cast prototypes. This section will discuss the correlation between representative test results and the results of CAE analyses.

4.1. Steering Vibration Test Results

Figure 5 shows the results of component tests of steering vibration (vertical natural frequency). Natural frequencies are higher in the case of the magnesium cross car beam than the steel cross car beam. The results of complete vehicle tests indicate that the magnesium cross car beam displays an equivalent level of performance to that of the steel cross car beam.

4.2. Correlation between Results of Static Load Tests and CAE Analyses

Figure 6 shows the relationship between load and stroke in side static load tests. Figure 7 compares

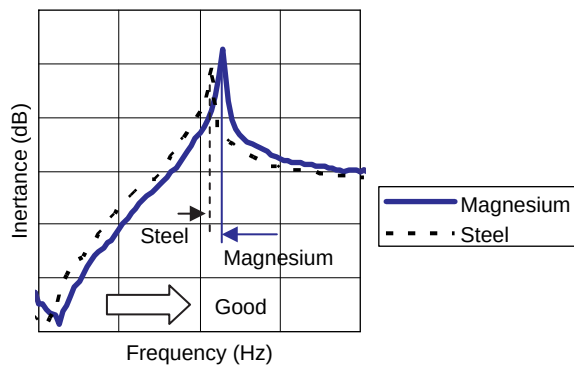


Fig. 5 Steering vibration test result (Vertical steering natural frequency)

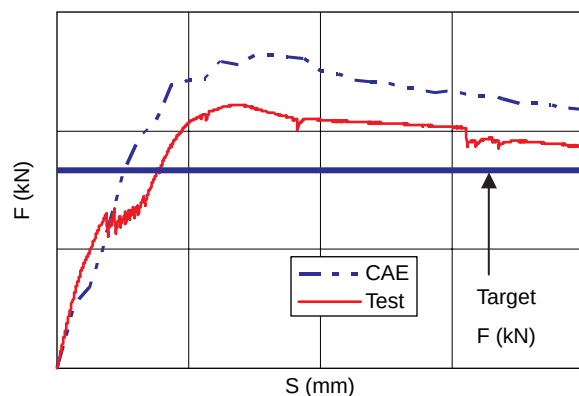


Fig. 6 CAE and test results for side static load: FF (kN)-S (mm)

deformation, and cracking under maximum load, in CAE analyses and tests. The target load was reached, but a comparison with test results shows that differences in the CAE analysis results exist. These CAE analysis differences should be taken into consideration in

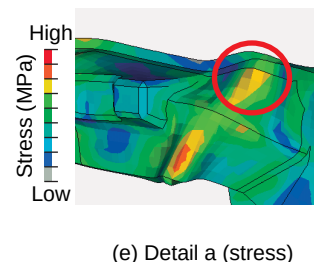
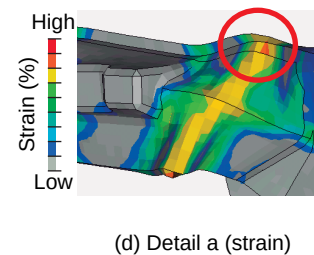
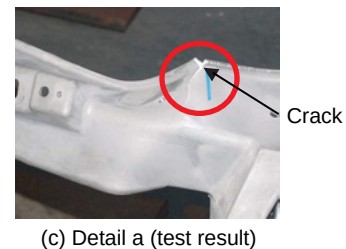
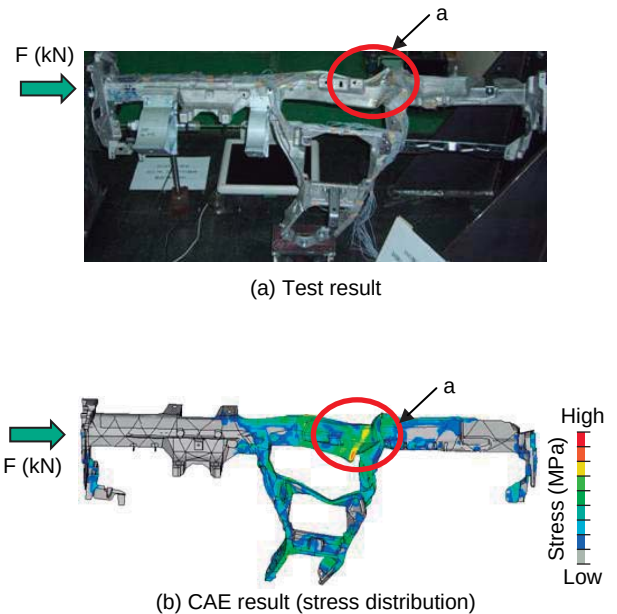


Fig. 7 CAE and test result for side static load

component design in the future. Test results were equivalent to those of the CAE results for deformation. At maximum loads, cracks appeared in the areas in which cracking had been predicted by CAE analysis, confirming the effectiveness of the coincident hot spot monitoring approach⁽⁵⁾.

Figure 8 compares deformation, and cracking under maximum load, in offset static load CAE analyses and

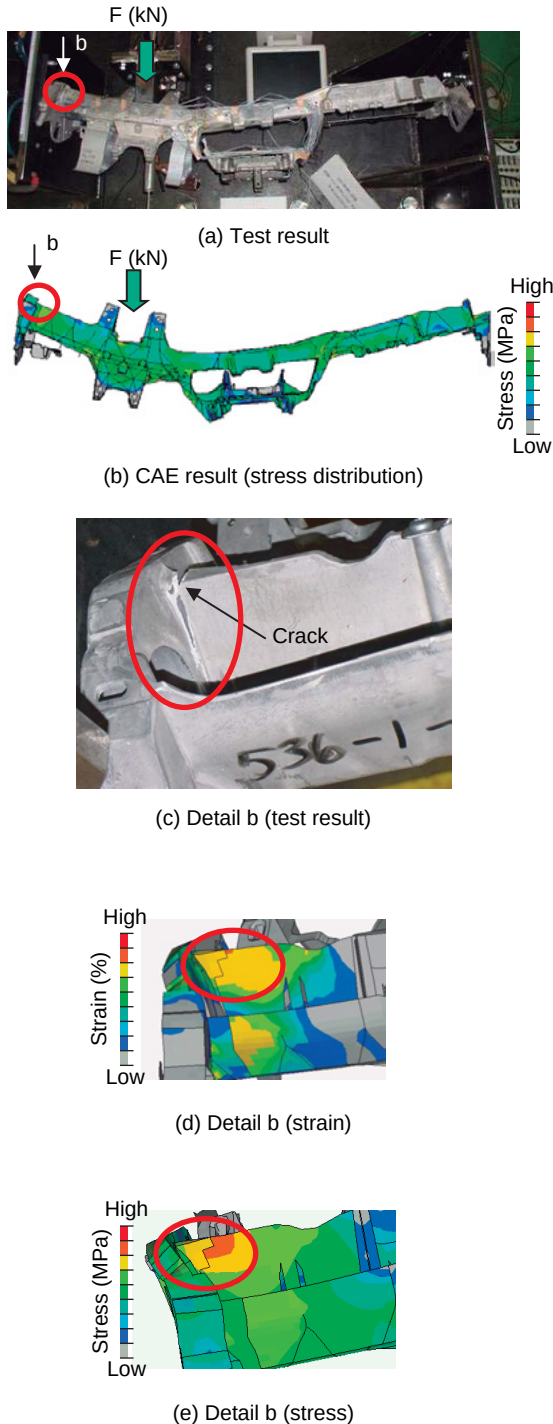


Fig. 8 CAE and test result for frontal offset static load

tests. Equivalent results were also obtained for frontal offset static loads.

4.3. Collision Test Results

Complete vehicle collision tests were conducted on the basis of the static load tests discussed above.

Figures 9 and 10 respectively show photographs of the results of a frontal offset collision test and a side collision test. No cracks occurred in the main beam in either case. Passenger injury values conformed to collision safety standards, and the level of deformation was equivalent to that of a steel cross car beam.



Fig. 9 Frontal offset crash test result



Fig. 10 Side crash test result

5. Conclusion

CAE analysis has been employed in the development of a magnesium cross car beam, with the following outcomes:

- (1) Test results confirmed the viability of predicting cracks using CAE analysis, verifying the effectiveness of CAE analysis in development. Differences between the results of CAE analyses and tests should be taken into consideration in advance when using the method.
- (2) No cracks were generated during complete vehicle collision tests using a static load test method, demonstrating the validity of using static load tests.

The project resulted in the development of a magnesium cross car beam that displays an equivalent level of performance to that of a steel cross car beam and can be fitted in an equivalent instrument panel space, while achieving a weight saving of approximately 40%.

References

- (1) Simonds, G., Su, B.: Jidousya ni okeru Magunesiumu Tekiyō no Kongono Houkousei to sono Yuuisei, Magnesium, Vol. 35, No. 10, p. 8-13 (2006) (in Japanese)
- (2) Li, N., Chen, X., Hubbert, T., Berkmortel, R.: 2005 Ford GT Magnesium Instrument Panel Cross Car Beam, SAE Paper, 2005-01-0341 (2005)
- (3) Uto, H.: Trend on Application of Non-ferrous Materials for Automobiles to Save Weight and Size, Journal of Society of Automotive Engineering of Japan, Vol. 59, No. 11, p. 11-16 (2005)
- (4) Application Guide of Magnesium Alloy, Handbook of Advanced Magnesium Technology, The Japan Magnesium Association, Kallos Publishing Co., Ltd., p. 385-391 (2000)
- (5) Simonds, G.: Designing Magnesium Casting for Structural Applications, Alutopia, Kallos Publishing Co., Ltd., Vol. 37, No. 8, p. 25-30 (2007)
- (6) Alain, R., Lawson, T., Katool, P., Wang, G., Jekl, J., Berkmortel, R., Miller, L., Svalestuen, J., Westengen, H.: Robustness of Magnesium Castings, Transactions of Society of Automotive Engineers of Japan, Vol. 36, No. 6, p. 151-156 (2005)
- (7) Casting of Magnesium Alloy, Handbook of Advanced Magnesium Technology, The Japan Magnesium Association, Kallos Publishing Co., Ltd., p. 157-158 (2000)

■ Author ■



Yohei KUWANO



Yasunori SAKAMOTO



Ayumu UNO



Tsunehisa HATA



Takeharu ENDO



Sean ATKIN

Mechanism of Trapping Air Cleaner Particles and High-performance Filter Element

Seiichi TANAKA*

Toru TANAKA*

Takayuki HOSOYA*

Kenji KOGA*

ABSTRACT

Attempting to extend the life of the air cleaner filter element, a consumable part, the project discussed in this paper layered wet- and dry-type non-woven filters to develop a high-performance long-life element.

Based on the results of an analysis of the mechanism of capturing dust particles, the lipophilic properties of the fibers of the non-woven used in the wet layers were enhanced to increase oil retention, enabling dust to be accumulated in specific areas and thus reducing clogging. Dry layers have also been used to produce a multi-layered structure, reconciling the achievement of extended life with a higher level of efficiency in capturing particles of all sizes and types.

1. Introduction

In an effort to protect the natural environment, in the process of automobile development attention is being focused on achieving increased fuel efficiency, greater recyclability, and reduced exhaust emissions. Active efforts are also being made to reduce waste and increase convenience for users by extending the interval for maintenance of oil (engine oils, etc.) and the life of consumable parts. The air cleaner filter element ("filter element" below) is a part that calls for periodic maintenance and replacement. Different filter element materials are used and different maintenance intervals are set depending on the characteristics of the substances to be filtered in different regions. Particularly in dusty regions, where fine particles need to be filtered, it is necessary to use short-life filter elements with fine mesh. Based on an understanding of the mechanism by which particles are captured by filter materials, a new concept has been used to enable the development of a high-performance filter element that has a long life and is able to capture fine dust particles. This development has enabled the interval for filter element maintenance to be extended.

2. Performance Requirements for Filter Elements

There are three basic performance parameters for filter elements.

- (1) Dust life
The amount of dust that can be captured up to the driving distance established in the market for replacement of the filter.
- (2) Cleaning efficiency
Ratio of amount of particles of differing diameters captured to amount of particles filtered.
- (3) Air flow resistance
Ability to enable passage of air
Dust life and cleaning efficiency are generally in an antagonistic relationship. For example, when a filter element with a fine mesh is used to increase filtering efficiency in order to reduce the infiltration of dust into the engine, clogging occurs more easily, reducing the dust life of the filter, and shortening the product replacement cycle.

3. Types of Substances Trapped by Filter Elements

Filter elements used in the market were collected and the substances trapped in them were analyzed. These substances can be broadly classified into three types on the basis of their composition and properties.

- (1) Carbon
Particles of 1 μm or less in diameter, e.g., particulate matter (PM) present in the air.
- (2) Inorganic dust
Particles from 1-50 μm in diameter, mainly silicates of

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mineral origin (sand, clay).

(3) Other substances

Substances other than (1) and (2). Often rubber dust generated by tire friction.

Figure 1 shows an example of the ratios of these substances.

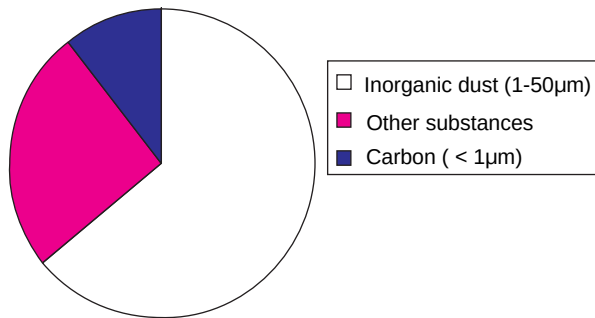


Fig. 1 Classification of trapped particles from used elements in Japan

4. Mechanism of Capture of Particles

(1) Mechanism of capture of carbon particles

Because carbon particles have a small diameter, they are normally captured using the static electricity generated by friction between the air and the fibers of the filter element⁽¹⁾, i.e., by the charge that builds up in the filter element. The higher the volume resistance, the higher the charge that builds up, and cleaning efficiency therefore increases with the volume resistance (Fig. 2).

(2) Mechanism of capture of inorganic dust and other particles

Figure 3 shows an image of dust trapped in the fibers of a filter element. Dust is trapped in the spaces in the fiber, but the mechanism by which the particles are trapped differs depending on their diameter. Figure 4 shows the relationship between the space ratio of the filter element and its cleaning efficiency in the case of large-diameter

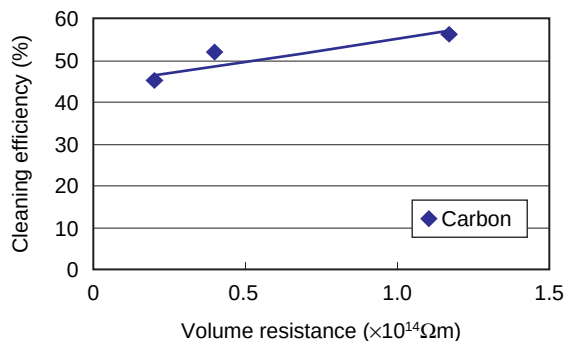


Fig. 2 Cleaning efficiency by Volume resistance

particles. The lower the space ratio, i.e., the finer the mesh, the higher the cleaning efficiency of the filter. For ultraparticles of 5 μm or less in diameter, capture by static electricity, as in the case of carbon particles, is highly effective (Fig. 5).

In wet-type filter elements (paper-type filter elements that have been impregnated with oil), the dust captured by the oil on the surface of the filter is infiltrated by the oil, and this dust in turn captures more dust, generating a chain reaction. This capture mechanism is known as cake filtration⁽²⁾ (Fig. 6).

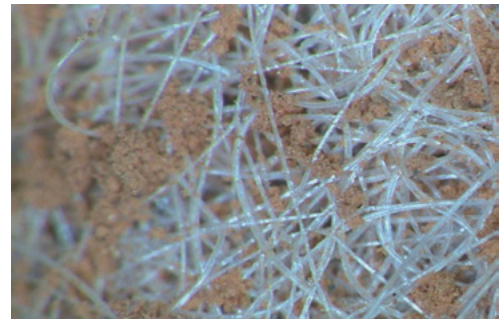


Fig. 3 Dust (1-50μm) and other substances trapped in filter-fiber

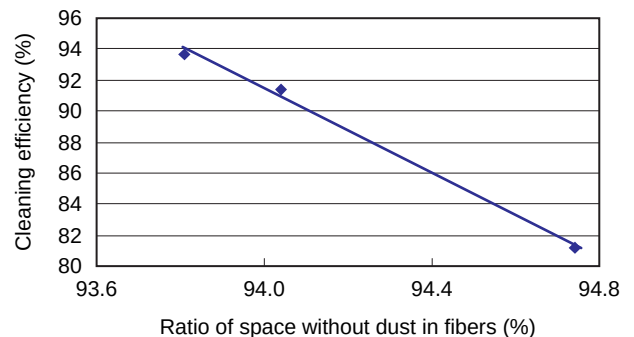


Fig. 4 Correlation of space ratio and cleaning efficiency

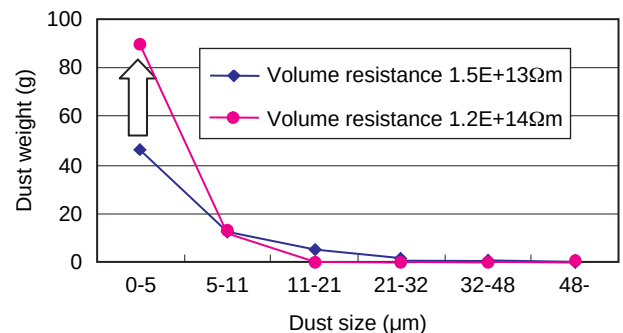


Fig. 5 Ultraparticle dust capture by static electricity

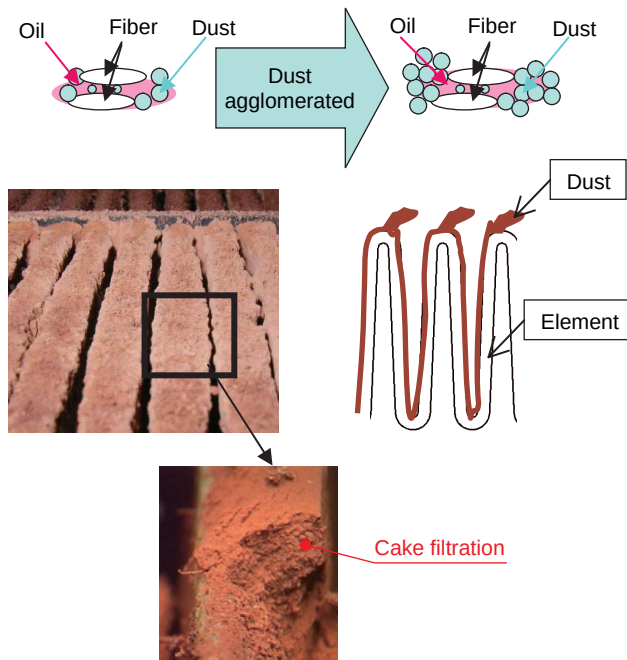


Fig. 6 Cake filtration

5. Types of Filter Elements and Characteristics

Paper, non-woven, and porous filter elements are standard types. Classified by material, the main types are paper and non-woven filters. These can be further divided into wet or dry types depending on whether or not additives are used (impregnated with oil).

A combination of three types is generally used, from considerations of dust cleaning efficiency and carbon

cleaning efficiency. The characteristics of these various filter types are shown in Fig. 7. Figure 7(a) shows dust cleaning efficiency, Fig. 7(b) shows dust life, Fig. 7(c) shows carbon cleaning efficiency, and Fig. 7(d) shows carbon life. Dry paper-type filters display a high cleaning efficiency, but their dust and carbon lives are short. Wet paper type filters have long dust lives, but low carbon cleaning efficiency. Dry non-woven filters have long dust lives and display high carbon cleaning efficiency, but their dust cleaning efficiency is low.

The high degree of freedom of design and manufacture of non-woven filters enables the density and thickness of each layer to be varied, and, as Fig. 8 shows, multi-layering enables dust cleaning efficiency to be increased at identical levels of decline in pressure.

However, non-woven filters are unable to achieve a balance between an extended dust life and cleaning performance on the level of a dry paper filter. For this

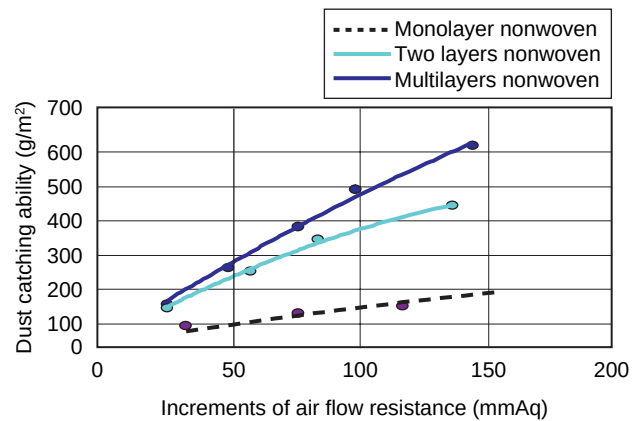


Fig. 8 Effect of multilayer structure

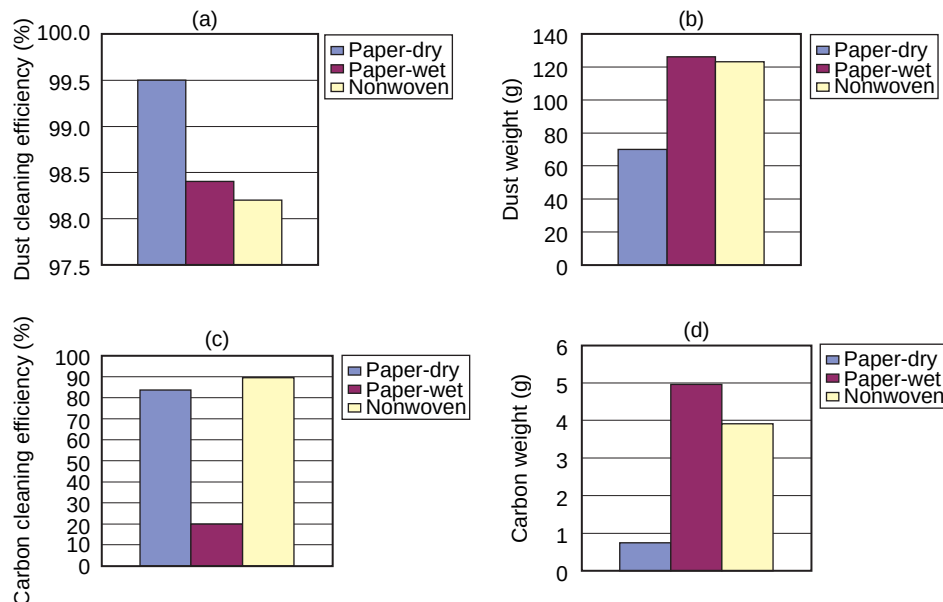


Fig. 7 Filter performance by structure

reason, dry paper filter elements with fine meshes are used in regions characterized by a high volume of fine particles, and maintenance using an air blower, etc., is called for, for example, every 10000 km.

6. Development of High-performance Filter Element

Due to the procedure used in their manufacture, paper filter elements have fine meshes, and this makes the achievement of longer life a challenging issue. A combination of a long-life wet-type paper filter and a non-woven filter was therefore examined as a method of achieving a longer filter life. This would enable filtration by the capture of particles in the spaces between the fibers of the non-woven filter, at the same time as cake filtration by the capture of particles on the surface of the wet-type filter.

6.1. Oil-impregnated Non-woven

The ability of the fibers to hold oil is an important issue in achieving cake filtration using a non-woven filter. Fibers with unusual forms that resulted in increased surface area were therefore compared in terms of oil adhesion and retention. Figure 9 shows cross-sections of the fibers. Figure 10 shows oil retention. Oil retention is highest in the high surface PET.

Comparison of the performance of a wet non-woven with a standard circular cross-section PET and a wet non-woven with a high surface PET showed that the latter

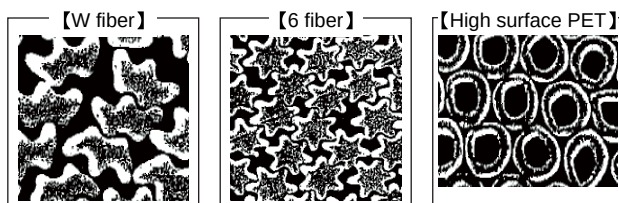


Fig. 9 Photo of fiber cross section

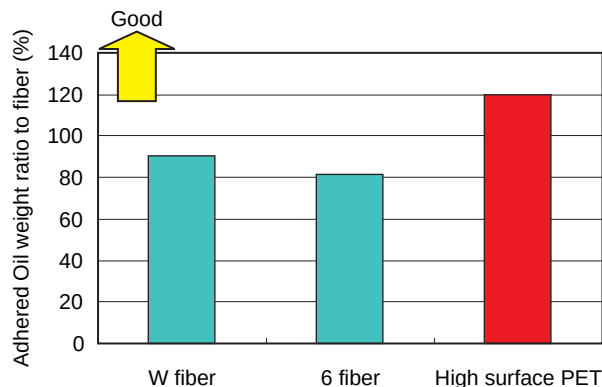


Fig. 10 Property of oil adhered to fibers

displayed lower air flow resistance at identical levels of cleaning efficiency (Fig. 11). This is believed to be because particles are captured on the fibers themselves rather than into the meshes. However, because making the filter a wet type reduced the amount of static electricity built up in the fibers and thus reduced carbon cleaning efficiency, a carbon capture layer was called for.

6.2. Optimization of Filter Performance and Dust Life by Multi-layering

Figure 12 shows an exemplar layer structure of the developed filter element with an added dry layer for carbon particle capture.

The use of a multi-layered configuration with rough wet layers of oil-impregnated fibers on the dust side and dry layers with a high density on the clean side has enabled the achievement of increased dust and carbon cleaning efficiency and increased dust life.

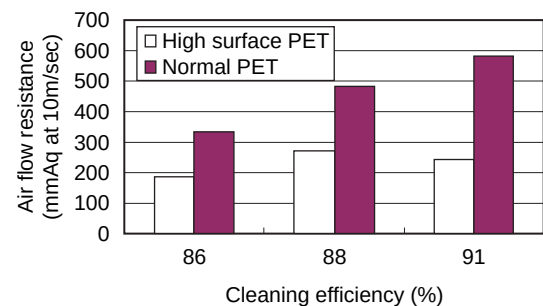


Fig. 11 Dust cleaning efficiency performance

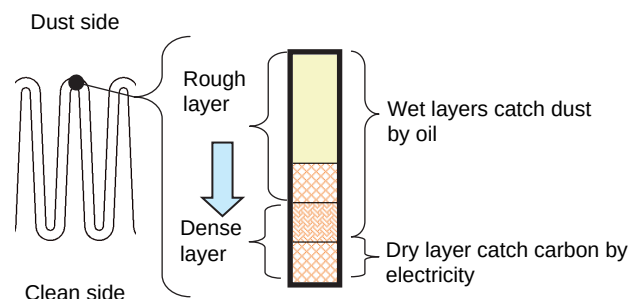


Fig. 12 Filter composition

7. Performance Level of Developed High-performance Filter Element

Figure 13 shows the dust life performance of the developed filter element.

Dust life has been increased against conventional filters without sacrificing cleaning efficiency or carbon life.

In addition, the optimization of the type of fibers employed and of the density of the fiber layers has

enhanced the ability of the filter to capture particles of all types and sizes, in particular JIS11 ultraparticles as shown in Fig. 14.

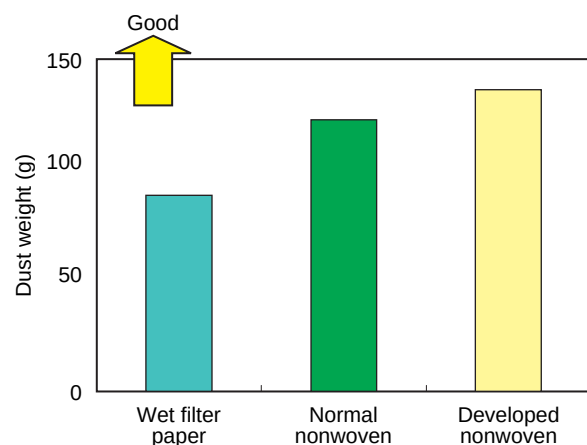


Fig. 13 Trapping dust weight by filter structure

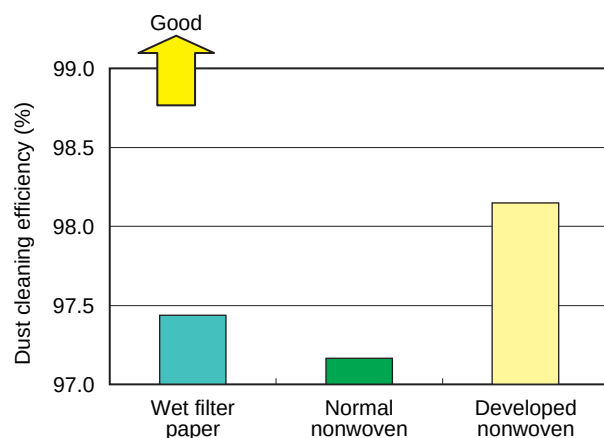


Fig. 14 Cleaning performance for ultra-fine particle (JIS Z 8901 TYPE11) dust

8. Conclusion

The achievement of long life and the enhancement of ultraparticle capture performance have represented issues in the development of filter elements. Based on an analysis of the mechanisms by which particles of various types are captured, the project discussed in this paper developed a filter with a multi-layered structure that reconciles the antagonistic needs of particle capture performance and long life.

The use of the new filter configuration has helped ensure dust capture performance in dusty environments at the same time as increasing dust and carbon life. The new filters have already gone into production, and have been employed in the new model ACCORD and FIT.

References

- (1) Sugimoto, T.: Roka-Mekanizumu to Rozai/Rokazyozai, Chijinshokan, p. 405 (1992) (in Japanese)
- (2) Takahashi, K.: Ouyouearozorugaku, Yokendo, p. 328 (1984) (in Japanese)

Author



Seiichi TANAKA



Toru TANAKA



Takayuki HOSOYA



Kenji KOGA

Paint Film Technology for Automotive Exterior

Hitoshi OHGANE*

ABSTRACT

A metallic finish decorative film that is able to be applied to automotive exteriors has been developed. Following application using a vacuum forming method, the film is UV-cured. The top layer is a clear UV-cured layer.

General purpose aluminum flakes have been applied in the base coat, and the paint viscosity and coating conditions have been adjusted to enable the achievement of a metallic finish. In addition, embossing of the top layer enables various design expressions, such as a matte satin plating. The new film shows greater elongation during forming and superior adaptability to parts than conventional decorative films, and is also more flexible than metallic plating.

The new film has been applied on the front grille of the new Acura TSX.

1. Introduction

A variety of methods of achieving a decorative finish on plastic components in order to increase their texture are in general use, including molding in color, coating, and plating of, and application of decorative films to, the plastic materials. The use of films is known as a decorative technology that involves less use and discharge of solvents and harmful substances than coating and plating^{(1), (2)}, and which is also highly adaptable to design initiatives such as the use of printed patterns. Today, increasingly stringent environmental regulations and increasing demand for more attractive styling in automobiles are driving the invention and development of new automotive film decoration technologies.

These technologies are also extensively used by Honda, for example for wood grain patterned paneling for vehicle interiors. However, because there is little need to use the printed patterns as design initiatives on vehicle exteriors, the exterior use of these decorative film technologies has been limited to certain areas – for example, to match the color of the door protectors to the color of the body as a substitute of paint. This situation made it desirable to develop methods of exploiting the adaptability of decorative films to design initiatives for use on vehicle exteriors.

2. Concept of Exterior Decorative Film

2.1. Decorative Colors of Exterior Plastic Components

Figure 1 shows the decorative colors used on the front grilles of Honda vehicle for Japanese market models as

an example of the demand for decorative coloration of exterior components. There is a greater need for styling design of the front grille than for other exterior components, and there is a high level of demand for metallic finishes, with almost three-quarters of the decorative finishes on the front grilles being metallic finishes achieved by plating or metallic coatings.

2.2. Performance Requirements for Exterior Films

The achievement of high-intensity coloring using physical vapor deposition of indium and the use of films to color the side protectors can be indicated as examples of the types of decorative techniques applied to plastic components on vehicle exteriors. While side protector films perform well when they used as a substitute for the body color paint, there is some concern that the use of metallic finishes will make surface deterioration and pollution (from damage caused by washing the vehicle, adherence of chemicals, etc.) more obvious. In addition

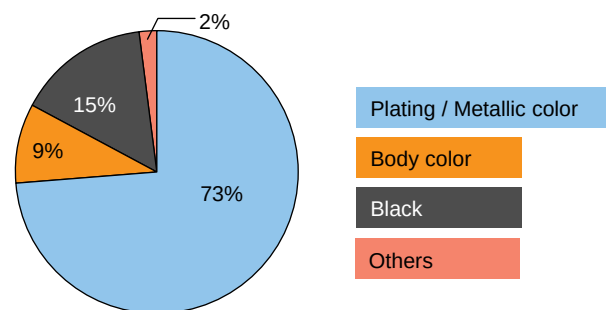


Fig. 1 Honda front grille color

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to meeting basic film performance requirements such as adhesion performance, a film used for a metallic finish would be expected to achieve a finish at least equivalent to that achieved by physical vapor deposition of indium in terms of external appearance following durability tests (resistance to damage, resistance to color change caused by chemicals, etc.).

In addition, because the shape of the front grille is more complex than that of the side protectors, the film would be expected to show a higher elongation rate in order to maintain both film performance and the correct color when the film was used on the grille.

3. Basic Specifications of Film

3.1. Layer Construction of Film

Figure 2 shows the layer construction of the film. The majority of standard automotive decorative films are applied using a sheet of a thermoplastic such as polymethyl methacrylate (PMMA), which is produced by extrusion. The project discussed here took a new approach and used a carrier film to form the coating. A clear layer, a color layer, and an adhesive layer are positioned in that order on a carrier film, and the adhesive layer is applied to the substratum plastic. This method offers the advantage of enabling the preforming and trimming procedures applied when using a thermoplastic backing sheet for a conventional decorative film to be discontinued, and releases a lower quantity of solvent during the production process than spray painting.

Because the film shows the metallic finish, a UV-cured layer with high scratch resistance and chemical resistance has been applied.

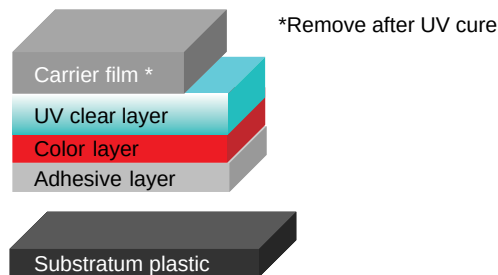


Fig. 2 Film layer construction

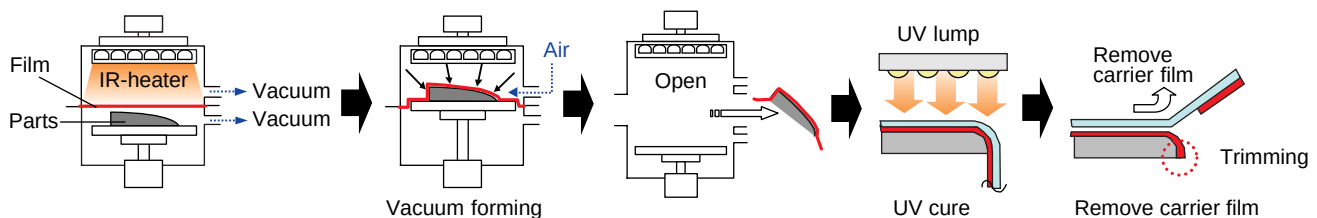


Fig. 3 Vacuum forming and UV cure process for paint film

In addition, from the perspective of repair costs, it is desirable for exterior plastic components to not be easily damaged by minor impacts. A highly impact-resistant alloy of polyamide and acrylonitrile butadiene styrene (PA+ABS), which has been used in front grilles and plastic front fenders, was therefore selected as the substratum plastic in this project, and an adhesive layer showing reliable adhesion with PA+ABS was developed.

3.2. Method of Overlay

A vacuum forming method is used to help ensure overlay of the film on the component. Figure 3 shows an overview of this method.

In a completely sealed vacuum chamber, the film is heated to render it flexible, and it is overlaid to the component in a vacuum forming procedure. At this stage, cross links have not formed in the UV clear layer, and it remains highly ductile. After the film has been overlaid to the substratum plastic, ultraviolet light is shined on it from above the carrier film in order to harden the UV clear layer. In the final procedure, the carrier layer is removed, leaving three paint layers on the surface of the component.

The use of UV curing following overlay of the film in this method helps ensure that the film can be formed onto the substratum when overlaid, and that a high cross-linking density is achieved in the top layer following the production process.

4. Metallic Finish

4.1. Achievement of a High-intensity Color Layer

Physical vapor deposition of metals to produce a laminated film is one example of the commercial use of metallic finish films. However, a larger number of procedures are involved in the manufacture of laminated films, and the films also have a higher number of layers. The project discussed here used general-purpose aluminum flakes as a simpler and lower-cost method of producing a metallic finish.

The color layer was applied over the UV-clear layer using a coater. Figure 4 shows a schematic of the film coating process.

Figure 5 shows the relationship between the paint viscosity of the color layer and intensity value (brightness

measured from the front of the component). Until a viscosity of about 5000 cps, the intensity value increases with viscosity. When this level of viscosity is exceeded, intensity values become saturated and basically constant. As the viscosity increases, imperfections such as streaks in the coating begin to appear. The range from 2000 to 6000 cps was therefore set as the appropriate viscosity for the achievement of a high intensity value.

Figure 6 shows the relationship between coating velocity and intensity value. The intensity value increases with coating velocity until a velocity of 10 m/min is exceeded, at which point the intensity value becomes saturated and basically constant. These results indicate that one point to be considered in achieving a high-intensity value finish using film coating is how to apply shear force to the base paint containing the aluminum flakes. It was conjectured that the application of a strong shear force to the base layer would generate a stronger alignment in the aluminum flakes, resulting in increased intensity value. Figure 7 shows a comparison between the intensity value

of a normal spray-painted metallic finish front grille and the film developed in this project. Film coating resulted in the achievement of a higher intensity value than spray-painting on the component used in the comparison. It is hypothesized that the alignment of the aluminum flakes is more easily enhanced when applying film coating than when applying spray-painting.

4.2. Embossing of the Surface Layer

Exploiting the characteristics of the laminate overlaying method, the use of embossing of the carrier film as a design element was examined. Figure 8 shows an image of the embossing procedure. Used in combination with the base layer that produces the metallic finish, this method enables the achievement of different designer finishes, such as a satin (matte) plating finish.

Figure 9 shows a prototype front grille using a satin plating finish film. Table 1 shows appearance data on satin plating and the satin plating finished film. Optimization of the intensity value of the base layer and

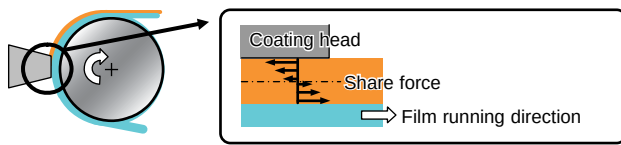


Fig. 4 Image of base paint coating

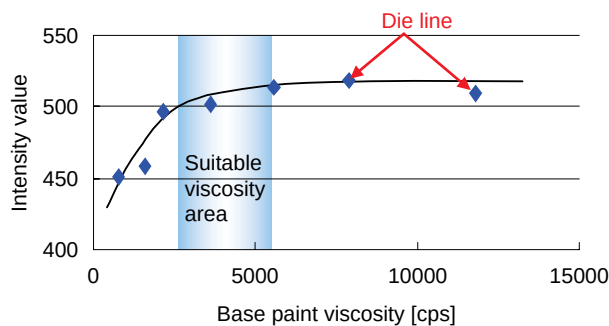


Fig. 5 Relationship between paint viscosity and brilliance

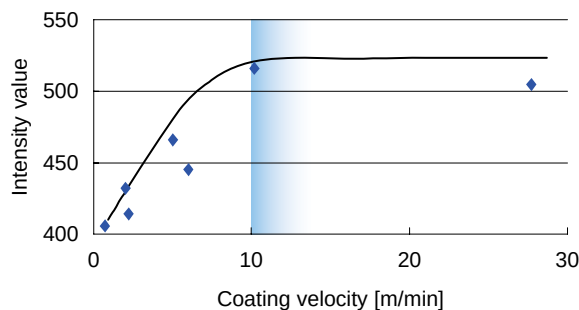


Fig. 6 Relationship between coating velocity and brilliance

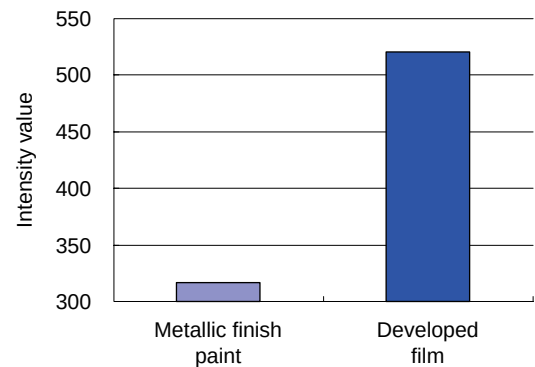


Fig. 7 Comparison between spray paint and film

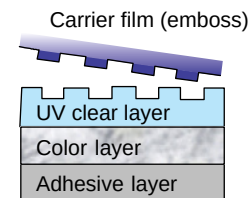


Fig. 8 Image of embossing

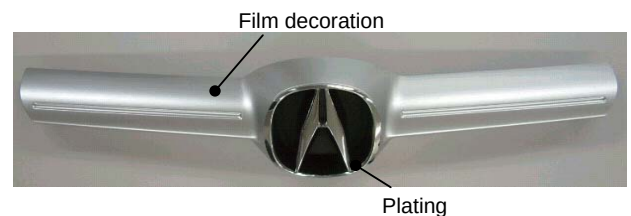
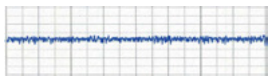
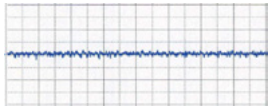


Fig. 9 Satin film proto-part

Table 1 Comparison between satin plating and developed satin film

	Surface roughness chart	Intensity value	Gross
Satin plating		450	55
Developed satin film		480	58

the embossing procedure has enabled the achievement of appearance close to those of the satin plating. In addition, the type of pigment used in the base layer and the type of embossing applied to the carrier layer can be changed, increasing the range of design variations available for the metal plating.

5. Product Performance

5.1. Flexibility

The flexibility of films can be indicated as one factor making film decoration superior to metallic plating. However, the standard UV-cured paints used for applications such as vehicle headlight lenses have low flexibility, and are therefore not superior to metallic platings without modification. Taking its use on flexible substratum plastics into consideration, the project therefore modified the UV-cured film to increase its flexibility. Flexibility was evaluated by bending tests conducted with the film overlaid to the substratum plastic. The bending test method is shown in Fig. 10. Test pieces coated with films were bent at 90° across a steel pipe of 1/2 inch in diameter for approximately 1 second, and the film was checked for breakage. The results of the tests are shown in Table 2. As comparisons, a UV hard coat and a standard plastic paint were tested at the same time. The substratum plastic in all cases was PA+ABS. The results indicate that the developed film shows sufficient flexibility for use on exterior components.

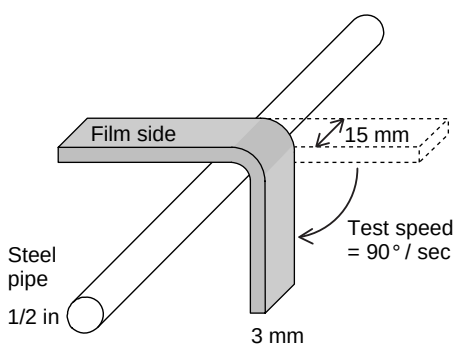


Fig. 10 Bending test method

Table 2 Bending test result

Test temp.	Criteria	UV hard coat	Painted front grille	Developed film
Room temperature	Film non-break	Break	Non-break	Non-break
-30°C	Base resin non-break	Break	Non-break	Non-break

Table 3 Car wash machine test result

		Top layer material	Rating point of car wash resistance
Film	Developed	UV cure type acrylic resin	1
	Body color film for door molding	PVDF / PMMA	5
Spray paint		Polyurethane	1

Rating point: GOOD ← 1 2 3 4 5 → POOR

Table 4 Film elongation and property

Item	Film elongation rate		
	100% (initial)	150%	200%
Color retention	Initial	$\Delta E \leq 1.5$	$\Delta E \leq 3.0$
Adhesion	100/100	100/100	100/100
Chemical resistance	No change	No change	No change
Gasohol resistance	≥ 60 min	≥ 60 min	≥ 60 min
Rating point of car wash resistance	1 point	1 point	1 point
Bending resistance	Non-break	Non-break	Non-break
Weatherability	No problem	No problem	No problem

5.2. Film Performance

Table 3 shows the results of a test of damage in a car wash machine. A rating of 1 represents the highest level of resistance to damage. The use of a UV-cured clear layer has increased the resistance of the film to car wash damage against a standard film for exterior use, and has enabled the achievement of the target, an equivalent level of damage-resistance to a vapor-deposited decoration of indium. The film also satisfies other performance requirements for decorative films used on vehicle exteriors, including gasohol resistance.

Table 4 provides an overview of the properties of the film at different elongation rates. The film satisfies requirements, including color retention and durability, up to its maximum elongation rate of 200%.

5.3. Use on Components

The developed film has been applied on the front grille of the new Acura TSX. In addition, because the film has the properties listed below, it is expected to be used on a wide range of components in future.

- (1) The developed film is more flexible than metallic platings, and film breakage will not result from a certain degree of deformation, e.g. as a result of minor impacts,

and a reduction in repair costs can therefore be expected. The film is also expected to be used in applications in which there are restrictions on the use of metal platings, for example at the outer edge of the transmission area of millimeter wave radar. In addition, no harmful substances such as heavy metals are used in the manufacture of the film.

- (2) Less solvent is emitted in the application of the film to components than in spray painting, and the film enables the realization of designs that would be difficult to achieve using spray painting.
- (3) Compared to a conventional film, the developed film achieves a reliable balance between elongation during the forming process and surface performance on the component. In addition, because no backing sheets are used, the pre-forming and trimming procedures can be discontinued or abbreviated.

6. Conclusion

- (1) A decorative film featuring a UV-cured clear layer that is UV-cured following lamination to the component in a vacuum forming method has been developed.
- (2) The developed film enables the achievement of metallic finishes (satin plating finishes, etc.), and satisfies the performance requirements for use on exterior components, including resistance to damage in car wash machines.
- (3) The developed film has reliable bendability, and a low level of harmful substances is discharged during its manufacture.
- (4) The developed decorative film has been applied on the front grille of the new Acura TSX. It is expected to be used on a wide range of components in future as one method enabling a metallic finish to be achieved on exterior plastic components.

References

- (1) Kasahara, H.: Yuki Haiki Shori Shisutemu, Kankyo Taiougata Hyoumenshorigijutsu, Tekunoshisutemu, p. 389-392 (2005) (in Japanese)
- (2) Nakamura, T.: Purasutikkumetaraijingu Gijutsu to Kankyou Taiou, Kankyo Taiougata Hyoumenshorigijutsu, Tekunoshisutemu, p. 571-575 (2005) (in Japanese)

■ Author ■



Hitoshi OHGANE

Development of New Pearl White Color for Body Coating

Keisuke KOJIMA* Shinichi IKEHARA**

ABSTRACT

Color plays an important role in styling, which is a major element in the appeal of a vehicle. Pearl white is particularly important as a color imparting a “premium” quality to a vehicle. Because of this, the rate of use of the color in the domestic market is high, and it has reached market maturity. In order to increase the commercial appeal of the color, the project discussed here focused on the development of a new high-quality pearl white coating. First, a survey of customer preferences was conducted, enabling quantitative axes for the evaluation of feelings in relation to color to be established. Development targets were set on this basis. The development of a white primer surfacer with high yellowing resistance and color hiding ability enabled the process of application of a white color base coat to be discontinued. As a result, a higher level of atomization could be achieved and the mica base coat could be applied in two stages, producing a higher level of orientation of the mica. This has enabled the realization of a pearl white color with a strong pearl feeling previously unattainable on a conventional mass production line.

1. Introduction

Styling elements represent one aspect of the appeal of a vehicle. In the 2002 APEAL Study conducted by J. D. Power and Associates, styling elements topped the list of aspects of a vehicle that appeal to customers (Table 1). The term “styling” tends to produce an image of the shape of the vehicle body, but the visual quality of the paintwork is also an important element of styling, placing seventh in a list of 116 categories. Color is a major element in the visual quality of the paint. Vehicle colors are influenced by the social trends, the state of the economy, and other aspects of the specific period in question. A survey of color trends today shows silver to be the most popular vehicle color, followed by white. In the Japanese market, super white was the most-used white color in the 1980s. While the popularity of the color showed a decline in the 1990s, white has continued to be extensively used, and remains a staple color. Today, in almost all cases, pearl white is the white color employed in the Japanese market. Used as a color for luxury vehicles, pearl white is also becoming an important color in enhancing the appeal of premium brands in the North American market.

Against this background, value can be seen in moving away from the use of a color that has reached maturity

in the domestic market, and the development of a pearl white giving a stronger image of a “premium vehicle” for the North American market is desirable, but restrictions on the vehicle painting process and on manufacturing costs have made this a challenge.

This paper will discuss the development of a new pearl white paint that can be used on mass production lines and offers a high sense of quality.

2. Criteria for Evaluation of Pearl White Color and Development Targets

It is important to obtain a grasp of customer preferences in order to attempt to increase the appeal of a product in a mature market. A factor analysis was therefore conducted to determine the nature of the sense of quality customers received from pearl white colors. Models of sports cars were coated with 12 pearl white variants. Prior to the factor analysis, 15 descriptive adjectives from the field of color design and their antitheses were selected (Table 2). A survey was conducted in which these adjective pairs and customer preferences were ranked in seven stages. The test subjects were Honda employees (38 men and 23 women) with no special knowledge in the area of color, ranging in age

* Automobile R&D Center

** Honda Motor Co., Ltd.

Table 1 Correlation coefficient of "Fun to Drive" score and score of each question

Ranking	Questionnaire		Correlation coefficient
1	Style	Overall rating	0.931
2	Style	Side profile appearance	0.928
3	Style	Uniqueness of your vehicles overall styling	0.925
4	Style	Front end style	0.923
5	Style	Exterior styling	0.918
6	Style	Appearance of exterior molding and trim	0.911
7	Style	Appearance of exterior paint	0.897
8	Handling	Feel of steering wheel	0.896
9	Style	Ext/int color coordination	0.891
10	Style	Appearance wheels/rims	0.890
11	Style	Rear end style	0.887
12	Handling	Steering effort	0.854
13	Other	Heater keeps interior warm	0.844
14	Interior	Styling of the seats	0.838
15	Handling	Brakes smooth in panic stop	0.835
16	Interior	Overall rating	0.834
17	Interior	Interior styling	0.834
18	Interior	Interior smell	0.834
19	Handling	Brakes slow vehicle quick and safe	0.831
20	Handling	Hold driver when cornering	0.830
21	Other	Rate how quickly the heater gets warm	0.830
22	Style	Open/close side door	0.829
23	Handling	Overall braking	0.825
24	Interior	Interior color coordination	0.821
25	Other	Front defroster performance	0.817
26	Handling	Stability on winding roads	0.815
27	Interior	IP design	0.815
28	Handling	Overall rating	0.813
29	Power plant	Perf in 2-wheel drive	0.811
30	Interior	Understand gauges/instr	0.811
31	Interior	Look/feel of ip materials	0.804
32	Power plant	Smoothness during hard accel	0.801

Table 2 Adjective pair and result of factor analysis

Adjective pair				Factor loading			
				1st factor	2nd factor	3rd factor	4th factor
7 ← Score → 1				Pearl feeling	Novel feeling	Male-female feeling	?
Feminine	女性的な	Masculine	男性的な	0.0166	0.1941	0.9071	0.2989
Natural pearl	天然パールのような	Artificial pearl	人工パールのような	0.7373	-0.1129	0.6604	0.0792
Silky	シルキーな	Glare	ギラギラしている	0.8101	-0.2202	0.4122	-0.0201
Delicate	落ち着いた	Glitter	派手な	0.5361	-0.8026	0.1970	-0.1456
Three dimensional	3次元的な	Non three dimensional	3次元的でない	0.7742	0.2242	-0.0330	-0.3200
Bright	明るい	Dark	暗い	-0.2307	0.6338	0.1509	0.5502
Luxury	ラグジュアリー	Sporty	スポーティ	0.3789	-0.1100	0.8620	-0.1712
Color travel	色が変化する	Non-color travel	色が変化しない	0.5971	0.7856	-0.0562	-0.0688
Gentility	上品な	Vulgarity	下品な	0.8179	-0.4007	0.2891	0.0430
Valuable	高価に見える	Cheap	安っぽく見える	0.9187	0.0676	0.2503	-0.0728
Novel	目新しい	Commonplace	ありきたりな	0.0901	0.9349	-0.0739	-0.0009
Fine particles	粒子が詰め込まれた	Rough particles	粒子が詰め込まれていない	0.9002	0.1620	0.2311	-0.0910
Gorgeous	ゴージャスな	Simple	シンプルな	0.1892	0.8785	0.3065	-0.0602
Warm	暖かい感じ	Cool	冷たい感じ	0.3223	-0.0780	0.9099	-0.1068
Contemporary	先進的な	Classic	クラシックな	-0.3141	0.7466	-0.3526	0.4018
Like	好みのカラーだ	Dislike	嫌いなカラーだ	-	-	-	-
Contribution ratio(%)				37.62	25.92	25.48	3.56
Accumulative contribution ratio(%)				37.62	63.54	89.02	92.58

from their 20s to their 50s.

The results of this factor analysis are shown in Table 2. Up to the third factor, the accumulative contribution ratio was 89%, but from the fourth factor, the contribution ratio was less than 3.6%, and this was therefore excluded

from consideration. The first factor was judged as the axis representing the feeling of pearl in the color, as selected from the adjective pairs with the highest factor loading, the second factor as the axis representing the feeling of novelty of the color, and the third factor as the axis

representing the feeling of “masculinity” or “femininity” of the color. Figure 1 shows the correlation between scores for these three factors and the preference scores that were surveyed in parallel with them. The factor score for the feeling of pearl in the color displayed a strong correlation coefficient at 0.8325, but no correlation was observed in the case of the factor scores for novelty and masculinity-femininity, with correlation coefficients of 0.0700 and 0.1442 respectively. Based on these results, despite the fact that customers would perceive the sense of quality in the pearl white color in terms of these three factors, because only the “feeling of pearl” factor would be used in evaluating preference, increasing the feeling of pearl in the color was established as the strategy for increasing the appeal of the color.

Three axes were established for the evaluation of the feeling of pearl in the color. An appearance of three-dimensionality (“three-dimensional feeling” below) and the sense that the mica flakes in the pigment were arranged in a high density (“feeling of fineness and high density” below) were selected as evaluative axes from the adjective pairs with the highest factor loading for the first factor, and the brightness on the face, providing an image of “advancement,” was selected as the third axis based on a unique design taste. The level of “flip-flop” (FF value)

was used as the quantitative target for the three-dimensional feeling, HB value for the feeling of fineness and high density, and IV value for the brightness on the face. FF values are an index that expresses the level of contrast between highlighted sections and shadowed sections. The higher the value, the more three-dimensional the curved sections of the vehicle body will appear. HB values are an index expressing the level of glare of the flakes used to achieve brightness. The denser the flakes are arranged, the silkier the appearance and the lower the HB value. IV values express the level of brightness of the highlighted sections. The higher the value, the brighter they appear.

The development target for the new pearl white color was set as the achievement of higher figures in terms of each of these evaluative axes than those of the current pearl white color (Fig. 2).

3. High-quality Pearl White Paint

3.1. Orientation of Mica and Pearl Feeling

With a few exceptions, the structure shown in Fig. 3 is used in the majority of pearl white automotive body coatings. It was conjectured that the feeling of pearl in the color would change depending on the degree of

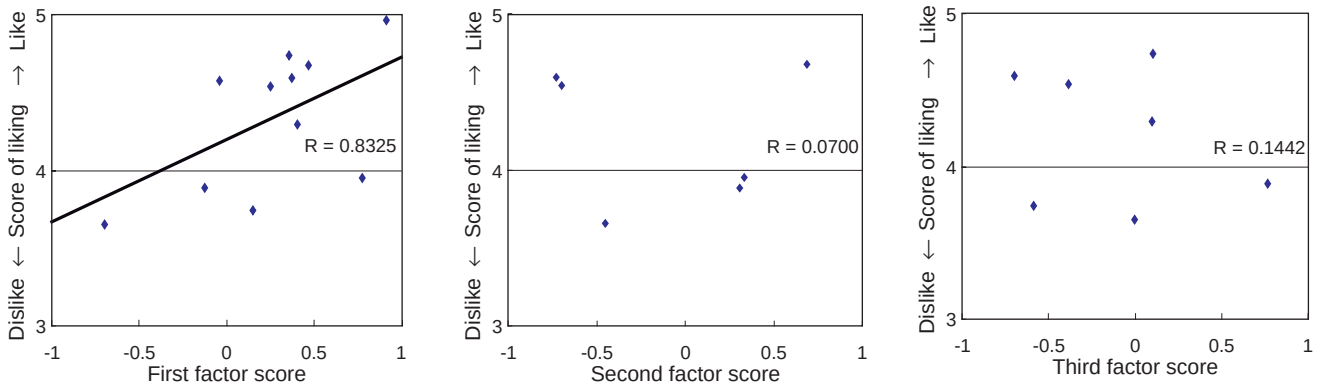


Fig. 1 Correlation between score of liking and each factor score

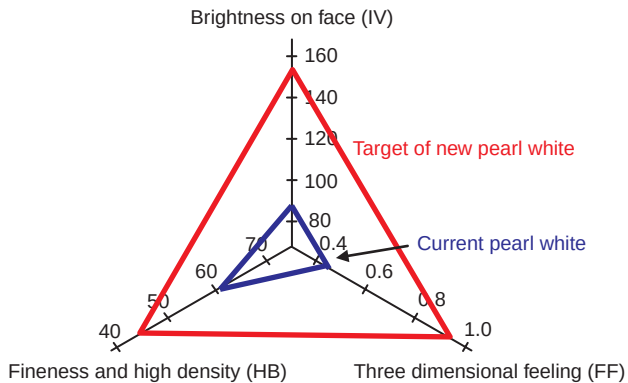


Fig. 2 Target of new pearl white

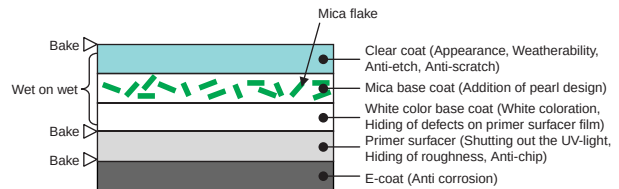


Fig. 3 Current film system of pearl white color for body coating

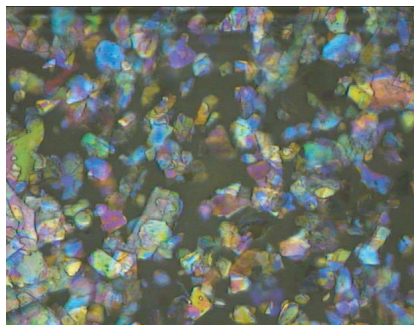
reflection, transmission, and interference of light due to the orientation of the mica in the mica base layer. Paints with two different levels of mica orientation were produced and analyzed in order to determine the relationship between the orientation of the mica and the pearl feeling (Fig. 4). Sections in which the mica is oriented in parallel with the surface of the paint show as white, while sections in which the mica is not oriented in parallel show as grey. Sample B, which displayed a higher whiteness ratio, had a higher level of mica orientation, and recorded good FF, HB, and IV values. This indicated that there was a correlation between an increased level of mica orientation and an increased pearl feeling.

3.2. Status and Issues of Pearl White Color Coating

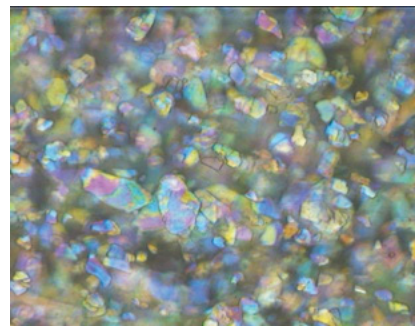
The achievement of the targets discussed above using the current painting process and current paint materials represented a challenge. Broadly speaking, there were two reasons for this. The first of these was the one-stage application of the mica base coat. Following baking of the e-coat and the primer surfacer, the white color base coat

is first applied, after which the mica base coat is applied while the former is still wet (Fig. 3). This wet-on-wet application in the current painting process means that unlike other colors, in which the same coat is applied in two stages, the mica base coat that determines the feeling of pearl in the color is applied in only one stage. Because of this, there is no choice but to achieve a high flow rate for the mica base coat, which reduces the level of fine atomization, in turn limiting the level of orientation of the mica.

The second factor was the wet-on-wet application of the white color base coat and the mica base coat. As shown in Fig. 5, an increased feeling of pearl is achieved when the mica base coat is applied following baking of the white color base coat than when wet-on-wet coating is employed. The mechanism behind this is thought to be the generation of a convection current between the layers ("layer mixing" below) during wet-on-wet application (Fig. 6). In addition to disordering the orientation of the mica, this reduces the usable amount of mica due to its permeation into the white color base layer, thus impeding the increase of the mica orientation.



Sample (A) applied by spray (Low-oriented mica)
IV:90, FF:0.45, HB 65



Sample (B) applied by barcoater (High-oriented mica)
IV:137, FF:0.76, HB 54

Fig. 4 Micrograph of different level of mica orientation

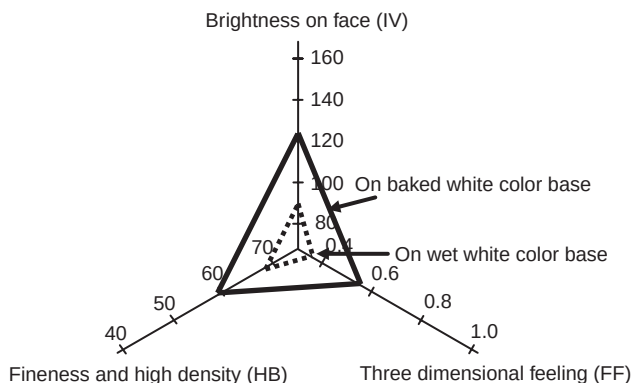


Fig. 5 Pearl feeling difference between on baked white color base and on wet white color base

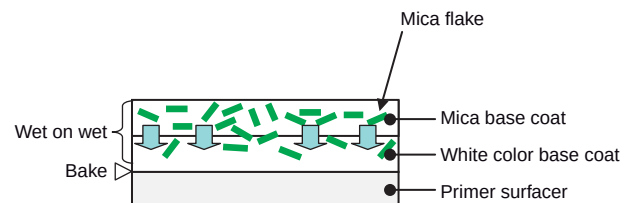


Fig. 6 Mechanism of disorder of mica orientation by convection of white color base coat and mica base coat

3.3. Technology for Achieving Increased Orientation of Mica

Removing the two factors discussed above was the key to increasing the feeling of pearl in the color. The first issue, the one-stage application of the mica base coat, could be addressed by applying the coat in two stages. Doubling the stages of application would halve the requisite flow rate in each stage. This would increase the level of fine atomization, in turn increasing the orientation of the mica via the mechanism shown in Fig. 7.

The method studied to enable this was the replacement of the former first stage, the application of the white color base coat, by the application of a mica base coat, resulting in a two-stage application of the coat.

In the same way, the second issue, the wet-on-wet application of the mica base coat to the white color base coat, could be addressed by incorporating the functions of the white color base coat in the primer surfacer film, thus enabling wet-on-wet coating to be done away with. Because the primer surfacer film was a hard film, there would be no layer mixing with the mica base coat.

The application of the methods discussed above enabled the achievement of the targets for the pearl feeling using existing coating lines, with no increase in space (Fig. 8).

3.4. Technological Issues and Responses

The major technological issues associated with the application of the above methods related to the incorporation of the functions of the white color base coat in the primer surfacer film. Several issues arose in this connection, and these related to imperfections in the primer surfacer film. Because the mica was employed in the form of transparent flakes, the imperfections in the primer surfacer tended to be visible. These visible imperfections would make it challenging to present a quality product to customers.

The first of these imperfections was yellowing of the primer surfacer film. This yellowing occurs because the peroxide chromophores that are a by-product of the oxidation of the plastic during baking are yellow⁽¹⁾⁻⁽³⁾. The degree of yellowness is dependent on the baking temperature and the time spent in baking. On the production line, the baking temperature and time changes

depending on the section of the vehicle body, the length of residence in the baking oven during the rest period, and the application of repairs to the top coat, among other factors. When these factors are in operation during baking at high temperatures and for extended periods, yellowing occurs in the current primer surfacer film, but because of the application of the white color base coat, the imperfection is ultimately hidden. However, this would not be the case when the white color base coat was no longer applied.

The second imperfection was visibility of the color of the e-coat. The e-coat film, which sits beneath the primer surfacer film (Fig. 2), is dark grey in color. Using only the white primer surfacer coat, this color would be easily visible. At present the white primer surfacer and the white color base coat help prevent the color from being visible, but the removal of the white color base coat would enable it to be seen.

To address these technological issues, it was decided to increase the yellowing resistance and enhance the color hiding performance of the white primer surfacer coat. Modification of the primer surfacer was therefore examined.

The target for yellowing resistance was set as a yellow value (color notation: Δb^* value) of 0.5 or less, such that a difference between a film that had received the maximum thermal history projected for the production line and a film that had received the standard thermal history could not be perceived in a visual comparison. Based on

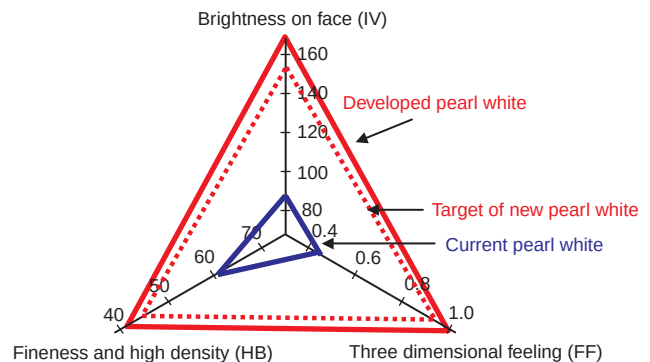


Fig. 8 Pearl feeling potential of new pearl white technology

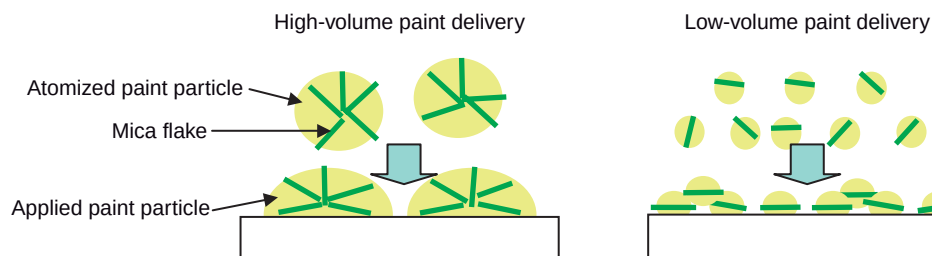


Fig. 7 Mechanism of enhancing mica orientation by low size atomization

the mechanism of yellowing, in order to enhance resistance to yellowing, studies were conducted to determine the type and amount of an anti-oxidant agent to be added to help prevent oxidation, and of a peroxide decomposing agent to break down the peroxides that had formed in the oxidized plastic.

On the basis of the yellowing resistance target value and the degree of hardening of the material, the design values for the coating were set at 1.0 parts per hundred resin of a special anti-oxidant agent and a peroxide decomposing agent (“parts per hundred resin” is abbreviated as PHR below) (Fig. 9).

The target for color hiding performance was selected as lack of visibility of the base color through a film of 27 μm in thickness, based on the assumption of 3 μm being abraded from the surface of a film of the lowest thickness of 30 μm . (3 μm is the normal amount abraded from the surface in repairing an imperfection). The definition of lack of visibility was a color difference (color notation: ΔE^* value) of 0.3 or less in a comparison of an area of film of a thickness able to hide white and black and a 27 μm thick area of film, such that no difference could be determined visually.

Color hiding performance was enhanced by adding aluminum flakes^{(4),(5)} and increasing the amount of the white pigment titanium oxide that was employed. Depending on the amount added, the addition of

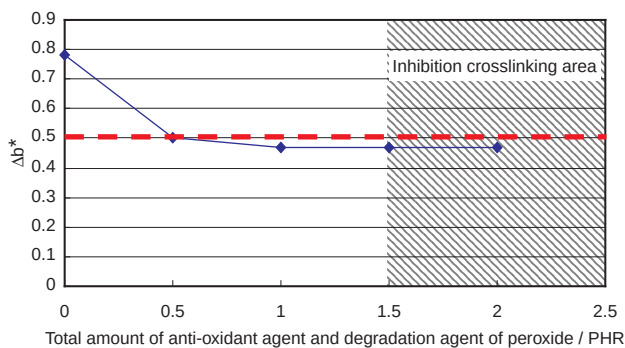


Fig. 9 Effect of addition of additive for anti-yellowing

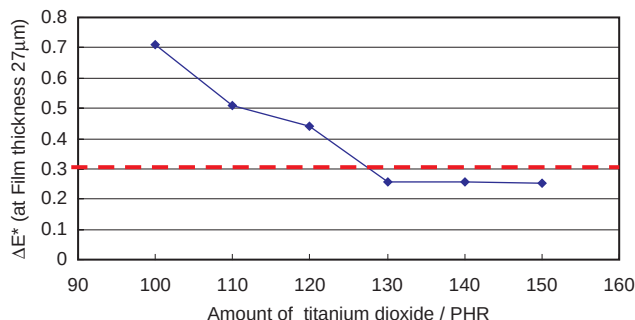


Fig. 10 Effect of addition of titanium dioxide for color hiding

aluminum flakes is an effective method of enhancing color hiding ability, but because the substance is grey in color, there is a limit to the amount that can be added while maintaining the target whiteness value (color notation: L^* value) of 92. The limit was set at 3 mass% of the mass of titanium oxide added. The amount of titanium oxide to be added was set at 130 PHR, a figure at which color hiding ability becomes saturated (Fig. 10). The application of these methods enabled the achievement of target performance, with color hiding at a film thickness of 26 μm .

4. Conclusion

The use of the technologies discussed above has enabled the realization of a pearl white color with a pearl feeling previously unattainable on current mass production lines. The development can be summarized as follows:

- (1) The feelings of customers towards white pearl colors (pearl feeling, feeling of novelty, feeling of “masculinity” or “femininity”) were isolated. Development targets were set using the pearl feeling axis, the only axis that demonstrated a strong correlation with customer preference.
- (2) It was determined that it would be necessary to increase the level of orientation of the mica flakes in the paint in order to increase the pearl feeling of the color. In order to increase the fineness of the atomization of the paint and increase the level of orientation of the mica, the functions of the white color base were incorporated in the primer surfacer film, enabling the white color base application process to be abandoned and the mica base coat to be applied in two stages.
- (3) The new issues raised by imperfections in the primer surfacer film were addressed by increasing the resistance to yellowing and the color hiding ability of the primer surfacer.

5. Afterword

In the 1980s, pearl white was a color reserved for luxury vehicles in the Japanese market. It was able to be applied only to luxury vehicles because of its high production cost. At the time, the primer surfacer was applied in two coats, and no enhancement in terms of yellowing performance or visibility, of the type discussed above, were made. Increasing the amount of coating procedures on a normal coating line would generate issues of productivity and cause efficiency to decline, and a specialized coating line was therefore established. In the 1990s, the strong commercial appeal of the color led to increased demand for its employment on regular vehicles. To enable this, the coating method currently in use, in which the primer surfacer is applied in one coat, was developed. This resulted in rapid diffusion of the color, and it has now reached a stage of market maturity. This

made it challenging to develop a pearl white with a stronger pearl feeling, to distinguish it from the pearl white colors used by competitors. For this reason, techniques involving the use of mica and other brightening agents in special coatings in order to produce a sense of individuality have been employed. The technology discussed in this paper represents a base technology that enables the realization of a stronger pearl feeling while maintaining the current level of productivity, and can be expected to contribute to further evolution of the pearl white color. Use of the new pearl white coating will commence with the 2008 year model ACURA RL, and it will begin to be employed in a wider range of models following this.

References

- (1) Okatsu, Y.: Dai 18 kai Kobunshi no Rekka to Anteika Kiso to Ouyou Kouza, Kobunshigakkai Kouen Yoshisyu, Tokyo, 1998-7-2/3, The Society of Polymer Science of Japan, p. 1-5 (1998) (in Japanese)
- (2) Tsunooka, M.: Dai 18 kai Kobunshi no Rekka to Anteika Kiso to Ouyou Kouza, Kobunshigakkai Kouen Yoshisyu, Tokyo, 1998-7-2/3, The Society of Polymer Science of Japan, p. 6-13 (1998) (in Japanese)
- (3) Sasaki, M.: Dai 18 kai Kobunshi no Rekka to Anteika Kiso to Ouyou Kouza, Kobunshigakkai Kouen Yoshisyu, Tokyo, 1998-7-2/3, The Society of Polymer Science of Japan, p. 55-58 (1998) (in Japanese)
- (4) JP, 2609513, B (1997)
- (5) JP, 3755844, B (2006)

■ Author ■



Keisuke KOJIMA



Shinichi IKEHARA

Verification Test of Solar-powered Hydrogen Station (SHS) with Photovoltaic Modules

Masanori OKABE* Koji NAKAZAWA*
 Kenji TARUYA* Kiyoshi HANDA*

ABSTRACT

A solar-powered hydrogen station (SHS) with photovoltaic modules has been established to produce hydrogen with zero CO₂ emissions. The SHS has been stably producing hydrogen for almost four years, and also, the hydrogen supply for the Honda FCX fuel cell vehicle has been demonstrated. This operational status has demonstrated that stable hydrogen production can be achieved using a renewable energy source. Using only the variable power generated by the photovoltaic modules, the SHS system operates at an efficiency of approximately 53%, and produces approximately 1500 Nm³ of hydrogen per year, equivalent to 8000 miles-run by the FCX. Using verification tests, feasibility studies of a household renewable hydrogen station, projected as a future mode of hydrogen supply, have been completed.

1. Introduction

Honda has developed fuel cells as the ultimate clean power plants for the next generation, from the viewpoints of developing a substitute for fossil fuels, reducing exhaust gases, and reducing the effect of automobiles on global warming. It is desirable that hydrogen, which is used in a fuel cell vehicle, be produced as far as possible employing a method that does not use fossil fuels in the production, storage, and refueling processes. In other words, it is desirable to use renewable energy (for example electric power generated by photovoltaic modules), which does not affect the global environment, to produce hydrogen in the future.

However, if the input uses renewable energy independently, power fluctuations will occur due to the characteristics of such energy. Consequently, in the case of a large scale station system, it is challenging to predict the operation mode in advance, thus high efficiency during actual running cannot be expected. Generally, currently available photovoltaic modules are connected to the power grid. However, it is conceivable that as these modules come into increasingly widespread use, variable power that cannot be connected to the power grid will increase. The production of hydrogen for fuel modules using such variable power alone is effective from the viewpoints of utilizing renewed energy and smoothening electric power. Consequently, a system that can cope with fluctuations of

input power and is capable of operating at higher efficiency is needed for equipment that uses renewable energy to supply hydrogen. Accordingly, the development of a small hydrogen station that could cope with variable power and supply power from photovoltaic modules directly to a hydrogen production system has been pursued. In July 2002, a second generation solar-powered hydrogen station (SHS) incorporating Honda's unique technology was installed in Los Angeles in the state of California⁽¹⁾. In addition, in 2003, the weak points extracted via a verification test on the SHS were modified, and technical evolution was carried out to realize a hydrogen station of even higher efficiency⁽²⁾. This SHS continues to be subjected to a proving test in which hydrogen is produced from electric power generated by photovoltaic modules alone.

This concept of attempting to efficiently obtain hydrogen from the variable power of photovoltaic modules alone is relevant to the form of a household hydrogen station as a hydrogen supply configuration in the future. The SHS was installed for the following two goals, as a means of thinking about the form of a compact, highly efficient water electrolysis station.

- (1) The stable production of hydrogen from renewable energy
- (2) The production of hydrogen that enables the FCX to travel 10000 miles per year

This paper sets out a report on the results obtained

* Automobile R&D Center

with respect to the above goals, from the verification test of the SHS which has been carried out over a period of approximately 4 years.

2. Solar-powered Hydrogen Station (SHS)

Figure 1 shows the configuration of the SHS subjected to the verification test. The SHS consists of the photovoltaic modules, which generate electricity, and three other additional units: the water electrolysis unit for producing hydrogen, the dispenser unit that compresses the produced hydrogen and charges it to the FCX, and the high pressure tank unit that stores the high-pressure hydrogen.

From the viewpoint of reducing CO₂ emissions, it is desirable that the photovoltaic modules be thin film photovoltaic modules consisting of a copper-indium-potassium-selenium compound (CIGS). Accordingly, in the autumn of 2003, the photovoltaic modules were changed from single-crystal silicon photovoltaic modules to CIGS thin film photovoltaic modules. Figure 2 shows the installation condition of the photovoltaic modules.

The water electrolysis stack shown in Fig. 3 is mounted on the water electrolysis unit, aiming at compactness and higher efficiency. A highly active, highly durable ruthenium-based (Ru) catalyst, which is a newly

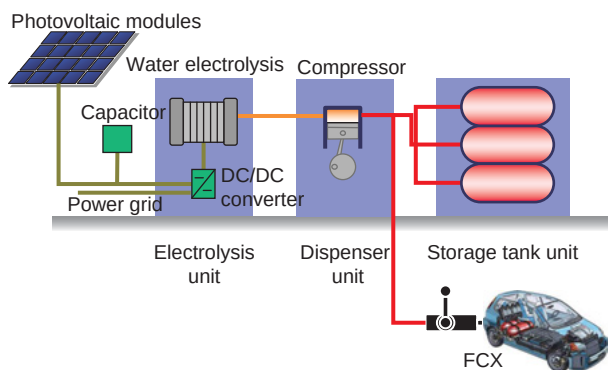


Fig. 1 Schematic diagram of SHS



Fig. 2 CIGS thin-film photovoltaic modules (prototype; manufactured by Honda Engineering Co.,Ltd.)

developed anode catalyst, is used for the stack.

All of the electric power generated by the photovoltaic modules is supplied to the system, and converted into hydrogen. Regarding the amount of hydrogen produced by the SHS, the amount that enables the FCX to travel 10000 miles per year is set to 2000 Nm³ from the fuel economy of the FCX⁽³⁾, and in order to achieve this, a sufficient number of photovoltaic modules to form a system of approximately 6 kW were mounted in the stack.

The SHS is actually a hydrogen supply station intended for performing a running test on the FCX, so it can also produce and store hydrogen by using the commercial power grid in order to cope with variations in weather and running distances.



Fig. 3 Water electrolysis stack using newly developed Ru-based catalyst

3. Verification Test of Hydrogen Production Using the SHS

3.1. Hydrogen Production Using Photovoltaic Modules

3.1.1. Production of hydrogen in one day using photovoltaic modules

Figure 4 shows the relationship between the amount of hydrogen produced in a typical day and the system efficiency. The system efficiency is the value of the produced hydrogen energy divided by the total amount of input power (energy). This value indicates the efficiency of the conversion of energy into hydrogen.

It was found that there was a tendency for the amount of hydrogen generated and the system efficiency to increase along with the increase in the generated power, which varies throughout the passage of the day. The total amount of hydrogen produced during this 1-day period is 5.4 Nm³, which enables the FCX to travel approximately 27 miles. This means that if this amount of hydrogen can be produced throughout the year, the target value will be achieved.

Along with the increase in the amount of electric power generated, the system efficiency reached an

instantaneous value of approximately 70% at the peak time of day. However, along with the intermittent startup of the compressor, the instantaneous efficiency during startup of the compressor fell by approximately 20%. Also, in the morning and evening and other time slots when the amount of power generated was low, the proportion of power generated by auxiliary devices increased, hence the amount of power used for hydrogen production decreased, thereby reducing the efficiency. As a result, the mean system efficiency calculated from the total amount of power generated and the total amount of hydrogen produced in one day was approximately 51.3%.

Figure 5 shows the relationship between the instantaneous amount of power (system input power) generated by the photovoltaic modules, and the system efficiency. The system efficiency showed a tendency to rise along with the increase in the input power, and indicated a possibility of the efficiency increasing if the input power was increased further. The reason for this is that for a rated output of 2 Nm³/hr (input power approximately 10 – 12 kW), the operation of the photovoltaic modules is a maximum of approximately 1.2

Nm³/hr (max power approximately 5.2 kW), enabling the input power to increase, and the power ratio of the auxiliary devices to be reduced. Also because of the power consumption due to startup of the compressor, a curve appeared even in the part where the instantaneous system efficiency fell by approximately 20%. Among the auxiliary devices, the power consumption ratio when the compressor started up was large.

3.1.2. Production of hydrogen for one month using photovoltaic modules

Figure 6 shows the amount of power generated, the amount of hydrogen produced, and the system efficiency for the whole month of August 2006. Apart from August 3, the weather was more or less fine, and it can be seen that a stable amount of electric power was generated. On almost all days, the generated output was at least 35 kWh/day. The amount of hydrogen produced was approximately 5.2 Nm³ per day and reached a maximum of 6.2 Nm³. The actual amount of hydrogen produced during this month was 160 Nm³, which enables the FCX to travel about 800 miles. If the production of hydrogen for this month remains stable throughout the entire year, it means that the FCX will achieve the target traveling distance of 10000 miles.

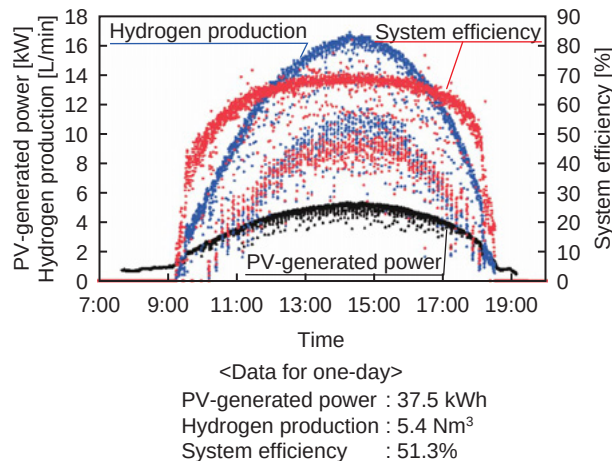


Fig. 4 Operating results for one-day in August 2006

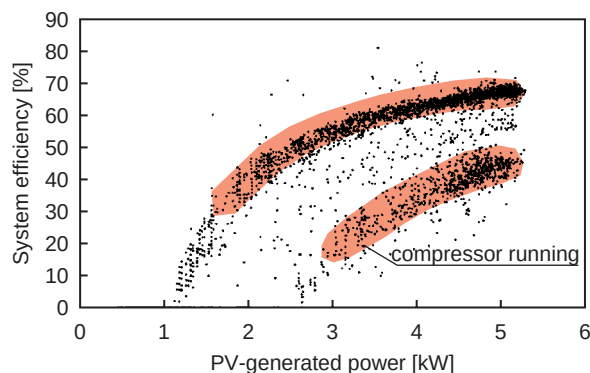


Fig. 5 Operating result for one-day in August 2006 (PV-generated power versus system efficiency)

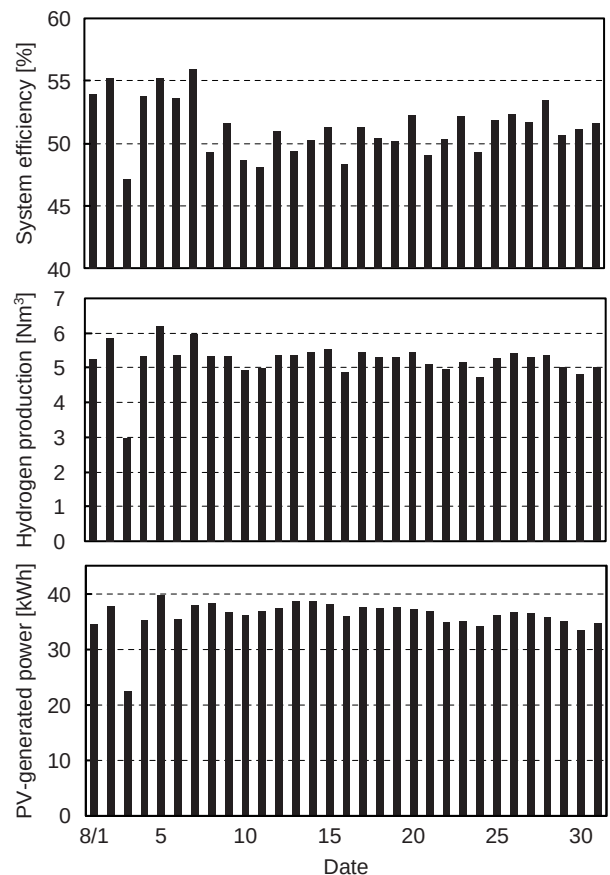


Fig. 6 Data for whole month of August 2006

However, the daily system efficiency varied between 48 and 56% even during the one month period in which stable hydrogen production was verified. One reason for this is that the power consumed by the compressor differs according to the difference in the storage tank pressure.

Figure 7 shows the power consumed by the compressor, for each storage tank pressure. The difference in the power consumption resulting from a change in the discharge pressure of the compressor between 7 MPa and 35 MPa is approximately 200 W/Nm³. This value is equivalent to 2-3% difference in conversion efficiency. Other reasons for the variation in efficiency are the fact that the necessary power for cooling the various parts (Peltier device, and the like) increases due to the rise in the atmospheric temperature, and also the fact that the auxiliary devices, such as the absorption tower recycling heater used in the production of hydrogen, start up.

From the above results, it can be said that the day-to-day fluctuations in the system efficiency were affected by the starting and stopping of the fluctuating auxiliary devices to a greater extent than the increase and decrease in the amount of power generated (input power) in one day. From this, it can be said that the reduction of the efficiency of the hydrogen production system which uses variable electric power can be minimized by using small devices that are relatively unaffected by the starting and stopping of the auxiliary devices.

3.1.3. Annual amount of hydrogen produced using photovoltaic modules

In order to evaluate the efficiency of an SHS that uses photovoltaic modules, it is recommended that a comparison of the efficiency be carried out by measuring the amount of hydrogen produced over a period of one year because the hydrogen production efficiency of the station varies according to the time, weather, season, and other factors.

Table 1 shows the amount of hydrogen produced over the past four years and also the corresponding system efficiency. The hydrogen production efficiency is 53%,

Table 1 Comparison of annual SHS performance

Year	2004	2005	2006	2007*
PV-generated power [kWh/day]	26.7	26.2	28.2	28.3
Hydrogen production [Nm ³ /day]	4.1	3.9	4.2	4.1
System efficiency [%]	54.1	52.2	53.2	52.3
Amount of produced hydrogen* [Nm ³]	1485	1400	1550	1520

*Data from January to July, 2007

and varies by $\pm 1\%$ over one year. This variation is smaller than the abovementioned day-to-day fluctuations, and indicates stable conditions. From this result, it was verified that in the case of the SHS, stable hydrogen production was maintained over a period of four years by using the variable power from the photovoltaic modules. Also, stable production of hydrogen using renewable energy, which is one of the goals of this research, has been achieved. When the amount of hydrogen produced in a year is estimated from the above efficiency value, a figure of approximately 1500 Nm³/year is obtained. This is equivalent to an FCX traveling distance of approximately 8000 miles.

Until now, hydrogen has been charged to the FCX one hundred and several tens of times using the SHS, and it is intended to continue performing this hydrogen refueling verification test.

3.2. Production of Hydrogen Using the Commercial Power Grid

In the production of hydrogen at the rated power using the commercial power grid, the electric power consumed by the auxiliary devices is the design value, so it is predicted that the SHS efficiency will be higher. In addition, it is considered that in the case of low power such as the power generated by photovoltaic modules, low current density electrolysis occurs, and the resistance loss is reduced, so reduction of efficiency does not occur. Accordingly, the efficiency obtained when the SHS was driven by constant electric power was compared with the necessary power consumption for producing 1 Nm³ of hydrogen. The results are shown in Fig. 8.

When the SHS was driven by a current of 50 A, which is equivalent to a current used in photovoltaic modules, the efficiency was 60.9%. In contrast, when the SHS was driven at the system rated current of 90 A, the efficiency was 66.3%. A detailed comparison of efficiency was performed, and it was found that when the system was driven at the rated system current of 90 A, the effectiveness of the power consumption ratio of the

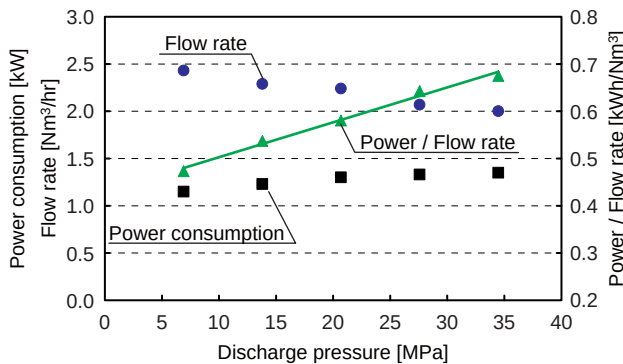


Fig. 7 Power consumption of compressor versus discharge pressure

auxiliary devices and the reduction of conversion loss due to operation at the high efficiency point of the DC/DC converter contributed to the increase in efficiency. In contrast, when the system was driven at 50 A, despite the fact that a reduction of loss in the water electrolysis stack was predicted, the electrolysis loss power actually increased due to the reduction of the temperature of the electrolysis stack. This is due to the fact that the amount of waste water from the heated water increased because the amount of pure water generated remained constant regardless of the electric power, and this is also due to the fact that the loss energy at low output is small, and the water temperature does not rise adequately.

It was found from the test results that the deficiency of hydrogen with respect to the initially planned amount of hydrogen to be generated from the abovementioned photovoltaic modules in one year was due to the following two factors.

- (1) Nonconformity between the actual zone in which the power converter (DC/DC converter) was used and the higher efficiency point
- (2) Reduction of the water electrolysis rate due to an insufficient increase in temperature in the highest operation current density zone of the water electrolysis stack (Stack not maintained sufficiently warm)

The above results suggest that even during operation at low output when photovoltaic modules are used, the stack efficiency can be raised by maintaining the electrolysis water temperature. Also, the prospect for raising system efficiency has become apparent. Furthermore, it was anticipated that the system efficiency could be increased by carrying out these measures in the case where photovoltaic modules were used, so the prospect for achieving a hydrogen production of 2000 Nm³, which would enable the FCX to travel 10000 miles per year, has also become evident.

3.3. Comparison with Other Hydrogen Stations

Figure 9 shows the results of comparing the efficiency

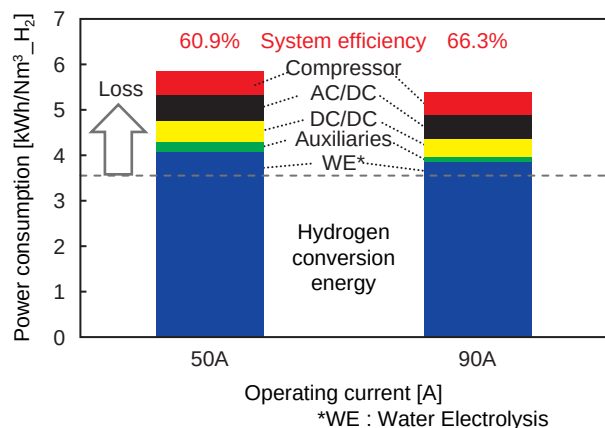


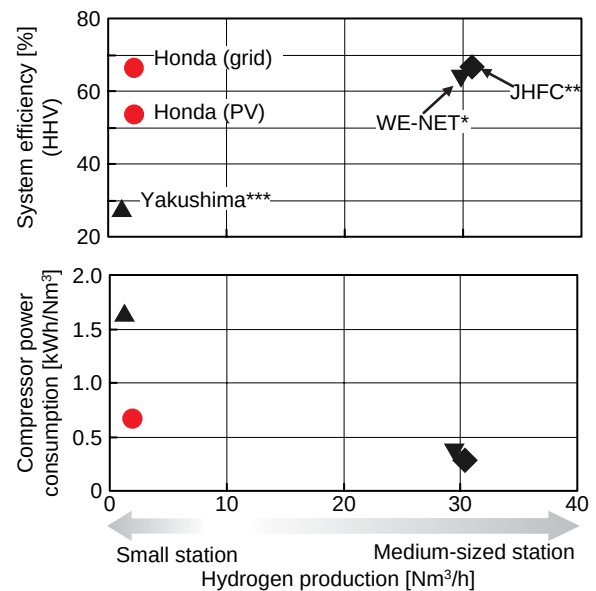
Fig. 8 Power consumption in power grid operation

of the SHS of this research with currently publicized electrolysis type hydrogen stations^{(4) - (6)}.

The efficiency of the SHS is equivalent to the efficiency of a medium scale station. Also, the SHS has higher efficiency than that of a small station that produces only a small amount of hydrogen. Generally, the efficiency of the compressor relies on the hydrogen production amount, and it is predicted that the efficiency of a small station will be low. In the case of the SHS, however, the reduction of efficiency is minimized, enabling high efficiency to be achieved.

Also, the efficiency of the compressor is affected by friction loss, so it varies depending upon the amount of hydrogen produced. It is thus conceivable that higher hydrogen production amount results in the higher efficiency of the station. In this respect, a large scale station is more advantageous.

Table 2 shows the breakdown of power consumed during the production of hydrogen at each station. All of the stations show an efficiency of slightly less than 70%, but there are differences in the contents of the efficiency. The electric power consumed per unit amount of hydrogen by the compressor of the SHS is larger than that of a medium scale compressor, and the power loss in the compressor is compensated for by highly efficient operation of the water electrolysis stack. The compressor of the SHS is a commercially available model, so its system conformity is inadequate. In order to raise the efficiency of the hydrogen station, it is necessary to enhance the method of controlling the pressure boosting section and also the system, and there is still room for



* WE-NET : World Energy NETWORK project (Japan)

** JHFC : Japan Hydrogen and Fuel Cell demonstration project

*** Yakushima : Yakushima zero emission project

Fig. 9 Performance comparison of hydrogen refueling stations

Table 2 Comparison of hydrogen refueling stations

Manufacturer (Location)	WE* efficiency** (HHV)	Power consumption [kWh/Nm ³]	
		WE*	Compressor
Honda (Los Angeles)	95.1%	4.749	0.675
WE-NET (Takamatsu)	90.6%	5.165	0.308
JHFC (Sagamihara)	—	4.940	0.275
Yakushima project	—	5.769	1.638

* WE : Water Electrolysis

** Operating temperature : 80 °C
Current density : 1 A/cm²

developing the SHS as a household hydrogen refueling system. Also, it is evident that the efficiency of the water electrolysis stack of the SHS is higher than that of the stacks of other stations.

4. Water Electrolysis Stack with New Ru Catalyst Mounted on

It has already been mentioned that the efficiency of the water electrolysis stack of the SHS is high. This is because a stack construction which reduces the cell resistance and a new catalyst were adopted. In this subsection, the water electrolysis stack will be described in detail.

4.1. Features of the Stack Construction

Figure 10 shows an expanded view of the water electrolysis stack. The main feature of the developed water electrolysis stack is that the circulation line for supplying the necessary water for electrolysis and all of the auxiliary

devices are integral with the stack. As a result, miniaturization was achieved and stack temperature control made easy. Pure water, which is the feedwater, is supplied from the pure water production equipment to the oxygen gas-liquid separator, which is integrated with the anode end plate, and is taken to the cell by the water pump, which is integrated with the anode end plate, and electrolyzed. At the anode catalysis, oxygen is generated, and returns together with pure water to the oxygen gas-liquid separator, which integrated with the anode end plate. Because the circulation line and auxiliary devices are integral with the stack, the water passage shortens, enabling the power that is necessary to drive the water pump to be reduced, and thus achieving compactness and high efficiency.

Regarding the cell stack, current collectors consisting of sintered titanium fiber web plates are mounted on both electrodes of the membrane electrode assembly (MEA), and titanium separators are mounted on the outside of them. To help prevent the resistance at the point of contact between the feeder and the separator from increasing due to the formation of titanium oxide, the surfaces of the separator and current collectors were platinum-coated. The number of layers in the stack was set to 27 cells from the power supply voltage (48 V), and the catalyst area was made 100 cm² (100 × 100 mm) from the hydrogen production (1 Nm³/hr). Two of cell stacks were installed in order to generate the rated hydrogen production of 2 Nm³/hr. There is an optimum value of the loading between the current collectors and the MEA. In this stack, disc springs are inserted between the cathode end plate and the back-up plate so that the load between the MEA and the current collectors becomes the optimum value.

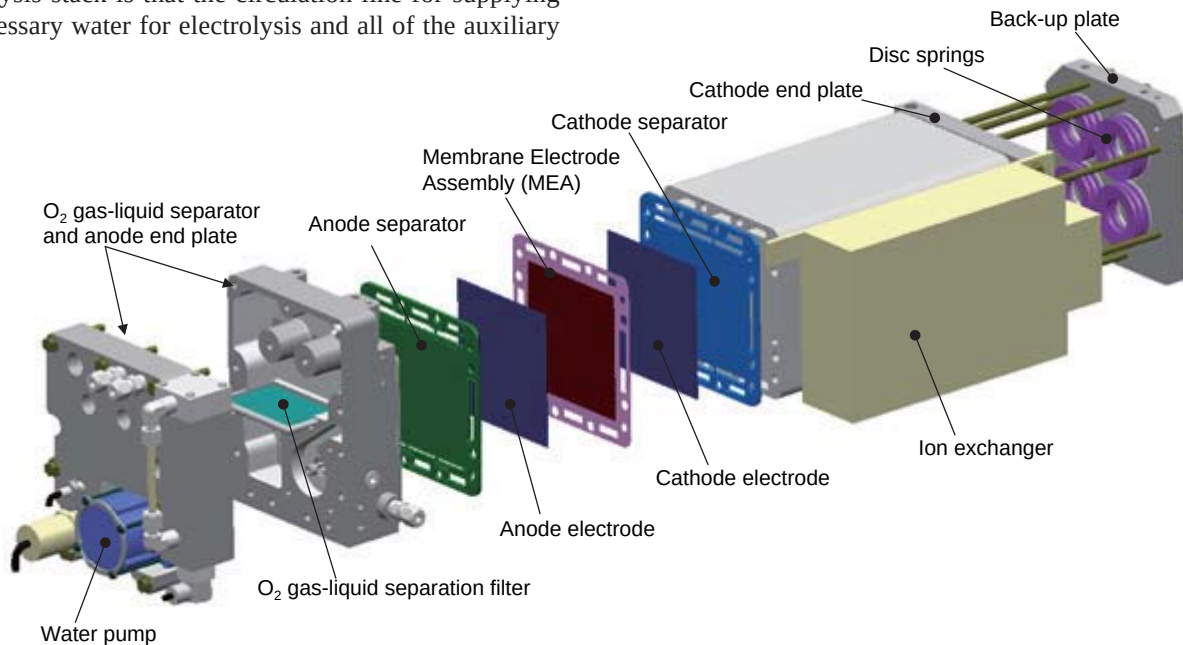


Fig. 10 Expanded view of water electrolysis stack

4.2. Features of the Newly Developed Anode Catalyst

Figure 11 shows a TEM photograph of the newly developed anode catalyst. The primary particle diameter of this catalyst is several nanometers, substantiating the fact that the catalyst is highly active. This catalyst is a compound oxide consisting of the three elements ruthenium, iridium, and iron (RuIrFeOx). Generally, it is known that RuO₂ exhibits high activity as the anode catalyst for water electrolysis, but has an issue with durability. However, because the highly active Ru of this catalyst is combined with Ir and Fe to form a compound oxide, the elution of Ru was suppressed.

It was confirmed as a result of a single cell test that this catalyst exhibits high activity and long life. Regarding the catalyst activation, the power efficiency found as a result of performing a single cell test was found to be 97% at a current density of 1 A/cm². Also, as the single cell durability performance, it was confirmed that the reduction of efficiency after 10000 hours was within 3%.

4.3. Stack Unit Performance Evaluation

Figure 12 shows the initial current-versus-voltage curves for the water electrolysis stack as a unit mounted

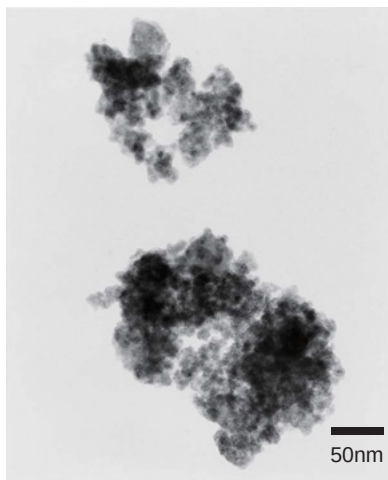


Fig. 11 TEM image of RuIrFeOx catalysts

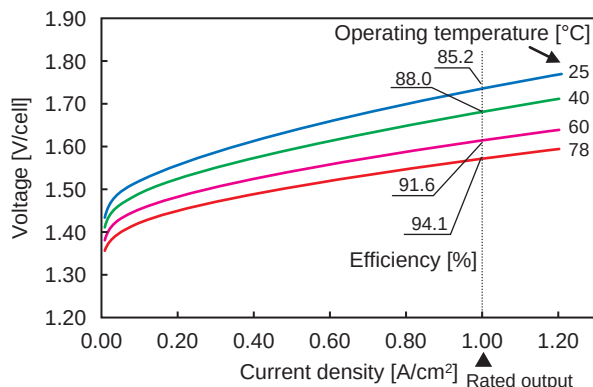


Fig. 12 I-V curve of water electrolysis stack

on the SHS. The efficiency shows a tendency to increase along with the rise of the operation temperature, and temperature control of the stack is effective for enhancing the water electrolysis efficiency. The initial efficiency of this stack is 94.1% at 78°C, and the single cell performance is maintained after the cell is mounted in the stack.

Also, as shown in Fig. 13, the performance of the cells varies between 93.8 and 94.4% for the 27 cells arranged in a straight line. This variation is within 1%, thus proving that the loading and the supply of water are uniform for the 27 cells comprising the stack.

Figure 14 shows the initial performance of the stack as a unit mounted on the SHS, and the change with time. The stack has been operated continuously for about four years without maintenance. The single cell durability test results are shown for comparison. The performance of the stack mounted on the SHS lies on an extension line of the single cell test, and the stack durability agreed with the prediction. No reduction of current efficiency due to

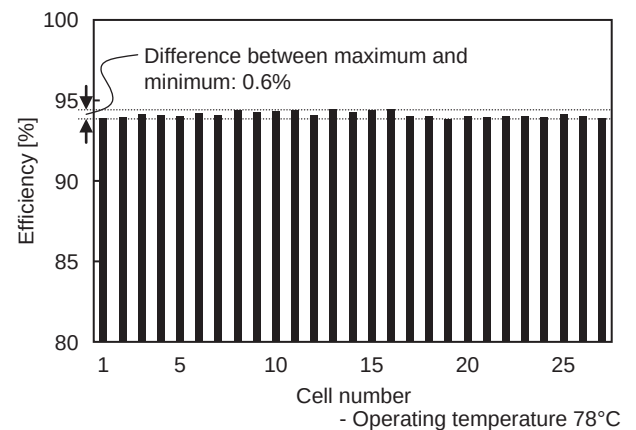


Fig. 13 Efficiency of water electrolysis cells

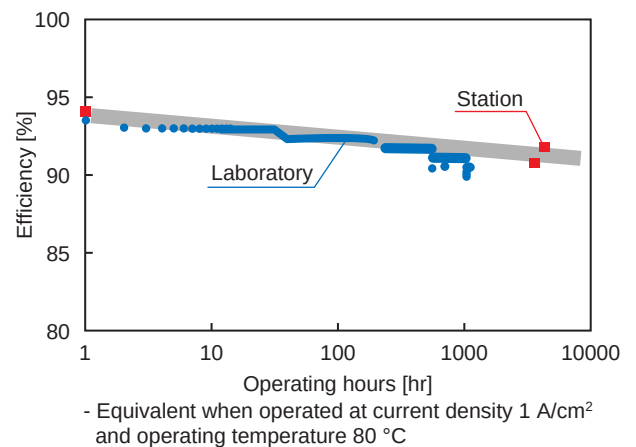


Fig. 14 Durability performance of water electrolysis stack (comparison of laboratory and station results)

deterioration of the membrane was found, thus verifying the durability of the stack. The stack mounted on the SHS showed no marked reduction of performance even when used outdoors or used under variable power. Also, the performance change was equivalent to the result obtained in the laboratory, thus proving that the stack can be used effectively as a water electrolysis stack for a household size hydrogen station.

5. Conclusion

A verification test of a hydrogen station that used photovoltaic modules for the purpose of reducing CO₂ emissions was carried out over a period of four years. The following results were obtained.

- (1) The system operated stably for about four years, and hydrogen continued to be generated without any emission of CO₂.
- (2) The efficiency of the annual hydrogen production over four years when only photovoltaic cells were used was $53 \pm 1\%$.
- (3) The hydrogen production for each 1-year period was approximately 1500 Nm³, which is equivalent to a traveling distance of 8000 miles for the FCX.
- (4) The hydrogen production efficiency at the rated power reached 66.3%, even for a small station. By raising the efficiency of the stack, the efficiency of production became the same level as that of medium and large scale stations.
- (5) The efficiency of the stack was higher than that of other stacks. The key technology used here was the RuIrFeOx catalyst. It was verified that this water electrolysis stack was effective as a water electrolysis stack for a hydrogen station.

A feasibility study of a household size renewable hydrogen station, which is one form of hydrogen refueling equipment that is expected to come into wide use in the future, was completed via a verification test.

References

- (1) Ueyama, M., Kita, M., Taguchi, S., Nakazawa, K., Nagaoka, H., Arakawa, S.: Introduction of Hydrogen Refueling Station with Photovoltaic Modules, Honda R&D Technical Review, Vol.15, No.2, p.31-38
- (2) Taguchi, S., Handa, K.: Study of Hydrogen Refueling Station with Photovoltaic Modules, EVS-22 proceedings, p.350-357 (2006)
- (3) Ogawa, T., Kimura, K., Uchibori, K., Fujimoto, S., Shimizu, K.: Development of New Power Train for Honda FCX Fuel Cell Vehicle, Honda R&D Technical Review, Vol.15, No.1, p.7-12
- (4) Japan Automobile Research Institute (JARI), Engineering Advancement Association of Japan (ENAA): Suiso Nenryodenchi Jissyo (JHFC) Project Dai 1 ki Houkokusyo, p.159-162 (2006) (in Japanese)

- (5) New Energy and Industrial Technology Development Organization (NEDO): Suiso Anzen Riyo Kiban Gijutsu Kaihatsu, Mizudenkai Kata Suiso Sutando no Unten Gijutsu Kaihatsu, H15-H16 Seika Houkokusyo, p.50-54 (2005) (in Japanese)
- (6) Kai, T., Uemura, Y., Takanashi, H., Tsutsui, T., Takahashi, T., Matsumoto, Y., Fujie, K., Suzuki, M. : A Demonstration Project of the Hydrogen Station Located on Yakushima Island - Operation and analysis of the station, International Journal of Hydrogen Energy, Vol. 32, No. 15, p. 3519-3525 (2007)

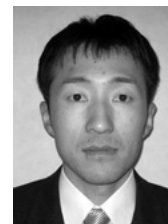
■ Author ■



Masanori OKABE



Koji NAKAZAWA



Kenji TARUYA



Kiyoshi HANDA

2007 Model CBR1000RRW for Suzuka 8 hours World Endurance Championship Race

Eiichi KANDA*

Masamune OHIGASHI*

Hiroshi UNUKI*

Nobuo SHIGEMIZU*

Yukihide AKITSU*

ABSTRACT

An endurance motorcycle has been developed to take part in the 2007 Suzuka 8 Hours Endurance Road Race. The calculation performance of the ECU has been increased against that of the 2006 model to enable more precise control, resulting in a 2.7% increase in power and the achievement of a balance between engine performance and fuel efficiency with no decline in the former. Increasing the inertial mass of the ACG rotor has moderated the transient characteristics during acceleration and reduced the engine brake load during deceleration. In addition, the use of slip control has increased stability and controllability and traction performance. The newly developed racing motorcycle displays reliable racing performance, and is capable of posting lower and stable lap times.

1. Introduction

From 2004, a change was made in the regulations in the Superbike class for racing motorcycles. Whereas previously 2-cylinder 1000 cm³ bikes competed with 4-cylinder 750 cm³ bikes, both 2-cylinder and 4-cylinder 1000 cm³ bikes will now be fielded. A balance between competitors is now achieved by basing the range of allowable modifications on the number of cylinders of the bikes. Honda has also pressed ahead with the development of production models to form the basis of its racing lineup. It has developed the 4-cylinder CBR1000RR to replace the previous 2-cylinder VTR1000SP and has commenced racing the bike. Figure 1 shows the 2007 model Honda Racing (HRC) race machine.

Honda won the Suzuka 8 hour world endurance championship race in 2004 and 2005.

From 2006 onwards, at the request of the organizers, Honda began competing in the Superbike category of the All-Japan Championships, the Japan Superbike (JSB1000) class. Compared to the previous Superbike regulations, the range of modifications that can be made to the engine is narrow, and thus, major increases in power cannot be expected. Honda has worked to enhance the performance and functions of the parts that are able to be modified and has conducted development programs that have resulted in enhancement of the total performance of the complete bike, but has not yet achieved an overall victory in the JSB1000 class.

The base performance of the 2007 model has not been considerably enhanced, but ECU performance has been enhanced and traction control has been employed, mainly focusing on slip control, in order to increase the level of power control. In addition to these changes, the motorcycle's fittings have been modified to enable the achievement of a consistent reduction in pit work times, which represents an important factor in an endurance race. This paper will discuss the technologies applied to the 2007 base model CBR1000RRW, including the parts that effectively increased performance, and unique parts employed for endurance race.



Fig. 1 2007 model HRC race machine

* Motorcycle R&D Center

Table 1 Comparison of regulations

	JSB Japan superbike	SBK FIM world superbike
Crankcase	No modification allowed	May be modified by welding or machining
Cylinder head	Only machining port area and base surface are allowed	May be modified by welding or machining
		Valve seats may be altered or replaced
		Valve guide may be altered or replaced
		Combustion chamber may be modified
Cylinder	No modification allowed	Sleeves, liner material may be changed
		Surface finish is free
Crankshaft	No modification allowed	May be altered or replaced
Piston	No modification allowed	May be altered or replaced
Piston ring	No modification allowed	May be altered or replaced
Piston pin	No modification allowed	May be altered or replaced
Piston pin clip	No modification allowed	May be altered or replaced
Connecting rod	No modification allowed	May be altered or replaced
Camshaft	May be replaced or modified	May be altered or replaced
Valve	No modification allowed	May be altered or replaced
		Valve diameter must remain as homologated
Valve spring	May be replaced. Material must remain as homologated.	May be altered or replaced
Valve retainers	No modification allowed	May be altered or replaced
Oil pump	No modification allowed	May be altered or replaced
Clutch	Clutch springs, friction disks, plates may be altered or replaced.	Aftermarket or modified clutches are allowed
	Quality of disks and plates must remain as homologated.	Back torque limiter is permitted.
	Addition of back torque limiting device is not allowed.	

2. Development Orientation

Until 2005, the Superbike class allowed an extensive range of engine modifications, enabling the desired performance level of the racing bike to be achieved without any major changes needing to be made to the performance of the production model used as the base model. Since 2006, the JSB1000 class has narrowed the range of allowable engine modifications, making it more challenging to achieve the desired peak power and partial power characteristics. It has therefore become necessary to enhance the total performance of the complete motorcycle in order to compensate for the decline in engine performance. In 2007, the company's second year of competition in the JSB1000 class, in addition to enhancing ECU performance in order to achieve an overall performance increase, Honda focused on the following areas:

- (1) Control of electrical equipment: Satisfaction of necessary drivability objectives while achieving a balance between traction performance and fuel efficiency.
- (2) Engine: Within the range of allowable modifications, the achievement of higher engine speed and enhanced functions and durability.
- (3) Frame: In addition to the use of parts designed

specifically for endurance race, the achievement of enhanced traction performance to enable effective transmission of power.

- (4) Fittings: Enhancement of maintenance operability in order to achieve a consistent reduction in pit work times.

3. Engine

Table 1 shows the range of engine modifications allowed in the Superbike and JSB 1000 regulations. Modifications can only be made to a limited number of parts in the JSB1000 regulations, and here only parts in which modifications have had an effect on performance and endurance are discussed.

3.1. Increase in Inertial Mass of Cam Shaft

In terms of the engine, increased rev cut engine speed and valve lift are necessary in order to achieve increased power. The cam chain is one of the parts for which the mass production specifications cannot be modified, and the reduction of the load on the part therefore represents an issue. Fluttering when the cam chain engages with the sprocket was focused on to increase durability, and the inertial mass of the cam shaft and the cam sprocket was increased to reduce the level of fluctuation in the speed

of the cam shaft. This increased the cam lift and the rev cut engine speed, maintaining the achievement of the necessary cam chain durability. In combination with these changes, valve timing was modified, contributing to increased power. Figure 2 shows a comparison of the form and inertial mass of the camshafts. Figure 3 compares the speed variation of the camshafts.

3.2. Increase in Inertial Mass of Crankshaft System

Reducing torque fluctuations during acceleration and reducing engine braking during deceleration were issues in the design of the bike. Class regulations prohibited modification of the mass production specifications of the crankshaft or clutch mechanism. Modification of ACG rotor was allowed, and the inertial mass of the rotor was therefore increased. To achieve the maximum mass in a limited space, the previous outer rotor configuration was replaced by an inner rotor configuration. As shown in Fig. 4, the inertial mass of the outer circumference was increased, which helps prevent sudden increases in engine

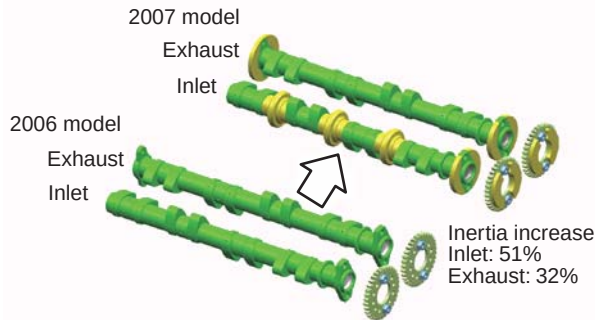


Fig. 2 Comparison of camshaft

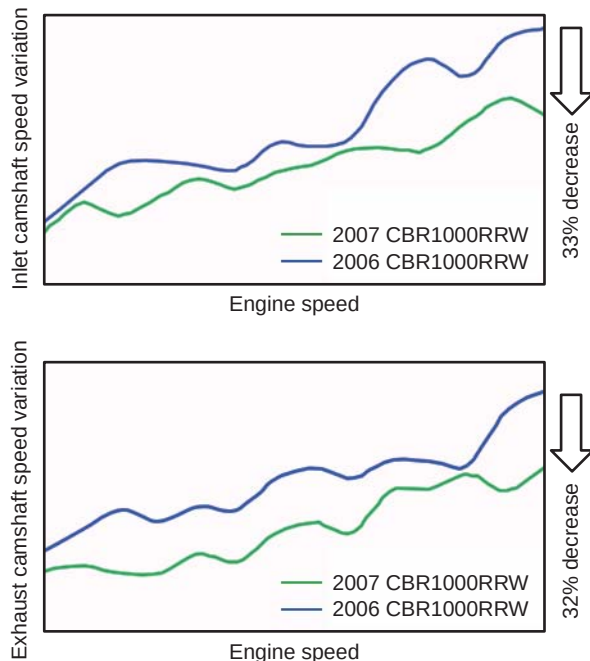


Fig. 3 Camshaft speed variation curve

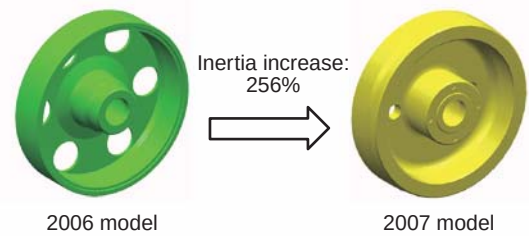


Fig. 4 Comparison of ACG rotor

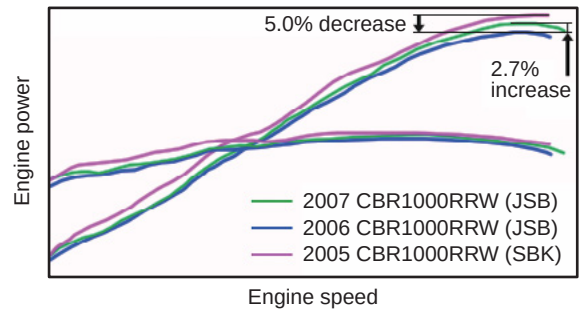


Fig. 5 Engine performance curve

speed that occur as a result of throttle operation, resulting in the achievement of a relaxed control characteristic. The increase in mass also reduced engine braking during deceleration, resulting in a smoother deceleration characteristic.

3.3. Increased Power

Building on the base of modified valve timing and increased cam lift, integrated management of parts tolerance selection and production lots was employed to control variations in specifications for each engine, resulting overall in a 2.7% increase in power and the reduction of power variation to 0.8%. Figure 5 shows a comparison of the power characteristic at wide-open throttle with Honda's 2004 Superbike. While a reduction in power is unavoidable, the modifications have enabled power to be stably provided.

4. Electrical Equipment/ Control

In order to respond to the decline in fuel efficiency with increased engine speed and realize traction control with a focus on power control, it was necessary to achieve fine ECU control. The ECU used until 2006, which was based on the production model, was therefore replaced with the higher-performance ECU used in MotoGP in 2007, which features a built-in data logger. This section will discuss the main benefits achieved through this change in the ECU.

4.1. Drivability

Until 2006, sudden increases in engine speed were judged as slip, and when they were detected, Δ ME engine

control (instantaneous change of engine speed) was applied to suppress them. In 2007, in addition to this system, the speed of the front wheel is being employed as a control parameter, and traction control that goes into effect when the speed of the front wheel is detected to differ from the speed of the back wheel is being employed. Δ ME controls sudden changes in engine speed and helps prevent slip from occurring. The employment of traction control in addition to this enables response to decline in tire grip and to changes in tire slip caused by deterioration of the quality of the road surface, etc. Figure 6 shows a comparison of riding data between the 2006 and 2007 models. Slip is reduced and smoother acceleration is achieved in the 2007 model.

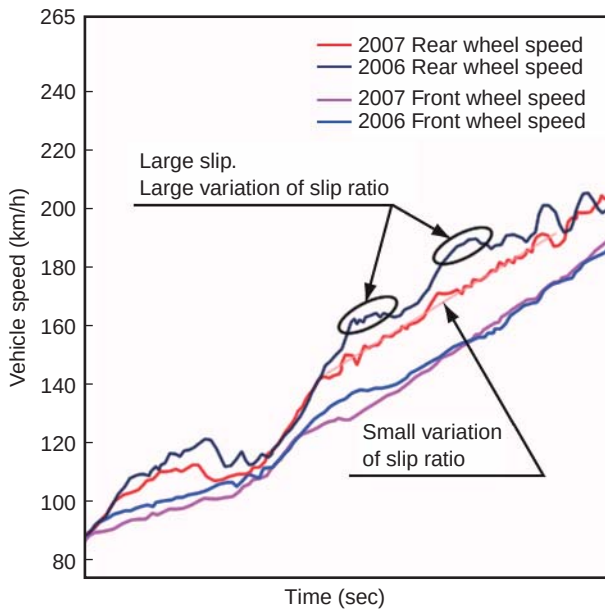


Fig. 6 Comparison of ECU control riding data (Hairpin exit on final lap of seventh stint)

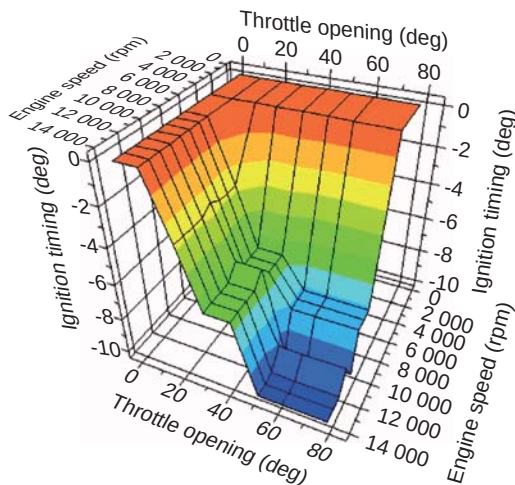


Fig. 7 Comparison of ECU control map

4.2. Fuel Efficiency

The use of an optional map without increasing the leanness of the base air-fuel adjustment has enabled an increase in leanness, which would cause a decline in the level of power achieved to date to be minimized, in turn enabling power to be used effectively and increasing fuel efficiency. In conditions under which tire grip declines and slipping occurs frequently, the rider is able to use the map switch to reduce loss of fuel efficiency due to slipping. Figure 7 shows the configuration of the map.

4.3. Setting Performance

The ability to find the optimum setting in a limited time is also an important factor. The modification of the ECU enabled the volume of setting data to be increased, enabling optional settings programmed as maps. Until 2006, the base map was adjusted and employed, but because riders are now able to select options while riding using a mode switch, in the 2007 model the settings have been made simpler and the amount of time it takes to set a mode has been decreased. The number of modes has been increased from two to three, increasing responsiveness to conditions during the race.

In addition, the integration of the data logger increased the ease of taking additional measurements of control parameters and control values, and the accuracy of the settings has been increased based on these measurements.

4.4. Pit Work

Wireless sending of setting data and wireless reception of riding data has been enabled. This has made pit work smoother, despite the fact that the mechanics who service the bike and the staff responsible for the settings are crowded together in a narrow space. In addition to reducing the time needed for pit work, wireless sending and reception has also enabled more time to be spent on adjusting settings.

5. Frame

The change in regulations involved in the change in class from Superbike in 2004 to JSB1000 did not considerably affect the frame. Because the base production model underwent a minor model change in 2006 and few changes were made for the 2007 model, this section will discuss only the changes made in the racing model to enhance the performance of the complete bike and the unique parts employed for endurance race.

5.1. Achievement of Enhanced Performance in Complete Bike

5.1.1. Swing arm and rear cushion

The width of the wheels had been increased to increase

the ease of replacing tires in the pit. This demanded the achievement of increased stability and controllability, and enhanced traction performance via the swing arm. The shape of the swing arm was modified to achieve increased rigidity and reduced weight, and the rear cushion reserve tank was positioned laterally, concentrating mass and making effective use of the space layout. The swing arm and rear cushion layout is shown in Fig. 8, and a map of swing arm rigidity is shown in Fig. 9. Maintaining torsional rigidity while reducing yaw angle rigidity and increasing the rear tire slip angle has enhanced turning performance (escape from cornering, etc.) and traction performance.

5.1.2. Front fork

From the 2005 model onwards, it was necessary to modify the rigidity of the front fork in order to balance stability during deceleration and cornering performance. Reinforcement of the outer tube with carbon fiber enabled longitudinal rigidity to be increased while maintaining lateral rigidity. In the 2007 model, the total length of the outer tube has been increased, resulting in increased stability and enhanced cornering. Increasing the rigidity of the outer tube itself would not have enabled the achievement of a balance between longitudinal and lateral rigidity, making reinforcement with carbon fiber the optimum method to be employed. Figure 10 shows the shape of the front fork and a comparison of rigidity.

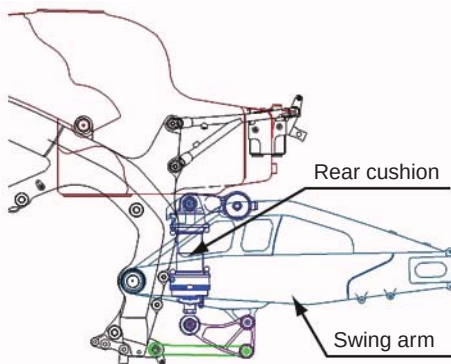


Fig. 8 Layout of swing arm and rear cushion

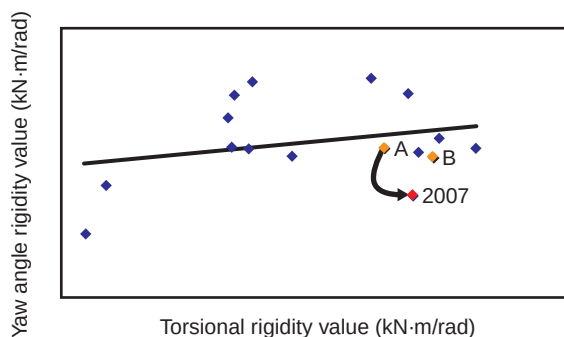


Fig. 9 Comparison of swing arm rigidity

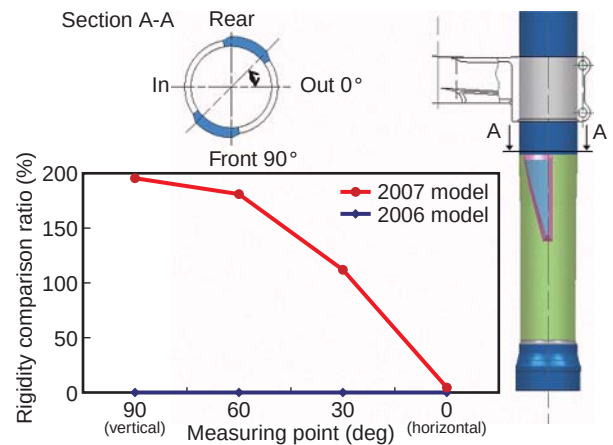


Fig. 10 Comparison of front fork rigidity



Fig. 11 Seat cowl shape

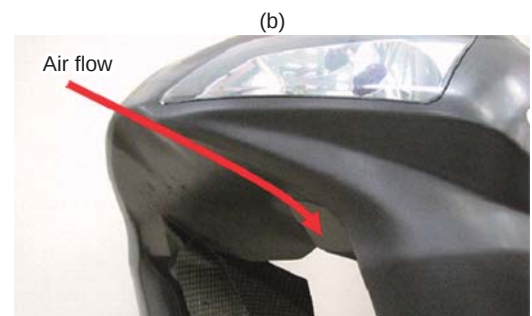
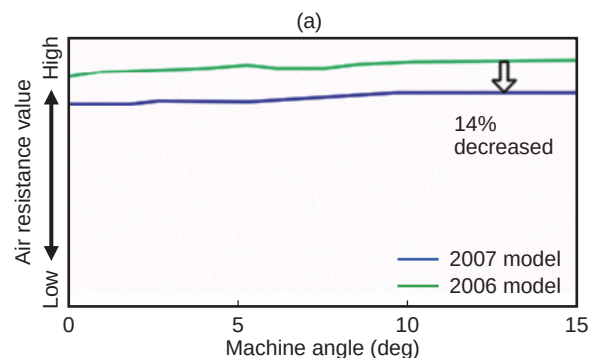


Fig. 12 Front cowl shape and characteristics

5.1.3. Aerodynamic performance

Maintaining the basic form of the production model while enhancing aerodynamic performance was established as a development goal, and the detailed shape of the bike was modified. A spoiler was added to the lower section of the front cowl and a duct was added to the rear of the seat cowl, reducing the amount of lift. Figures 11 and 12 show graphs of the front cowl and seat cowl lift characteristics.

5.2. Unique Parts employed for Endurance Race

5.2.1. Fuel tank

The design of the fuel tank sought to increase rider comfort and controllability while maintaining the maximum capacity of 24 L allowed by the regulations, in addition to producing a form that would reduce the necessary filling time as well as increase the accuracy of filling in terms of the volume of fuel supplied. Modifying the shelter type employed in the production model, the fuel tank in the racing model has been manufactured using aluminum, with the front half formed from carbon fiber, enabling the achievement of the requisite capacity while reducing weight. The fuel tank is shown in Fig. 13.

5.2.2. Accident guards

To protect the bike from damage in the event that it falls, plastic sliders have been fitted to the side of the frame, and a carbon fiber guard has been fitted on the swing arm to protect the rear axle. Figures 14 and 15 respectively show photographs of a slider and the axle guard. This has reduced the frequency with which parts need to be replaced if the bike falls, and has also reduced the rate at which bikes are retired from the race.

To increase safety if the bike falls, since the 2006 model, a quick filler with a locking function has been employed in order for the fuel filler to not open during a fall. The quick filler is shown in Fig. 16. The 2006 model used three claws, but the 2007 model has been provided with six claws to enhance the locking function.

5.2.3. Increased rider comfort

Because each session lasts approximately 1 hour, rider



Fig. 13 Fuel tank



Fig. 14 Slider



Fig. 15 Axle guard



Fig. 16 Quick filler with lock function



Fig. 17 Handle pipe weight

comfort is also an important consideration.

To reduce handlebar vibration, the small weight shown in Fig. 17 was fitted in the handlebar pipe. This measure has reduced vibration by approximately 10% against the handlebars of sprint bikes.

To protect the rider from heat, an air outlet duct has been added to the front cowl (Fig. 18), a large carbon fiber heat guard has been fitted around the step exhaust pipe, a heat-isolating washer has been used on the step arm, and a double-layered bottom plate, containing a layer of air, has been used for the seat.

To enhance visibility, an air duct has been used to help prevent misting of the windscreen, maintaining visibility when racing in rainy weather (Fig. 19).

5.2.4. Headlights

Because the 8-hour endurance race is also run after dark, headlights are a necessity. In order to maintain the basic configuration used in the production model while maintaining sufficient intensity at a low weight, high-intensity discharge (HID) headlights were fitted in a carbon fiber case, and the assembly was mounted in the cowl (Fig. 20).

5.3. Parts related to Pit Work

5.3.1. Front stand jack

During pit work, a front stand jack is inserted from

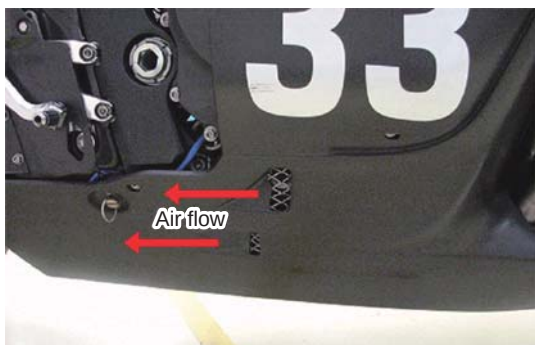


Fig. 18 Lower cowl air outlet duct



Fig. 19 Wind screen air duct

the side and used to raise the bike. To enable quick replacement of tires and refueling, it is vital that the bike be balanced stably when raising and lowering it. In the 2007 model, this has been achieved by replacing the link-type front stand with a slide pipe-type. In addition, in order to increase the ease of fitting the jack, the form of the guide on the insert section has been modified and the tire-type roller used to move the front stand has been replaced by a free caster-type, reducing the effort involved in using the jack. Figure 21 shows comparative photographs of the front stands.

5.3.2. Ease of replacement of tires

An opener mechanism that allows the brake calipers to be rotated while attached to the front forks is used for the front wheel, enabling the wheel to be removed by simply removing the axle shaft and pulling the wheel. In the 2007 model, the shape of the guide mechanism has been modified in order to reduce the amount of time to insert the wheel and assure consistent insertion times. Figure 22 shows a photograph of the wheel guide.

To increase the ease of removal of the wheel, a special rear wheel is employed with the rear brake disk fitted to the exterior. The change in the regulations in 2004 prohibits the driven sprocket from being fixed to the frame, making it challenging to employ a “pentagon.” Positioning of the driven sprocket at the side of the wheel means that the drive chain should be removed in pit work. A chain holder and a sprocket cover have been employed



Fig. 20 Head light mounting layout

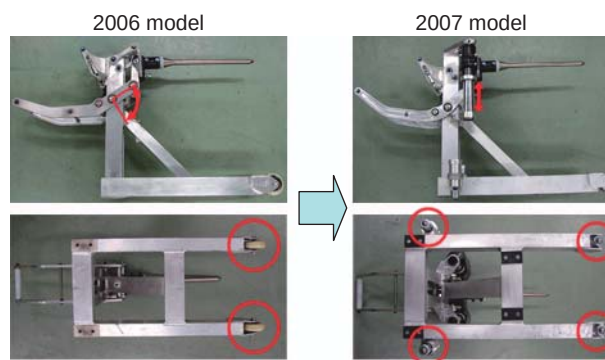


Fig. 21 Front stand

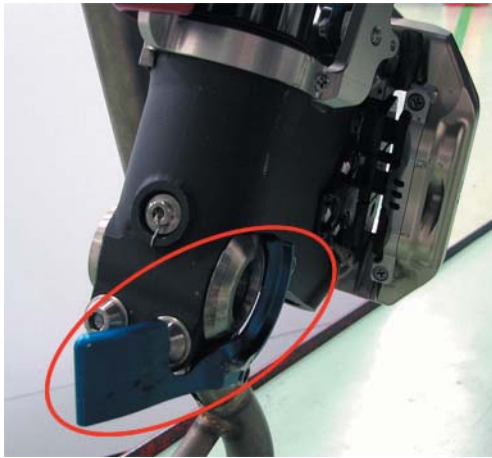


Fig. 22 Front axle wheel guide

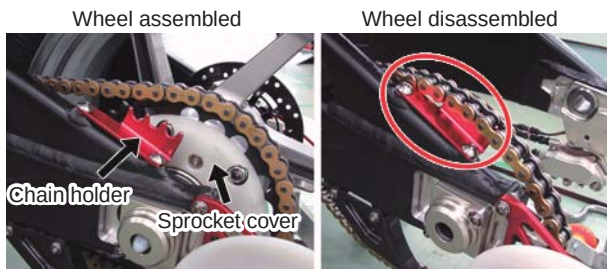


Fig. 23 Rear chain holder wheel guard

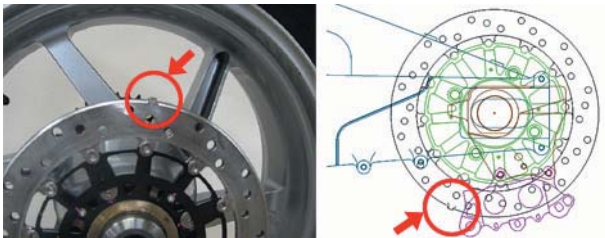


Fig. 24 Rear brake disk projection

to increase the ease of removal. Figure 23 shows a photograph of the chain holder. During the race, foreign matter collects around the rear brake disk and impedes removal work. A projection has therefore been used on the outer circumference of the rear disk brake that scoops out this foreign matter while the bike is running. The layout is shown in Fig. 24.

6. Performance Evaluation

The 2007 bike was run through more than 25 laps of the Suzuka circuit by both a test rider and an actual race competitor, enabling comprehensive evaluation of all parts. The average lap time achieved by the bike showed

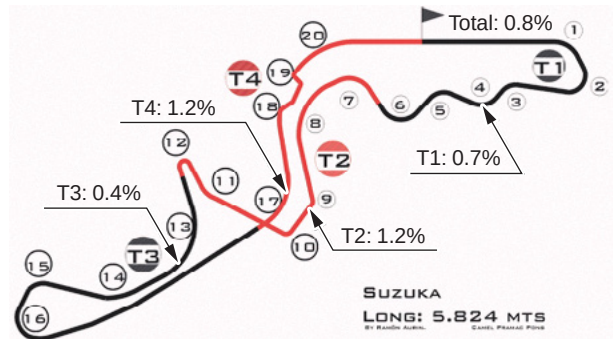


Fig. 25 Section performance enhancement at SUZUKA circuit

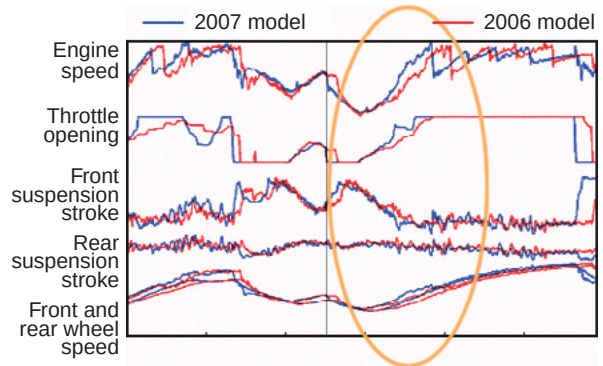


Fig. 26 Running data

a 0.8% increase against that in the former model.

As Fig. 25 shows, the new bike recorded lower times against the previous model on all sections of the course, as follows: T1 (0.7%); T2 (1.2%); T3 (0.4%); T4 (1.2%). The bike also recorded a 3 km/h increase in maximum speed on the back straight.

Figure 26 shows the enhanced performance of the new bike in terms of actual running data. The main area of enhanced performance is acceleration during cornering and escape from cornering. The results show that ECU control is functioning normally, and that traction control has been enhanced.

Rider comfort was evaluated under a number of different conditions (dry, wet, night, strong wind, etc.), and was demonstrated to be adequate.

Average pit work times were reduced by 7% against times recorded in the previous year. In particular, the time needed to change tires was consistent, as well as less time being necessary for refueling.

7. Conclusion

A variety of specifications were changed in the design of the 2007 model CBR1000RRW with a major focus on enhanced ECU performance, resulting in the achievement of a balance between enhanced engine performance and

fuel efficiency, while maintaining durability. The enhancement of the control system has resulted in better traction performance and the achievement of overall performance exceeding the previous year model. During the race, however, a penalty for a flying start meant that one Honda racing bike was unable to close the gap with the leader and took number two position. The other bike had to withdraw due to a fall.

While victory eluded the Honda team on this occasion, we will work to make continuous enhancements to the endurance bike, striving to realize the machine's full potential.

■ Author ■



Eiichi KANDA



Masamune OHIGASHI



Hiroshi UNUKI



Nobuo SHIGEMIZU



Yukihide AKITSU

Development of Small Fuel Pump Module for Motorcycles

Masaki UENO*

Minoru UEDA*

Takashi UDONO*

Shunji AKAMATSU*

Mineo TORIKAI**

Mitsuru FUKUDA**

ABSTRACT

A small, low-cost fuel pump module has been developed for use in motorcycles with smaller engines. Removing the diaphragm from the pressure regulator has simplified the structure and has reduced the volume ratio to approximately 40% that of the former model. The pump motor has been designed specifically for use in low-displacement engines. Optimizing the winding specifications and reducing the size of components enabled the total length to be reduced by 11 mm. Reducing the size of the pressure regulator and the pump motor also reduced the mounting diameter of the fuel pump module, enabling the axial face seal, previously used for the mounting area, to be replaced by a radial seal. A retainer slide has been used instead of bolts to fix the pump in place, enhancing workability and reducing the number of parts. Together, these changes have reduced the cost of the unit by approximately 30% and the mounting area by approximately 40%.

1. Introduction

Honda has set itself a severe numerical target in its commitment to reduce CO₂ emissions from its products and production processes worldwide by 10% or more against 2000 figures by 2010. The proposal and introduction of new regulation values around the world are also stimulating efforts to increase fuel economy in and reduce exhaust emissions from motorcycles. Table 1 shows a map of exhaust gas regulations currently being applied or under consideration.

The use of fuel injection (FI) is an effective means of responding to environmental needs without sacrificing the functions and performance levels of motorcycles, and Honda intends to use FI in most of its market models by 2010.

However, FI involves more parts than a carburetor system, and its cost is therefore higher. In particular, the fact that there is no space margin in smaller motorcycles as there is in larger motorcycles, in addition to the low cost of the smaller motorcycles themselves, demands the development of small, low-cost FI systems.

The project discussed in this paper reexamined the

specifications and production plans of every functional component of the small motorcycle FI system used in the 2005 Wave 125i motorcycle in an attempt to further reduce the size and cost of the system. In particular, it was important to reduce the size of the small fuel pump modules employed in the smaller fuel tanks used in motorcycles in developing nations. This paper describes the technologies employed to reduce the size of the fuel pump module used in the 2008 Wave 110, which will be marketed in Thailand.

2. Fuel Pump Module for Small Motorcycle: Issues and Approaches

2.1. Issues

Figure 1 shows the standard fuel tank layout used in the commuter motorcycles that represent the majority of motorcycles throughout the world. A fuel tank fitted with a fuel pump module is positioned under the seat between the luggage box and the rear fender. In this layout, there are height restrictions and limitations on the positioning of the fuel pump. The fuel pump module should also be fitted in a limited space to avoid the fuel filler opening,

* Motorcycle R&D Center

** Keihin Corporation

Table 1 Trends of exhaust gas emissions regulations for motorcycles

		EURO-2						EURO-3 or equivalent				
		2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
EU					EURO-2			EURO-3				
Japan								2nd (< 50 cc)				
								2nd (< 125 cc)				
Thailand		4th			5th (< 110 cc)					6th		
China					EURO-2				EURO-3			
Indonesia						EURO-2						
Vietnam								EURO-2				
Brazil						EURO-2				EURO-3		
India		4th				5th				6th		
USA	EPA							2007YM		ARB Tier-2		
								OFF/ATV 2006YM		ON & OFF		
								ARB Tier-1 2006YM				
	ARB				Tier-1 2004YM				Tier-2 2008YM			

located near the center of the upper part of the fuel tank. In addition, the height of the upper section of the pump is determined by its position in relation to the seat. The height of the pump is lower than the height of the tank by an amount equivalent to the height of the joints of fuel line and couplers of electric equipment, and any increase in the mounting area of the pump would result in a reduction in the size of the tank.

Conventional fuel pump modules are in need of a large space for mounting and use a large number of parts. Reducing the mounting space and cost of the units is therefore a major issue in terms of increasing the range of models in which they can be used.

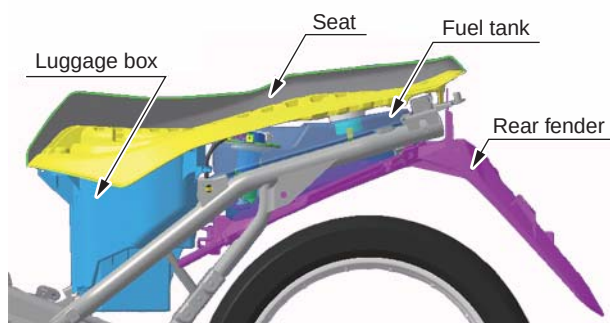


Fig. 1 Fuel tank layout

2.2. Approach of Issues

In this development, efforts to miniaturize the size and lower the costs of the pump focused on the following two points:

- (1) Development of a small fuel pump module
- (2) Simplification of the mounting structure for the fuel pump module

3. Major Technologies

3.1. Small Fuel Pump Module

Figure 2 shows a comparison of the inner configurations of the fuel pump module for the 2008 Wave 110 and the former model, the 2005 Wave 125i. The fuel pump module is composed of a pump motor, a pressure regulator (hereafter referred to as "P/REG"), a plastic case, a fuel filter, and a fuel level sensor. The module was miniaturized by downsizing each component and designing an optimum layout, employing the four technologies and techniques listed below. The use of this strategy resulted in the reduction of the diameter of the module insert hole in the fuel tank from $\phi 65$ to $\phi 49$ (Fig. 2).

- (1) Diaphragm-less P/REG
- (2) Reduction of pump motor size
- (3) In-line layout of P/REG and pump motor
- (4) L-shape layout of fuel level sensor

3.1.1. Diaphragm-less P/REG

Figure 3 shows the configuration of the former and

the developed P/REGs. In the former P/REG, a diaphragm receives a pressure (function of pressure-receiving). Motion of the diaphragm in response to the pressure changes the gap between a ball valve and a seat, which adjusts the return flow rate and maintains constant pressure. In the developed P/REG, the pressure-receiving

function was added to the ball valve that regulates the return flow rate, enabling the diaphragm to be removed, thus reducing the number of parts and the size of the unit.

The major performance criteria for the P/REG are as follows:

- (1) Stabilization of fuel-feed pressure to flow rate
- (2) Low fuel-feed pressure pulsation
- (3) Ability to hold residual pressure

The diaphragm-less P/REG should achieve these performance criteria. Regarding item (1), the former P/REG had a stable Q-P (fuel flow rate – feed pressure) characteristic up to a high flow rate, but the Q-P characteristic was expected to decline in the developed module because the pressure-receiving function is accomplished with the ball valve only. Regarding item (2), since the pressure-receiving and pressure-regulating functions were unified in the ball valve, it was thought that fluttering of the ball valve caused by the fuel flow might generate a large pressure pulsation. Item (3) is a necessary function to facilitate restarting, avoiding a decline in pressure in the fuel line while the pump is stopped. In the new model, however, since the smaller area of the ball valve receives the pressure formerly received by the diaphragm, the spring load is also set lower. The contact pressure on the valve seat is therefore lowered, and the ability to hold residual pressure tends to decline.

In order to address these issues, the P/REG function was limited to the flow rate range in small motorcycles of 150 cm³ displacement or below, to achieve a stable characteristic. The developed P/REG configuration employs a valve guide to exert a uniform spring load using a spring with a larger coil diameter. This helps prevent a slant of the spring and equalizes the valve seat contact pressure, thus increasing the ability to hold residual pressure. Figure 4 shows the residual pressure characteristic of the former and the new configurations. Although the residual pressure with the diaphragm-less configuration is lower than with the former pump, it is not an issue in terms of actual use.

In addition, the design of a concave area in the valve guide that houses the ball valve has reduced the fluttering

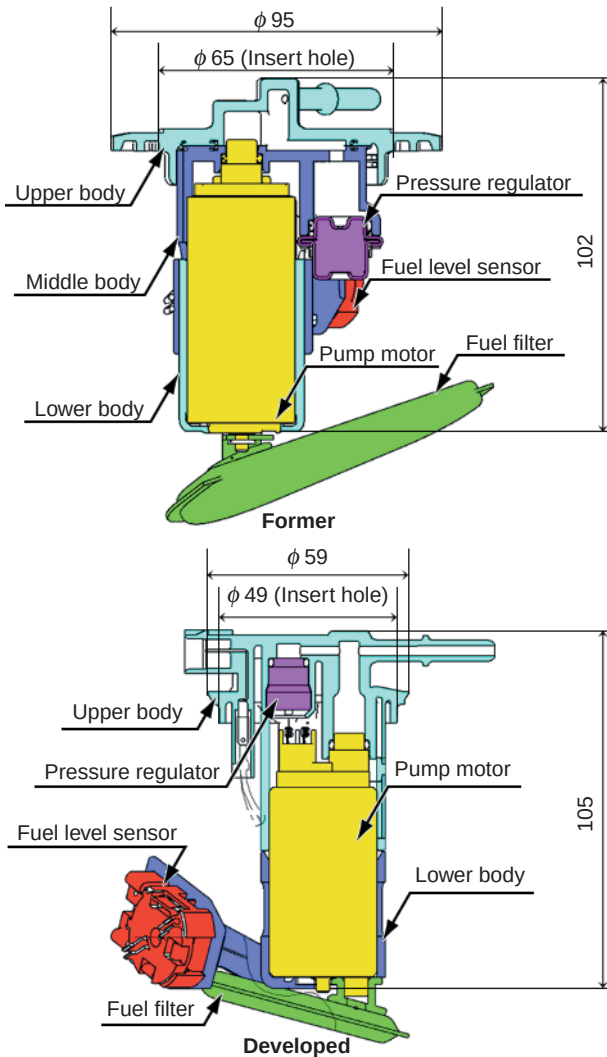


Fig. 2 Comparison of inner structure of fuel pump modules

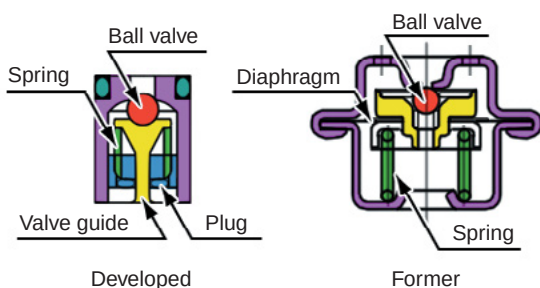


Fig. 3 Structure of former and developed pressure regulators

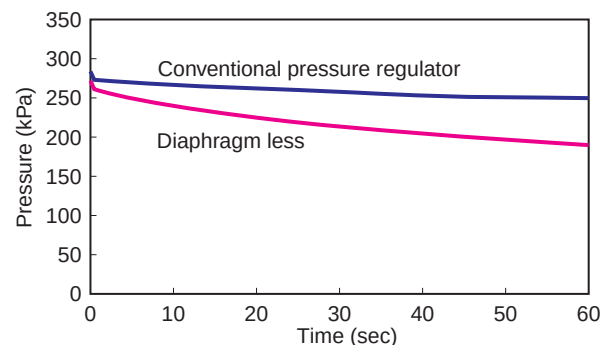


Fig. 4 Residual pressure characteristic

of the valve, enabling the stabilization of fuel-feed pressure.

As shown in Fig. 5, even without the diaphragm, these modifications achieved a Q-P characteristic equivalent to that of the former pump within the flow-rate range of small motorcycles.

3.1.2. Miniaturization of pump motor

Components of the pump motor were miniaturized for use in small motorcycles less than or equal to 150 cm³ displacement. In the pump section, the rotor and the flow paths employed the same shapes as before, but the thickness of the pump casing and the dimensions of the bearings were modified to achieve miniaturization. In the motor section, reducing the core laminate thickness, the total length of the magnet, and the coil winding space enabled the armature to be made smaller. In addition, optimization of the coil winding specifications allowed the achievement of a torque constant equivalent to that achieved by the former specifications, resulting in an equivalent motor characteristic. A check valve holds residual pressure in the fuel line when the pump motor is stopped, enabling the engine to restart easily. This check valve was also reduced in size without impairing its functioning. With these modifications, the total length of the pump motor was reduced by 11 mm against the former model, while an equivalent level of performance and functions was maintained.

3.1.3. In-line layout of P/REG and pump motor

In order to reduce the mounting space of the pump module, it is necessary to lay out the components in as small an area as possible in terms of each cross section when the pump is inserted. In the previous model, the P/REG and the pump motor were fitted parallel to the pump axis due to height restrictions. Miniaturizing the components as described above allowed the P/REG to be mounted on the top plate. This in turn enabled in-line layout of the P/REG and the pump motor without an increase in height, and allowed the diameter of the insert hole in the fuel tank for the pump module to be reduced.

In the former pump, a middle body was welded to the

top plate to build a path from the P/REG to the pump outlet. In the new pump, the pump outlet and the P/REG have been set on the outlet joint axis, simplifying the path structure and enabling the middle body to be removed (Fig. 2).

3.1.4. L-shaped configuration of fuel level sensor

Formerly the fuel level sensor was placed next to the pump, but it was necessary to separate it from the pump in the developed model due to the reduced diameter of the module insert hole. The fuel level sensor was set in an L-shape in the same direction as the fuel filter to accommodate height restrictions and for ease of insertion. This enabled the insert hole to be reduced to $\phi 49$, and the mounting space to be reduced.

3.2. Simplification of Pump Module Mounting Structure

The following two methods were used to modify the pump module mounting in order to reduce size and the number of components in conjunction with the smaller diameter of the pump insert hole:

- (1) Radial seal structure with O ring
- (2) Snap-fit retainer

3.2.1. Radial seal structure with O ring

As Fig. 6 shows, the former module used a rubber seal with a double lip, fitted in the planar direction, to seal the mount section. This increased the diameter of the pump module, and made a large flat section necessary for mounting.

In the new module, an O ring radial seal has been used for the pump mounting. The use of a radial seal on a module of the size of the former model would have increased the insertion load and affected workability, but the reduction in the diameter of the insert hole has enabled the load to be controlled to a level that maintains workability. Machining of the base plate helps achieve sufficient accuracy in the seal face on the tank side. The seal on the radial plane does not need a pressure load, and the seal performance is maintained as long as the load is not so large as to separate the O ring from the seal face, creating a highly reliable configuration.

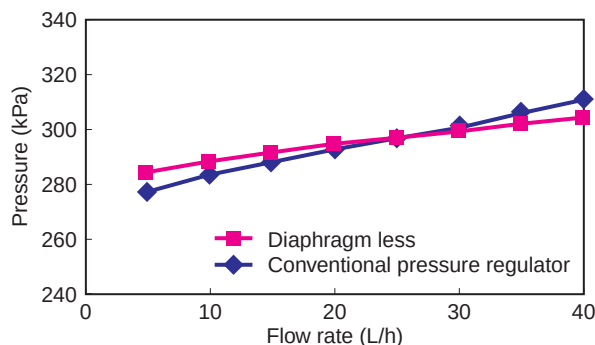


Fig. 5 Comparison of Q-P characteristics

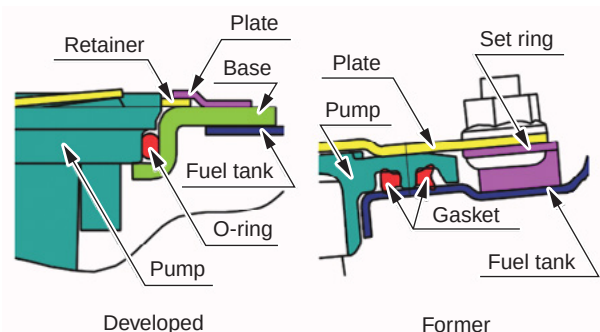


Fig. 6 Comparison of seal structure

The seal on the radial plane, in combination with the modification of the positioning of the parts, made possible an approximately 40% reduction in the diameter of the flange of the fuel pump module. In addition, the reduced use of high-cost rubber in the seal and the reduction of the size of the upper body have lowered materials costs.

3.2.2. Snap-fit retainer

Bolts were used to fasten the former module in place. In the new model, a sliding retainer holds the upper section of the module in place (Fig. 7).

In the former configuration, a ring plate used to fasten the fuel pump module was welded to the tank. Height accuracy was challenging to achieve, necessitating adjustment following spot welding, which increased costs. The use of five bolts also affected workability.

In the new configuration, the base plate that forms the pump mount is welded to the tank. Nickel plating is used to help prevent rust. A holding plate that forms a slit for the insertion of the retainer is welded to the base plate. When the retainer is pressed into the slit following insertion of the pump module, it fits onto protrusions on the slope formed on the upper section of the flange part,

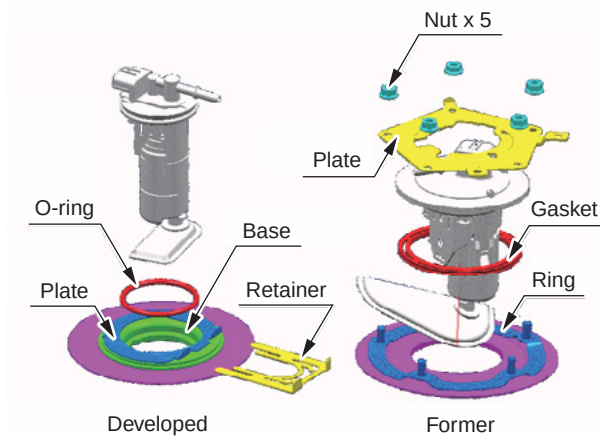


Fig. 7 Comparison of pump mounting

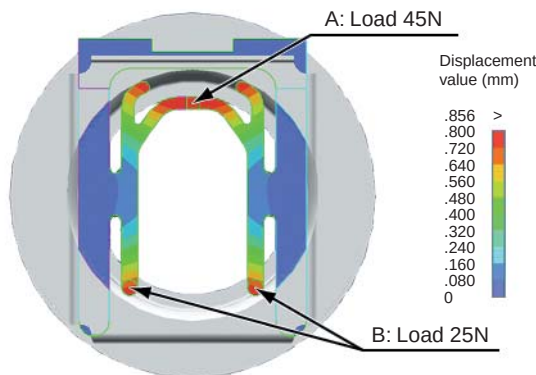


Fig. 8 Generated load at deformation of retainer

and a retaining load is generated in the direction of the pump axis. Figure 8 shows the results of a CAE analysis of the deformation of the retainer when the load needed to hold the pump in place is applied onto the protrusions on the slope section. These results were used to set the protrusion height and the retainer shape to obtain the necessary load.

The retainer has the locking shape shown in Fig. 9. During insertion the retainer is pushed by the sloping section. Following insertion, the locking section is immediately released from the holding plate and pops up, catching on the holding plate and keeping the retainer from moving. A screw is then used to accurately position the retainer. The use of this method rather than the former clamp screw method has reduced the workload involved in fitting the module by approximately 80% and the necessary mounting area by approximately 40%.

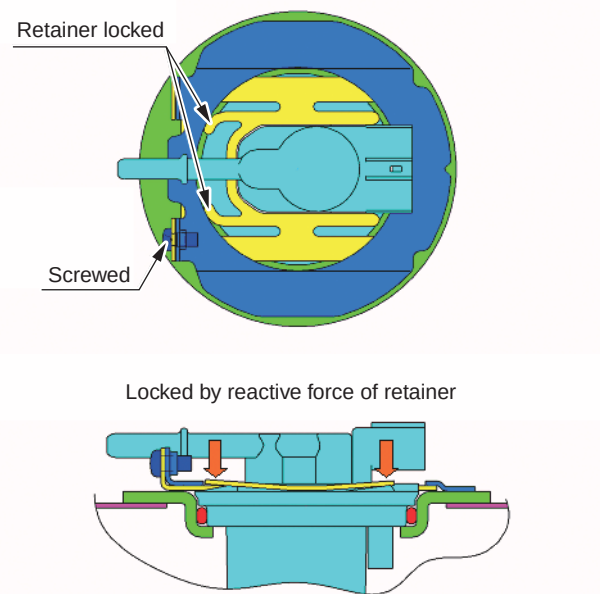


Fig. 9 Configuration of locking retainer

4. Conclusion

A small, low-cost fuel pump module for small motorcycles has been developed and employed in the 2008 Wave 110 motorcycle to be marketed in Thailand.

- (1) The removal of the diaphragm from the pressure regulator has reduced the size and simplified the structure of the component, while the use of a valve guide has been effective in achieving a performance level equivalent to the previous model in the range of fuel flow rates used in small motorcycles.
- (2) The pump motor has been designed for use in the range of flow rates used in small motorcycles of 150 cm³ displacement or below, and the coil winding

specifications have been modified, resulting in a reduction of 11 mm in the total length of the motor.

- (3) Reducing the diameter of the insert hole has enabled the use of an O ring radial seal, and a snap-fit retainer has also been employed, resulting in increased workability and a smaller mounting space.

Use of these strategies has reduced the mounting area of the module by approximately 40% and its cost by approximately 30%, enabling the developed module to be used in a wide range of small motorcycles.

■ Author ■



Masaki UENO



Minoru UEDA



Takashi UDONO



Shunji AKAMATSU



Mineo TORIKAI



Mitsuru FUKUDA

One-coat Paint for Motorcycle Engine Magnesium Cylinder Head Cover

Fujio UMEBAYASHI*

Shinsuke MOCHIZUKI*

Akiko TANAKA*

Hiroshi OKADA**

ABSTRACT

Two-coat painting is generally necessary to achieve both weather resistance and corrosion resistance in magnesium motorcycle cylinder head covers. A paint that enables the achievement of both weather resistance and corrosion resistance using one coat has been developed by adding epoxy resin to the main resin to promote modification, adding compounds to increase adhesiveness, and adding rust preventive pigments. The developed paint enables magnesium cylinder heads to be painted using one coat, and thus reduces the number of painting processes involved.

1. Introduction

Most motorcycle cylinder head covers are made of aluminum alloy (ADC12), but recently the need for magnesium alloy (AZ91D) cylinder head covers in order to reduce vehicle weight has been increasing. Figure 1 shows an example motorcycle cylinder head cover.

Cylinder head covers made from both types of materials are painted for rust prevention and decorative purposes, but aluminum alloy materials have relatively



Fig. 1 Cylinder head cover of CBR600RR

good corrosion resistance, so sufficient performance including corrosion resistance can be obtained with only one-coat of paint that has good weather resistance. In contrast, magnesium alloy materials have low corrosion resistance, so the paint used should have good corrosion resistance and adhesion properties. However, paint with such properties generally has low weather resistance, so magnesium alloys should be given two coats of paint, consisting of a primer coating using paint that has high corrosion resistance and then a top coating using paint that has good weather resistance. This increases the number of painting processes involved.

This study developed one-coat chromium-free paint that achieves both corrosion resistance and weather resistance in order to reduce the number of painting processes. This paint was developed by adding epoxy type primer resin to acrylic urethane resin to promote modification, and adding a polymer compound and rust preventive pigments to further enhance performance. This paper describes the paint design approach and results.

2. Paint Development

2.1. Development Points

In order to change the two-coat paint used for magnesium alloys to one-coat paint, the paint should simultaneously achieve the basic performances of

* Motorcycle R&D Center

** YUKOSHA CO., LTD.

Table 1 Points of development

Item		Purpose
Reduction of number of coats (2-coat to 1-coat)		Reduction of procedures
Basic performance	Adhesion	Satisfy all property of adhesion, corrosion resistance, and weather resistance requirement using 1-coat paint
	Weather resistance	
	Corrosion resistance	
Applicability to mass production	Re-coatability	Adhesion after re-coat
	Baking-temperature applicability	Applicability to mass production line

adhesion, corrosion resistance and weather resistance. In addition to these basic performance characteristics, recoatability for paint touch-up, a one-component paint, and adaptability to mass production lines that can flexibly support the paint conditions of multiple paint manufacturers are also important. Therefore, these performance characteristics were positioned as development points on the same level as those of basic performance characteristics. Table 1 lists the development points.

2.1.1. Paint design issues

The current paint configuration for magnesium alloy parts is generally a two-coat paint with primer paint applied first as a primer coating, followed by a top coating paint. When using this type of two-coat paint, the necessary functions can be divided between the primer and the top coating, so it is easy to obtain the various necessary performance characteristics. Primer paint is selected focusing on adhesion and corrosion resistance, so epoxy resin type paint is generally used. Epoxy resin has epoxy groups and hydroxy groups distributed at equal intervals throughout its molecular structure, so it features good material adhesion. In addition, the main chain of the molecular structure does not include an ester bond, so epoxy resin also has good water and chemical resistance characteristics⁽¹⁾. On the other hand, the weather resistance is quite low, and ultraviolet rays easily cause yellowing and chalking, so epoxy resin is considered unsuitable as a top coating paint.

In contrast, acrylic resin type paint, which has low adhesion and corrosion resistance but good weather resistance and appearance characteristics, is generally used as the top coating paint.

The issue when changing from two-coat paint to one-coat paint is to achieve both corrosion resistance and weather resistance. It is therefore necessary for the corrosion resistance and adhesion of epoxy resin to be assigned to acrylic resin, but it is challenging to achieve both performance characteristics simply by changing the resin. This paint development added a polymer compound that increases adhesion and functional pigments that increase corrosion resistance in order to simultaneously

enhance both performance characteristics. This resulted in the development of a one-coat paint that can manifest the roles of both a primer epoxy paint and top coating acrylic paint, which formerly necessitated a two-coat paint.

2.1.2. Paint line adaptability conditions

Paint exerts its natural adhesion under conditions of properly treated materials, proper painting and proper baking. However, different painting line facilities use different baking oven temperature rise conditions. Considering its applicability to multiple painting lines, the paint should support a wide range of baking conditions. Based on temperature data obtained from actual painting lines, the standard temperature for the developed paint was set at 150°C, and the target was to achieve adhesion with the materials over the baking range of 140°C to 160°C for 20 to 30 minutes.

2.1.3. Recoatability

Paint should also consider recoatability. The recoat painting process is performed when paint trouble occurs such as the adherence of dirt or bits, and consists of a sanding procedure to help eliminate the trouble and then repainting. In this case the recoated paint film should exhibit the same level of adhesion by the same kind of processes as normal painting, so this feature was also set as a goal for the developed paint.

2.1.4. Environmental compliance

The conventional painting pretreatment for magnesium alloy parts generally used hexavalent chromium. However, the one-coat paint aimed for by this development also had the environmental goal of paint that does not contain hazardous substances. Therefore, in addition to making the paint itself lead-free and hexavalent chromium-free, this development also removed hexavalent chromium from the pretreatment process.

2.2. Paint Design

2.2.1. Resin Types

(1) Main resin

The important performance characteristics for one-coat paint resins are good adhesion with materials and equivalent weather resistance to that of the conventional top coating paint. Based on proven results of adhesion performance to nonferrous materials, epoxy resin and acrylic resin were selected as candidates for the main resin. In addition, the baking temperature was set at the general temperature of 150°C, so melamine resin and blocked isocyanate resin were selected as candidates for the hardener.

Table 2 shows the results of preliminary verification of the main resin candidates. Epoxy resin has better adhesion compared to acrylic resin, but weather resistance as a top coating paint should also be considered, so development of an epoxy resin type paint was abandoned.

Table 2 Study of resin types

Resin type / Characteristics	Water resistance/ secondary adhesion	Corrosion resistance	Weather resistance	Hardness
Acrylic / Melamine	Low	Low	High	High
Acrylic / Urethane	High	Low	High	High
Epoxy / Melamine	High	High	Low	Low
Epoxy / Urethane	High	High	Low	Low

In addition, melamine resin has issues with water and humidity resistance, so it was excluded from consideration as a hardener.

Therefore, acrylic resin with reactive hydroxy groups was selected as the main resin, and development focused on increasing the adhesion performance of this acrylic resin.

Acrylic resin was adopted because it has been proven to support a wide range of diverse applications⁽²⁾ due to its compatibility with various monomers, glass-transition temperature (T_g), the ability to control the molecular weight, etc. Figure 2 shows the T_g and main performance characteristics of acrylic resin.

The hardness and solvent resistance of acrylic resin increase together with the T_g, but adhesion tends to decrease⁽³⁾. Therefore, optimization design was performed taking into account the correlation between T_g and adhesion.

Resin with blocked isocyanate groups that undergo a dissociation reaction when heated was selected as the hardener. In consideration of paint workability, the temperature inside the oven and other factors, the dissociation temperature was set at 130°C, which is equivalent to that of the hardening conditions for general top coating. In addition, the hardener characteristics focused on adhesion, and the compounding amount was adjusted in consideration of adhesion.

(2) Modified resin and polymer compound

One method of enhancing paint performance is modification, which consists of compounding or polymerizing other resins into the main resin. One-coat paint with stable adhesion could not be obtained simply by optimizing the acrylic urethane (blocked isocyanate) main resin, so a modification promoting epoxy resin and a polymer compound were added to the main resin with

T _g	Low	← Fixed T _g →	High
Resistance to solvent	Low		High
Adhesion	High		Low

Fig. 2 T_g performance of acrylic resin

the aim of increasing adhesion. The epoxy resin added for modification was a bisphenol type because polyisocyanate can be used as a common hardener for both this resin and the acrylic resin. However, the paint performance varies greatly depending on the compounding ratio of the epoxy resin, so the compounding ratio was determined from the viewpoint of weather resistance and corrosion resistance in consideration of the operating environment. Figure 3 shows the relationship between the epoxy resin compounding ratio and the weather resistance and corrosion resistance.

A polymer compound was also added to increase adhesion. Here, a silane coupling agent with functional groups that react with the hydroxy groups on the magnesium surface was used. Figure 4 shows the mechanism for increasing adhesion with the silane coupling agent, and Fig. 5 shows the relationship between the compounding amount and adhesion.

2.2.2. Pigment compounding

Color pigment was used to give the paint good appearance, body pigment to increase the paint strength,

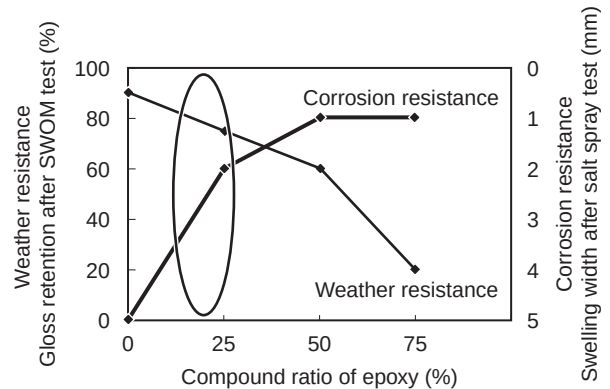


Fig. 3 Epoxy compound ratio versus weather resistance and corrosion resistance

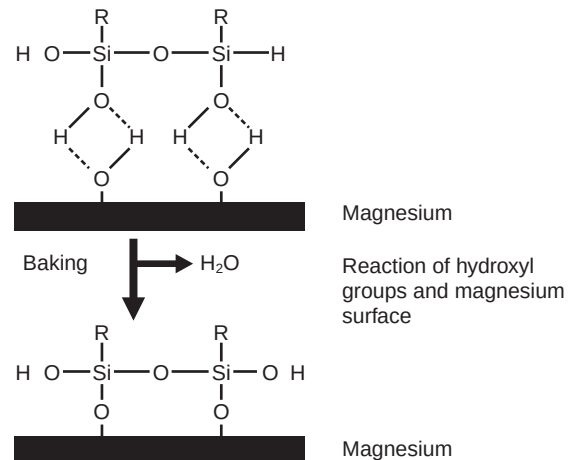


Fig. 4 Mechanism of adhesion to magnesium

and rust preventive pigment to provide corrosion resistance. Rust preventive pigment is not normally compounded with two-coat paint, but it was added to the developed paint to provide corrosion resistance. Chromium type rust-preventive pigment can generally be expected to provide rust preventive effects based on past results, but chromium-free type rust preventive pigment with good corrosion resistance was selected and compounded in consideration of environmental measures. Figure 6 shows the relationship between rust-preventive pigment type and corrosion resistance. Figure 7 shows that appearance diminishes when too much rust-preventive

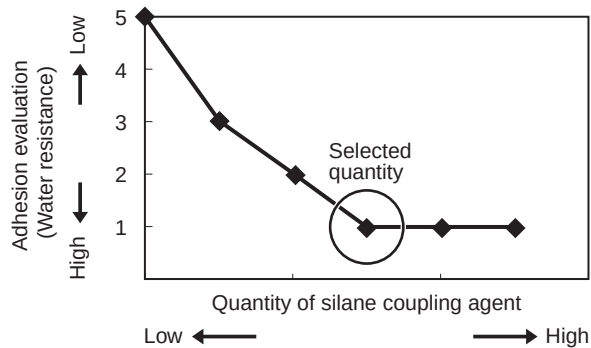


Fig. 5 Effect of silane coupling agent on water resistance

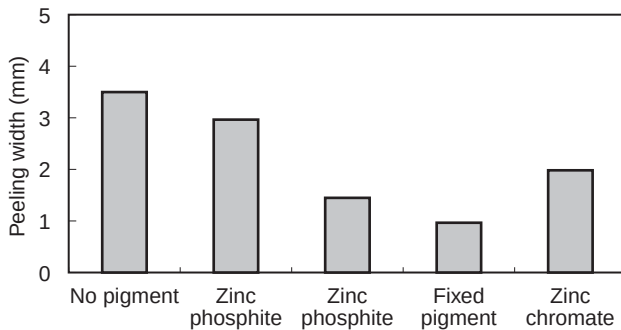


Fig. 6 Change in corrosion resistance by pigment

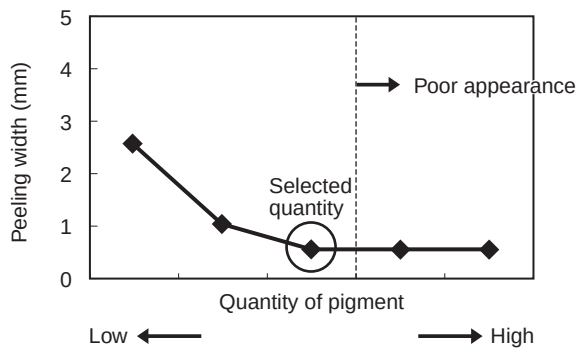


Fig. 7 Change in corrosion resistance and appearance by quantity of pigment

agent is added, so a quantity that achieves both corrosion resistance and appearance was determined and compounded.

3. One-coat Paint for Magnesium Alloy and Paint Film Performance

3.1. Basic Performance characteristics

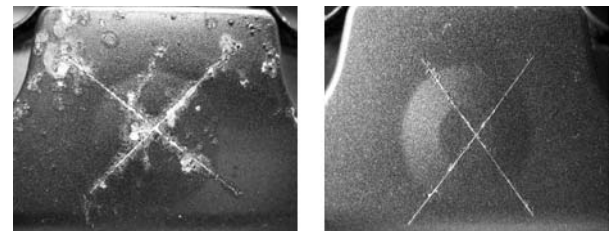
The developed paint made it possible to achieve the necessary performance characteristics of magnesium cylinder head cover paint with chromium-free type pretreatment plus one-coat paint instead of the conventional chromate type pretreatment plus two-coat paint.

3.1.1. Corrosion resistance

Corrosion resistance was increased, compared to conventional one-coat paint for magnesium surfaces, and the same corrosion resistance could be obtained as that of two-coat paint that uses primer. Figure 8 shows the appearance after the corrosion resistance test, and Fig. 9 shows the paint peeling width.

3.1.2. Weather resistance

The developed paint provides a level of weather resistance close to that of current paints, which poses no issues for practical use. Figure 10 shows the color difference and gloss residual ratio after the weather resistance test.



Conventional 1-coat paint
(acrylic resin type paint)

Developed 1-coat paint

Fig. 8 Corrosion resistance (salt spray test)

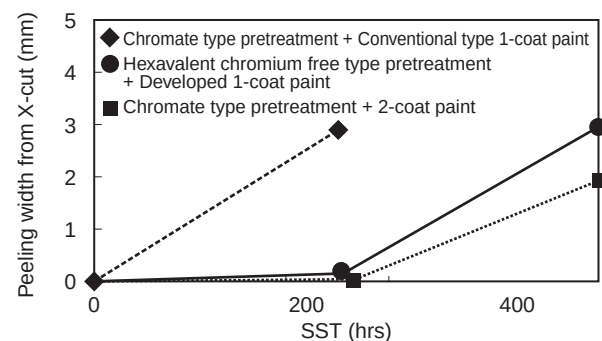


Fig. 9 Corrosion resistance (Salt spray test)

3.1.3. Galvanic corrosion resistance

Figure 11 shows the corrosion resistance test results in the actual mounted condition.

The influence of galvanic corrosion with the bolts used was confirmed to be the equivalent level to that for current mass-produced two-coat paints.

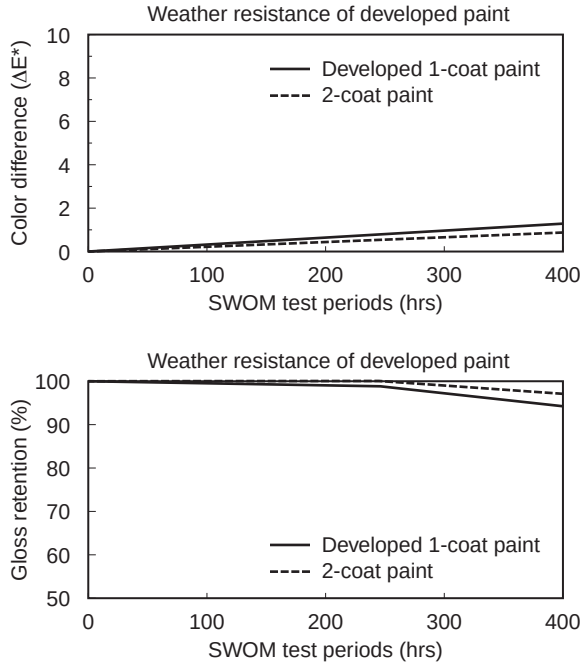


Fig. 10 Weather resistance

CCT cycle		30 cycle	100 cycle
Developed Hexavalent chromium free type pretreatment + 1-coat paint	Aluminum case		
	Bolt with Zn plating		
Current Chromate type pretreatment + 2-coat paint	Aluminum case		
	Bolt with Zn plating		

Fig. 11 Galvanic corrosion

3.2. Mass Production Characteristics

3.2.1. Adhesion stability

The adhesion at different baking temperatures and times was confirmed to evaluate baking temperature applicability. Figure 12 shows these results. Sufficient adhesion performance could be obtained over the wide temperature range of 140°C to 180°C, which is twice the target setting temperature range of 140°C to 160°C.

3.2.2. Corrosion resistance

Manganese phosphate type pretreatment, which is a type of hexavalent chromium-free treatment, was used as an environmental measure. However, the coating weight influences the corrosion resistance, so the optimum coating weight was determined. Figure 13 shows the relationship between the coating weight and corrosion resistance.

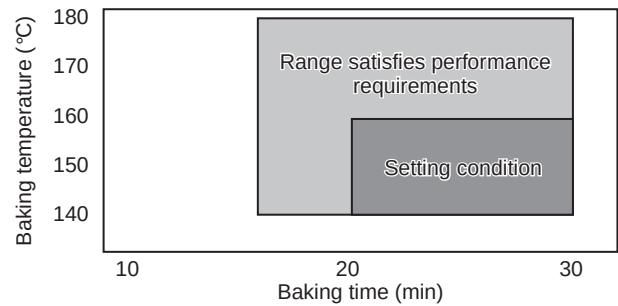


Fig. 12 Baking temperature applicability

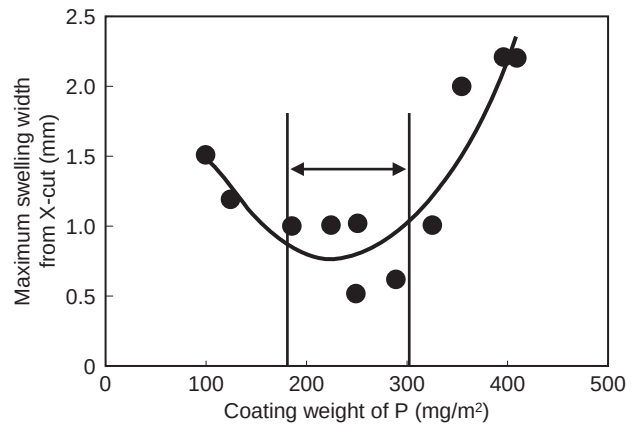


Fig. 13 Pre-treatment coating weight versus corrosion resistance

4. Conclusion

Two-coat painting is conventionally applied to magnesium cylinder head covers. The following items enabled use of one-coat paint, which reduced the number of painting processes by 30% or more.



Fig. 14 CBR600RR which applied developed paint

- (1) Corrosion resistance was increased by adding an appropriate amount of epoxy resin to the main resin to promote modification.
- (2) Adhesion was increased by adding a silane coupling agent that reacts with magnesium.
- (3) Rust prevention performance was increased by using chromium-free pigments in consideration of environmental compliance.

The developed paint was applied to the CBR600RR (Fig. 14).

References

- (1) Japan Paint Manufactures Association: Toryou Gairon, Toryou Bunrui, Koujou Tosou Rain ni Okeru Tosou Toryou Kanri Handobukku, Tokyo, p. 38-41 (2000) (in Japanese)
- (2) Sato, K.: Tomaku no Nendansei, Hashikakegata Tomaku no Nendansei, Gaisetsu Toryou Bussei Kougaku, Tokyo, p. 85-94 (1973) (in Japanese)
- (3) Sato, K.: Tomaku no Fuchaku, Tomaku no Sosei to Fuchakusei, Gaisetsu Toryou Bussei Kougaku, Tokyo, p. 197-208 (1973) (in Japanese)

■ Author ■



Fujio UMEBAYASHI



Shinsuke MOCHIZUKI



Akiko TANAKA



Hiroshi OKADA

Development of Handle Type Electric Wheelchair Simulator

Tadahiro YAGUCHI*

Kazuhiro MINATO*

Hiroo KANKE*

ABSTRACT

Enhancing the understanding of traffic rules and the ability to anticipate the potential dangers in mixed traffic of pedestrians, bicycles, motorcycles, automobiles, and the like, would be an effective way of helping to prevent accidents for the electric wheelchair users. A handle type electric wheelchair simulator was accordingly developed to enable people to safely experience those potential dangers.

The simulator was given two configurations. The actual wheelchair type combines an actual wheelchair with a personal computer and large-screen display. The widespread use type has a steering handle unit and a notebook computer. The simulator screens are set up to be easy to follow and easy to operate for the elderly user, and the narration employs a frequency range that is easier to hear. A module that enables test subjects to check their own physical functionality and judgment capability was also included. The traffic scenario experience module was configured with several scenarios for situations that could easily turn dangerous, based on the particulars from a number of accidents.

This enables not only electric wheelchair users but also people who have never operated an electric wheelchair to have a driving experience by means of a simulator. It also enables traffic safety lectures to be held with a simulator experience included as part of the program.

1. Background

Recent years have seen the use of handle type electric wheelchairs as a means of transportation for many people who find walking difficult. The Japanese Industrial Standards classify these as the joystick standard type and the handle type. The handle type comes in three-wheel and four-wheel versions.

Ownership of electric wheelchairs⁽¹⁾ is increasing, and the demand for handle type models is high (Fig. 1).

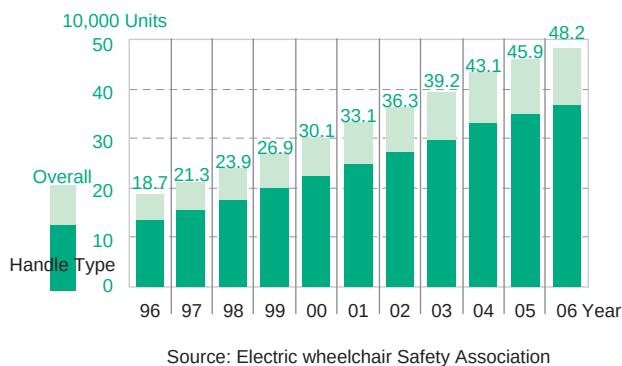


Fig. 1 Number of electric wheelchairs owned

The aging of society is bringing developments in the legal system (the Transportation Accessibility Improvement Law of 2000) and infrastructure. The use of electric wheelchairs is expected to increase accordingly. However, the growing number of users is paralleled by a rise in the number of electric wheelchairs involved in traffic accidents (Fig. 2).

Approximately 70% of electric wheelchair users who encounter accidents are aged 65 or over. Accidents

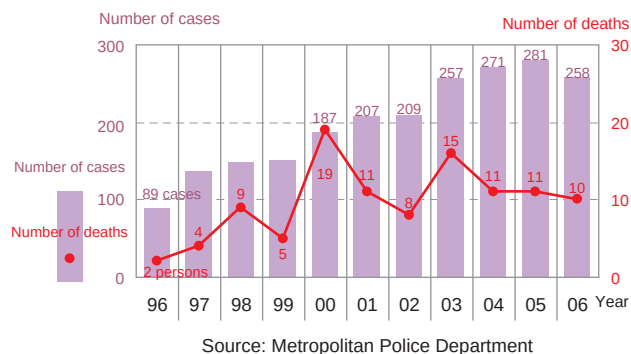


Fig. 2 Electric wheelchair transition of the number of traffic incidents and deaths

* Power Products R&D Center

involving contact with a motor vehicle while crossing a street are the most common (Fig. 3). In addition, many of the people who operate electric wheelchairs have not had automobile driver's licenses, amounting to 48.2% (reported at International Association of Traffic and Safety Sciences in 2002).

Electric wheelchair users need to be aware of the distinctive characteristic of electric wheelchair accidents enumerated below:

- (1) Electric wheelchair riders are positioned relatively low to the ground, making them less visible for automobile and other drivers.
- (2) The top speed of electric wheelchairs is fixed by law at 6 km/h, so that they require time to take evasive action.
- (3) Electric wheelchairs may enter the roadway when sidewalks are blocked by steps or obstacles.

As a manufacturer of motorcycles and automobiles, Honda has long proclaimed the concept of "safety coexistence," which seeks the safety of all people who live together in the mobility society. Honda is therefore engaging in safety initiatives by both technological (meaning hardware-based) and educational (meaning software-based) approaches.

In terms of vehicle-related measures, Honda considered the heightening of visibility for automobile drivers. Measures were taken on the number and placement of

lamps and lights on the Monpal ML200^{(2),(3)} with the adoption of Honda's ASV-3 LONG design. This raised the likelihood that automobile drivers could judge the distance to an ML200 by approximately 10%, compared to the first generation ML100.

On the other hand, approaches from the "soft" side include the provision of safety guidance at the time electric wheelchairs are purchased. Electric wheelchairs are conveyances that the Road Trucking Vehicle Law classifies as pedestrians, and a driver's license is not required. Honda has therefore been training wheelchair operation instructors and providing guidance in methods of operation and traffic rules, from the time the Monpal ML100 went on sale in 1999. (Fig. 4)

2. Development Purpose and Goals

Honda also seeks to provide users of these wheelchairs with a better understanding of traffic safety. In addition to guidance in wheelchair operation given at the time of purchase, Honda employs simulators that allow users to safely experience the kinds of incidents that can occur in actual operation on the streets. Honda has established a record with motorcycle and automobile simulators.^{(4),(5)} That experience was put to use in planning the development of a handle type electric wheelchair simulator with a focus on the potential users of electric wheelchairs and their family members.

The following development objectives were determined:

- (1) Ease of use by the elderly
- (2) Size and configuration to allow use at locations where potential users gather
- (3) Capability for objective assessment of electric wheelchair operating ability and judgment capability

Since many users are elderly, a method of development based on user interaction was adopted.

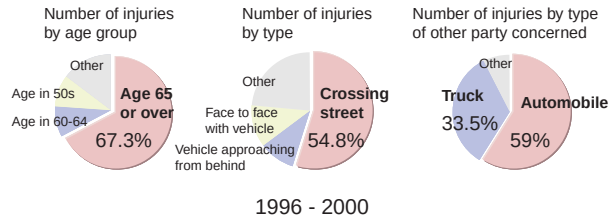
3. Simulator Construction and Content

3.1. Simulator Construction

3.1.1. Widespread-use type simulator

A simple simulator using the steering handle unit from an actual wheelchair together with a notebook computer was first made in order to collect customer comments and impressions. This simulator was taken to welfare equipment exhibitions, traffic safety lectures, and other such events, and people's comments were collected. That data was organized systematically, the corresponding technologies were applied, and the resulting simulator would then be tried out by test subjects. This process was repeated in order to pursue ease of use (Fig. 5).

The steering handle unit was equipped with a screw clamp to make it more convenient to mount on ordinary desks and tables. In order to reproduce the direct forward motion experienced in actual operation, the unit was



Source: International Association of Traffic and Safety Sciences 2002

Fig. 3 Current breakdown of handle type electric wheelchair injuries



Fig. 4 Guidance by the safety instructor

equipped with a return spring that brings the steering handle back to a neutral position (Fig. 6).

Wheelchair users were observed using these simulators from their own wheelchairs. Given this observation,



(a) At a driving school



(b) At a safety promotion event

Fig. 5 User interaction type development technique

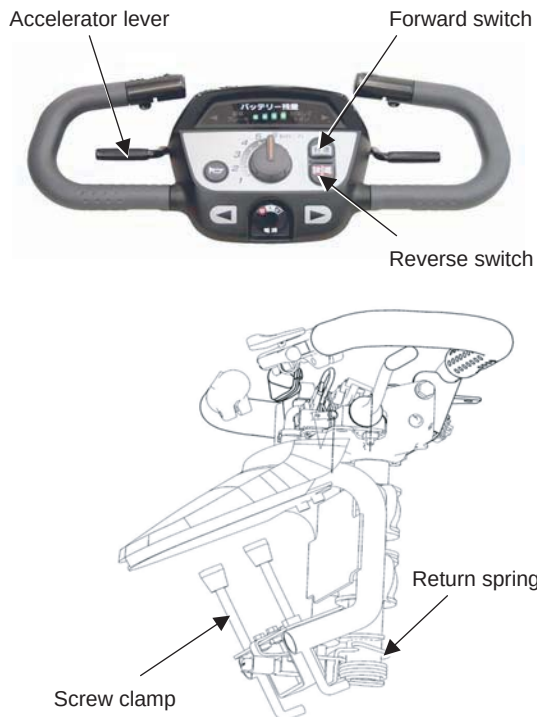


Fig. 6 Appearance of version for widespread use

together with the ease of installation and maneuverability of the simulators, it was confirmed that they could be used to provide simulated experience to larger numbers of people (Fig. 7).

3.1.2. Actual wheelchair type simulator

This simulator was envisioned for use at gatherings with large numbers of people so that beginners coming into contact with electric wheelchairs for the first time could have a more realistic simulated experience of actually riding in a wheelchair. The simulator was therefore made by combining an actual wheelchair with a large wide-screen display (Fig. 8).

The Monpal ML200 implements controller area network (CAN) communications between the motor drive unit ECU and control panel unit ECU in order to realize advanced fault diagnostics and reduce the number of harnesses. Sensor values from the drive lever are converted to digital data by a circuit board in the control panel and transmitted by CAN.

That communications data was used in this simulator in order to simplify the system. Moreover, connection to the diagnostic computer interface on the Monpal ML200



Fig. 7 Simulator operation by a wheelchair user



Fig. 8 Simulator configuration

enables simple setup and helps eliminate the need for dedicated simulator equipment. This system is therefore made easy to introduce at dealers that have actual wheelchairs on hand (Fig. 9).

3.2. Simulator content

3.2.1. Screen easy to see and narration easy to hear

Various measures were also devised in terms of content to help potential users who are considering use of an electric wheelchair gain a better understanding of traffic manners and rules.

The display was designed for ease of operation and a sense of security, removing the tension and apprehension that might be felt by the user when faced with a personal computer.

The menu is composed of folders that contain material under the three main categories of “Learning Operation,” “Learning How to Drive on the Street,” and “Other.” The menus within those folders are indexed so that users can easily look over their overall contents (Fig. 10).

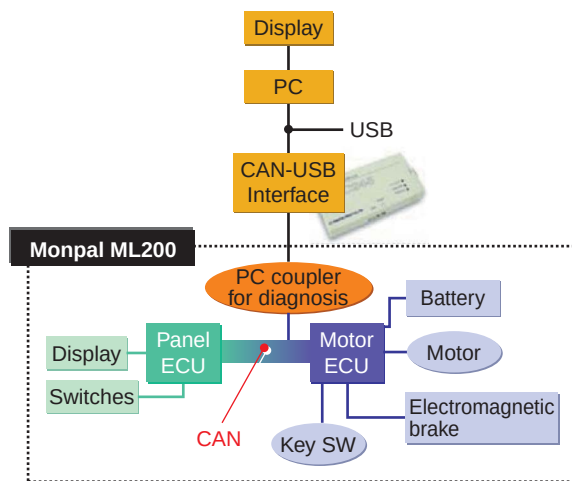


Fig. 9 Diagram of CAN-USB system



Fig. 10 Indexed menu

The simulator displays text using large, high-contrast characters that make the screens more easily visible.

The narration was also made easier to hear for the elderly by boosting the sound pressure in the 250-1000 Hz low-frequency band, based on the average hearing threshold level by age group⁽⁶⁾ (Fig. 11).

3.2.2. Practicing basic operation and checking physical functionality (visual acuity, delay in movement)

There were requests to make the simulators usable for objectively checking the physical capability of customers in their operation of electric wheelchairs (their reaction speed, grip strength, and so on) as well as their judgment capability where the wheelchairs are sold, and to make them useful in providing safety guidance. Among people interested in using electric wheelchairs, and their family members, a need was also felt for information on which to base decisions on whether they are suited to operating these wheelchairs.

The menu has an “Other” folder that provides access to functions for practicing basic operation as well as for measuring physical reaction speed, visual acuity and judgment capability.

Practicing basic operation involves becoming accustomed to how the wheelchair comes to a stop when the accelerator is released, which is a distinctive feature of electric scooters. There are driving practice courses where customers can learn this maneuver and the actions of going forward, turning, and stopping.

The screen for measuring delay in reaction movement works by having a traffic signal up ahead turn red while the test subject is driving and measuring how long the test subject takes to release the drive lever (to come to a stop). That time is displayed at the bottom of the screen (Fig. 12).

The screen for measuring visual acuity and judgment capability displays a message board with a brief written instruction. As the user drives, this gradually becomes larger. The user’s approximate visual acuity can be extrapolated from the size of the text at the point when

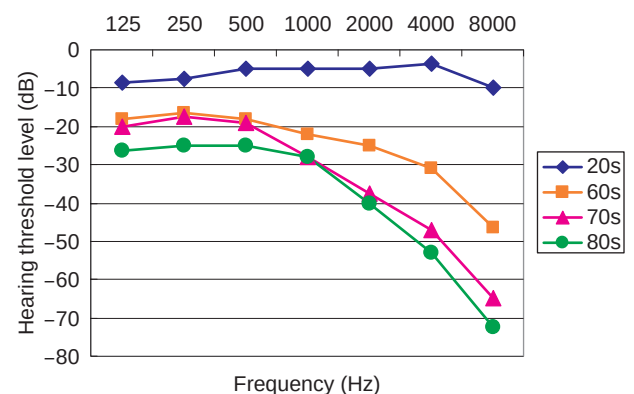


Fig. 11 Average hearing threshold level by age group

the user reads the instruction and carries out the indicated action. The visual acuity measurement is displayed at the bottom of the screen (Fig. 13).

These functions allow the test subjects to understand their physical and judgment capabilities for themselves. The flowcharts for these functions are shown in Fig. 14.

3.2.3. Setup of traffic scenarios

Analysis was made of actual accident particulars obtained from electric wheelchair accident statistics and from surveys of dealers and customers. The following traffic scenarios were selected for simulation:

- (1) Obstacle on the roadway
- (2) Intersection with traffic signal
- (3) Going over a railroad crossing
- (4) Pedestrian crossing without traffic signal
- (5) Vehicle crossing the sidewalk
- (6) Intersection with poor visibility
- (7) In crowds of people
- (8) Vehicles backing up
- (9) Face to face on a farm road
- (10) Going through automatic doors
- (11) Using an elevator



Fig. 12 Measuring delay in reaction movement

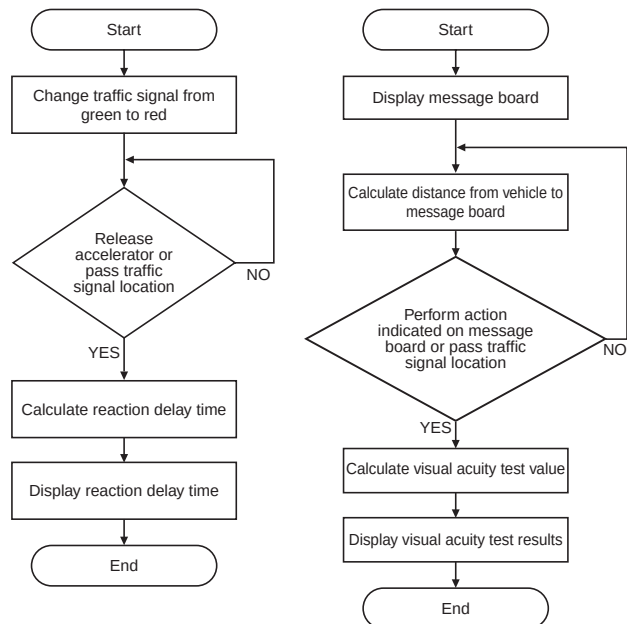


Fig. 13 Vision test

Scenarios can be combined to match the test subject's skills and learning objectives. The period of the virtual driving experience in these scenarios was shortened to approximately three minutes. This measure was devised so that test subjects would remain interested in the simulation, and so that more people would be able to experience the simulator when it is used at traffic safety lectures and other such events where learning times are limited (Fig. 15).

3.2.4. Ride simulation using imagery of actual scenes

A system that uses imagery of actual scenes rather than imagery generated by computer graphics was also made. A video camera was installed on a Monpal ML200, which was then operated on city streets and in parks. That video imagery was edited and the simulator was set up so that manipulating the Monpal simulator controls would cause



(a) Delay in reaction movement

(b) Vision test

Fig. 14 Flow chart



Fig. 15 Scene across a railroad crossing



Fig. 16 Scene of a junction

the video image to move. This system possesses the following functions:

- (1) Moving and stopping: Pressing down on the drive lever causes the video to play back, and releasing the drive lever pauses the video.
- (2) Speed control: The video plays back in slow motion according to the indicated speed.
- (3) Moving forward and moving in reverse: During forward movement the video plays back as normal, and during reverse movement the video plays back in reverse.
- (4) Branch in the road: At predetermined junctions, turning the handle causes the video to switch to imagery of the branch the wheelchair is moving into (Fig. 16).
- (5) Riding locations can be selected from the menu.

This system does not enable as much freedom of movement as in screens generated by computer graphics, but it enables users to experience something of the sensation of riding in actual urban settings and was devised to make people want to go out in their electric wheelchairs. Video imagery of local urban scenes in the user's community can also be utilized to make the simulator feel more familiar and approachable.

3.3. Comments from users

The simulator has been used to date by approximately 30 test subjects. The comments that have been received, based on their experiences, included the following:

"It gave me a sense of security to be able to train on the simulator before riding on an electric wheelchair."

"Its compactness and transportability are good."

"We would like to have the use of these at traffic safety lectures and senior citizens clubs."

The intention for the future is to evolve the system to provide greater educational effect, including methods of operation.

4. Conclusion

A handle type electric wheelchair simulator was developed for the purpose of providing training in traffic rules and manners to the elderly people who drive such

wheelchairs, as well as enhancing their ability to anticipate danger. This handle type electric wheelchair simulator possesses functions and characteristics as follows:

- (1) There are two simulator types, one using an actual wheelchair and one for widespread use, which can be selected to suit the size and purpose of the safety lecture;
- (2) The operating menu is simple and easy to use for elderly people;
- (3) The simulator can be used for learning basic operations (learning before riding an actual wheelchair);
- (4) It can be used to check physical capabilities; and
- (5) It enables experience of potentially dangerous situations in mixed traffic.

This has enabled not only electric wheelchairs users but also people who have never operated an electric wheelchair to have a driving experience by means of a simulator. It has also enabled traffic safety lectures to be held with a simulator experience included as part of the program.

References

- (1) <http://www.den-ankyo.org/transition.html>, 2007/9/1
- (2) Ichikawa, K., Hirose, Y., Yamamoto, T., Yamagishi, Y., Ishikawa, T.: Development of Monpal ML200 4-Wheel Scooter, Honda R&D Technical Review, Vol. 18, No. 2, p. 28-35
- (3) Yamagishi, M.: Styling Design of New MONPAL ML200, Honda R&D Technical Review, Vol. 19, No. 2, p. 7-11
- (4) Suzuki, K., Miyamaru, Y., Aoki, K., Ichimi, S.: Development of Bicycle Simulator and Its Features, 2007JSAE Annual Congress Proceedings, 20075135, No. 71-07, p. 15-18 (2007)
- (5) Ichimi, S., Miyamaru, Y., Aoki, K., Suzuki, K.: Development of Riding Trainer for Safety Riding Education and Its Features, 2006JSAE Annual Congress Proceedings, 20065627, No. 121-06, p. 15-18 (2006)
- (6) Nakano, A.: Rojinsei Nancho no Ichirei yori, Nyumon Souon Kogaku, Gijyutsushoin, p. 116 (1984) (in Japanese)

■ Author ■



Tadaihiro YAGUCHI



Kazuhiro MINATO



Hiroo KANKE

Removal of Grounding Cable from Hydrogen Fueling Process

Steve MATHISON*

Kiyoshi HANDA**

Shiro MATSUO***

ABSTRACT

Hydrogen, which is used for fuel in fuel cell vehicles, has the characteristic of being easy to ignite. Because of this characteristic, prior to fueling, static electricity from the vehicle body should be dissipated. Industry practice to mitigate this risk has been to connect a grounding cable to the vehicle to remove the static electricity from the vehicle body prior to connection of the fueling nozzle. However, this complex procedure is not user-friendly, nor is it fail safe as it depends on the user to implement.

Our research⁽¹⁾ shows that the maximum grounding resistance that will allow static electricity to be safely dissipated before the fueling nozzle can be connected is 100 M Ω . Two favorable fueling pad surfaces were found to be conductive paint applied on asphalt, and concrete. After application, the separate grounding cable connection is no longer necessary, and as a result, safe and user-friendly fueling is now possible. The practice of grounding through the tires is now being adopted by hydrogen stations, and surface resistance requirements have been written into the latest revisions to the International Code Council (ICC) International Fire Code (IFC).

1. Introduction

The fuel cell shows much promise as a clean power plant of the next generation because of its potential to displace the use of fossil fuels and reduce emissions, including those associated with global warming. In addition to developing fuel cell vehicles, it is important to study how hydrogen is supplied to fuel cell vehicles, as hydrogen supply will influence the appeal and marketability of fuel cell vehicles in the future.

2. Background

Hydrogen, which is used for the fuel in fuel cell vehicles, has some properties that make it quite unique from other vehicle fuels. The most common fuel in use today is gasoline, with natural gas (consisting primarily of methane) fueled vehicles a distant second. Table 1 compares some properties of these fuels⁽²⁾. Gasoline has the narrowest range of ignitable fuel/air ratio and relatively high minimum ignition energy. Methane has a slightly wider ignitable fuel/air ratio, and even higher

minimum ignition energy than gasoline. Hydrogen has a very wide range of ignitable fuel/air ratio and a very low minimum ignition energy of 0.016mJ, approximately 1/12th that of gasoline. It should be noted, however, that the minimum ignition energy in Table 1 is for stoichiometric mixtures (29% for hydrogen). At the lower flammability limit (LFL), the minimum ignition energy of hydrogen is nearly the same as that of methane.

In regards to the manner in which these fuels are dispensed, both hydrogen and natural gas are dispensed to the vehicle in a closed system designed to prevent leaks, whereas gasoline dispensing utilizes an open system where vapors can escape near the interface of the nozzle and receptacle. Additionally, the presence of natural gas and gasoline is easily detected by the user from their distinct odor, whereas hydrogen has no smell and no odorants currently exist.

The hydrogen fueling coupling and associated hydrogen storage system on vehicles is designed as a closed system in which hydrogen does not leak either

* HONDA R&D AMERICAS, INC.

** Automobile R&D Center

*** Honda Motor Co., Ltd.

Table 1 Ignition properties of hydrogen, methane and gasoline

Properties		Hydrogen	Methane	Gasoline
Minimum ignition energy	(mJ)	0.02	0.29	0.24
Ignition limits in air	(Vol %)	4-75	5.3-15	1.0-7.6

during fueling or operation of the vehicle. However, potential ignition sources should be removed or mitigated as much as possible for safe fueling in the event that a failure of the system results in a fueling leak. Because gasoline and methane have narrower ranges of ignition limits and much higher minimum ignition energies, and leaks can be easily detected by smell, this is not as high a concern when fueling these vehicles.

Static electricity can build up on the vehicle chassis during driving, and this static electricity may be a potential ignition source during fueling. Therefore, it is important to dissipate this static charge from the chassis before fueling the vehicle. Under current industry practice, a fuel cell vehicle user connects a grounding cable (referred to as GND cable) to the vehicle first, before connecting the separate hydrogen fueling hose/nozzle (Fig. 1). The opposite side of the GND cable is connected to earth. This sequence allows the vehicle to discharge the static electricity before the fueling hose is connected and fueling begins. This practice has been implemented at nearly all hydrogen stations in the U.S. to date, as a precautionary requirement.

When fueling the test fuel cell vehicle used in this study, first the user opens a lid containing the GND connection receptacle, then connects GND cable to the GND connection receptacle. After this, the user pulls a knob in the GND lid, which then opens a separate lid containing the fueling receptacle (Fig. 1). This sequence

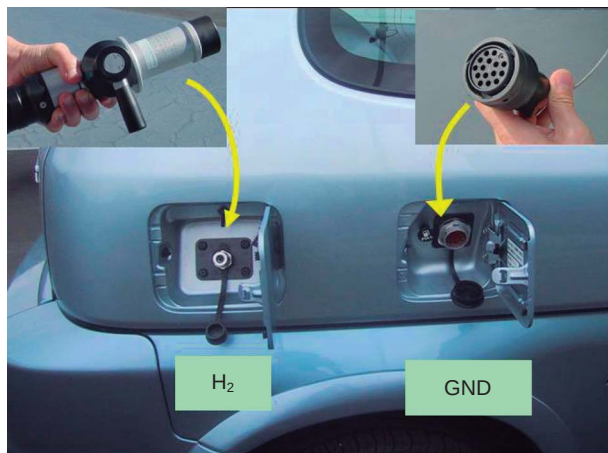


Fig. 1 Grounding cable connector/receptacle and H₂ nozzle/receptacle

is devised to remind the user to connect the GND cable before fueling, as a means to increase the safety of the fueling operation. However, if the user forgets to connect the GND cable or the connector isn't tightly connected, the GND cable can not work to remove the static electricity. This GND cable also increases the complexity of the fueling operation, and is not convenient for the user. Therefore, some other method to remove the static electricity surely and consistently without using the GND cable is necessary.

Although it is outside the scope of this paper, another important safety consideration when fueling a hydrogen vehicle (or even gasoline and CNG vehicles) is to help ensure that the user has discharged his / her body prior to connecting or disconnecting the nozzle. Many hydrogen stations require the user to touch a grounded conductive part on the dispenser before the nozzle can be released. Because a weak electrostatic spark from a human body releases about 10 mJ of energy (above the minimum ignition energy of all three fuels), grounding the user prior to connecting and disconnecting the nozzle is very important.

3. Requirements for adequate dissipation of static charge

Because the GND cable is not a reliable means of removing static charge from the vehicle chassis prior to fueling and because it is cumbersome to the user, we looked to an alternative, which is to use the existing contact between chassis and ground, i.e. the vehicle tires, as a means to removing the static charge. To help ensure that no ignition can occur, even if hydrogen is present, the grounding resistance, through the tires to earth ground, was calculated which will dissipate the static charge to a safe level within a short period of time after stopping the

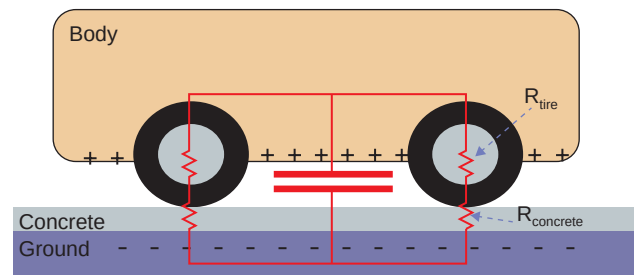


Fig. 2 Equivalent circuit of static electricity on vehicle

vehicle on the fueling pad surface. To make this calculation, an equivalent circuit of the static electricity on the vehicle is shown in Fig. 2.

The capacitance of the test vehicle was calculated to be approximately 0.5 nF by using Eq. 1. However, there may be numerous sizes of the vehicles in the future, some larger than the test vehicle. Therefore, a capacitance of 1 nF was used as a more conservative value. The literature also supports the use of 1nF as typical vehicle capacitance⁽³⁾.

$$C = \varepsilon \frac{A}{d} \quad (1)$$

C: Capacitance [F]
d: Pole interval [m]
 ε : Aerial permittivity [F/m]
A: The pole area [m²]

If the energy of the capacitor is smaller than the minimum ignition energy of hydrogen, hydrogen will not ignite. The capacitor's energy can be calculated from Eq. 2.

$$W = \frac{1}{2} CV^2 \leq 0.016mJ \quad (2)$$

V: Voltage of Capacitor [V]

When solving Eq. 2 for the condition of C=1nF, the answer is shown in equation 3.

$$V_t < 180V \quad (3)$$

Next we should consider the maximum voltage of the static electricity on the vehicle. There is a report which describes that a maximum of 2kV can be generated by the fuel pump in a conventional ICE vehicle⁽⁴⁾. Of course, on a fuel cell vehicle, because there is no fuel pump, the static electricity must be generated by a different mechanism. Because any given regional area may not be suitable to measuring the maximum static electricity voltage because of the high levels of atmospheric humidity, the 2kV value from the literature⁽⁴⁾ was adopted as a maximum potential for the vehicle.

$$V_0 = 2000V \quad (4)$$

For a capacitor, the voltage when discharging is shown by Eq. 5.

$$V_t = V_0 \times e^{-\frac{t}{RC}} \quad (5)$$

As a result, the resistance R can be calculated from Eq. 6.

$$R = \frac{t}{C \cdot \ln \left(\frac{V_0}{V_t} \right)} \quad (6)$$

To determine the required resistance, one must first establish how much time can be allowed for the static charge to dissipate to a safe level. If the static electricity is discharged to a safe level within 1 second after the vehicle stops at the station, there is no way fueling can be initiated before a safe condition is present, so this time value was chosen.

$$t < 1\text{sec} \quad (7)$$

When solving equation 6 for the above conditions,

$$R \leq 410M\Omega \quad (8)$$

Because this resistance value is considered under ideal conditions, it may be possible that the resistance between the vehicle chassis and ground could increase due to contaminants on the vehicle tires or on the fueling pad surface. Therefore, a four times safety factor was applied to the value in Eq. 8, resulting in a maximum grounding resistance requirement as shown in Eq. 9.

$$R \leq 100M\Omega \quad (9)$$

Also SAE J2578⁽⁵⁾ recommends that “the grounding resistance of the vehicle through the tires of the fuel cell vehicle should not exceed 25 M Ω ” while it refers to literature⁽³⁾. Therefore, if the vehicle tires meet the SAE J2578 recommended practice, the fueling pad surface itself should have a resistance of less than 75 M Ω .

4. Tests conducted to validate grounding through the tires

As discussed earlier, the goal of our research is to discharge the static electricity through the tires without the

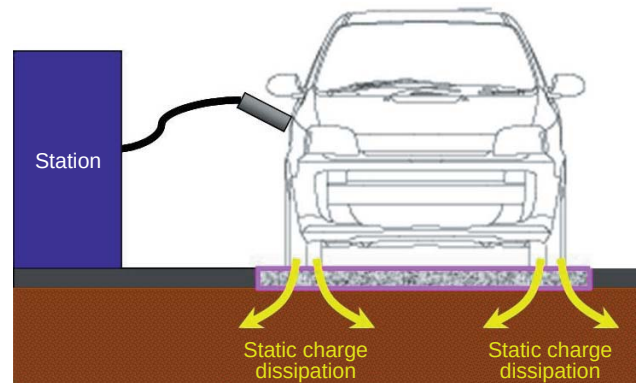


Fig. 3 Static charge dissipation through vehicle tires

use of a GND cable. If it is possible to discharge directly from the chassis through the tires to the Earth, the GND cable becomes unnecessary and it reduces the possibility of human error or negligence (Fig. 3). For this to occur, the grounding resistance of the vehicle chassis through the tires, including the parking surface, should be less than 100 M Ω as shown in Eq. 9. However, a tire is made of rubber (an inherently isolative material), and fueling pad surfaces at hydrogen stations are often made without any consideration for conductivity. Therefore, we conducted some validation tests as shown in the next section.

5. Validation Testing

5.1. Testing the basic resistance of the vehicle

In this test, we measured the resistance of the FC test vehicle on steel plates. The four tires of the test vehicle were placed on four steel plates which were connected in parallel electrically. We then measured the resistance between the steel plates and the chassis (Fig. 4). The result was a resistance of 1.7 M Ω . Because this resistance is much lower than the required resistance (100 M Ω), the test vehicle itself has enough low resistance to discharge the static electricity to the ground.

Next, we measured a number of conventional vehicles in the same way to understand the influence of tire selection. There were large differences in the results, ranging from 30 k Ω up to 370 M Ω (Table 2). The resistance was measured at a number of different locations on the chassis, and found to be the same, which indicates that nearly all of the resistance is contributed to by the tires themselves. An observation from our measurements is that high profile tires tend to have higher resistance values than low profile tires.

5.2. Testing the grounding resistance on asphalt

We measured the grounding resistance of the the FC test vehicle on an asphalt surface. The measurement result was 800 M Ω , which is much higher than the required resistance (100 M Ω). Therefore, an asphalt fueling pad

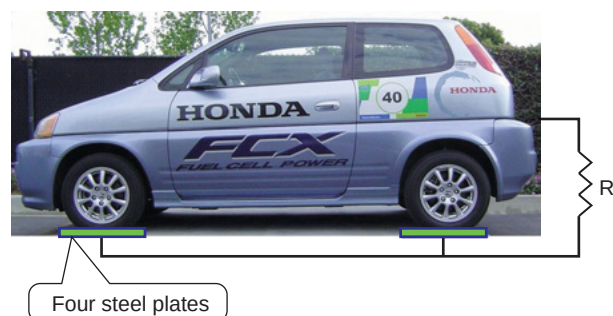


Fig. 4 Measuring resistance through tires parked on steel plates

Table 2 Resistance measurements for various cars and tires

Vehicle	Tire	Resistance
Fuel cell test vehicle	205/60R15	1.7 M Ω
Passenger car 1	195/60R15	35 M Ω
Passenger car 2	-	51 M Ω
Passenger car 3	245/40R18	8.3 M Ω
Passenger car 4	275/40R19	10.7 M Ω
Mini Van	225/60R16	19 M Ω
SUV 1	235/55R18	200 M Ω
SUV 2	235/65R17	370 M Ω
SUV 3	235/55R17	19 M Ω
SUV 4	245/75R16	1.2 M Ω
Sports car 1	255/40ZR18	1.3 M Ω
Sports car 2	255/40R17	0.03 M Ω

surface is not suitable to discharge the static electricity through the vehicle tires.

5.3. Testing the grounding resistance on concrete

At conventional gasoline stations, the fueling pad surface is usually made of concrete to protect from oil spills and other chemical contaminants. To see how this conventional surface performed, we measured the grounding resistance of the FC test vehicle on a concrete pad. This concrete was constructed using common construction methods, had no paint or coating on the surface, and the reinforcing bars were grounded to the earth. The result was a resistance value of 2.3 M Ω (Fig. 5). Therefore, a concrete fueling pad surface is suitable to safely discharge the static electricity through the vehicle



Fig. 5 Measuring resistance through tires parked on concrete test pad

Table 3 Resistance of FC test vehicle on various fueling pad surfaces

Steel	Concrete	Conductive Paint
1.7 M Ω	2.3 M Ω	2.5 M Ω

tires. Of course, there is a possibility that the resistance value would increase if paint or other coatings were applied to the surface.

5.4. Testing the grounding resistance on conductive paint

When installing a hydrogen station, asphalt may already be in place, or can be applied as the fueling pad surface much less expensively than with concrete. Replacing the asphalt fueling pad surface with concrete to remove static electricity may not be economical. Floor paint with high conductivity to remove static electricity is commonly marketed and available for semiconductor industries and other uses where it is important to minimize static electricity. We applied a conductive paint⁽⁶⁾, which was grounded to the Earth, onto the asphalt. We then measured the grounding resistance of the FC test vehicle. The result was a resistance of 2.5 M Ω (Fig. 6). Incidentally, because we could not find conductive paint specified for outdoor use, an indoor specification conductive paint was used.

Table 3 shows a summary of the resistance measurement results of the FC test vehicle on various surfaces.



Fig. 6 Measuring resistance through tires parked on conductive painted test strip

Table 4 Resistance of FC test vehicle on concrete under adverse conditions

Sand			Snow	Rain
3 mm	10 mm	20 mm	20 mm	N/A
8.4 M Ω	8.4 M Ω	8.0 M Ω	0.39 M Ω	0.08 M Ω

5.5. Testing the influence of environmental factors

Because a vehicle should operate in a variety of weather and environmental conditions, we cannot assume that fueling will occur under clean, dry conditions. Therefore, we measured the grounding resistance of the concrete fueling pad surface under a variety of adverse real world conditions, including dry sand, snow, and rain (Table 4).

In the case of dry sand, the resistance was somewhat dependent on the depth, but 8.4 M Ω was the maximum value measured (Fig. 7). We measured the resistance in snow in the northeastern part of the US, and the result was 0.39 M Ω (Fig. 8). And finally, in the case of rain, the measured result was the lowest, with a resistance of



Fig. 7 Measuring resistance through tires with sand between tire and concrete pad



Fig. 8 Measuring resistance through tires with snow between tire and concrete pad



Fig. 9 Measuring resistance through tires on rain soaked concrete pad

only $0.08 \text{ M}\Omega$ (Fig. 9). In all cases, the grounding resistance values were less than the required resistance ($100 \text{ M}\Omega$). Therefore, for all weather and environmental conditions we tested for, we found the ability of the concrete fueling pad surface to safely discharge the static electricity was not affected.

As the results of the above five test regimes show, the use of conductive paint applied onto an asphalt surface, or the use of commonly constructed concrete for the fueling pad surface at a hydrogen fueling station can safely remove the static electricity from the FC test vehicle without the use of a GND cable.

6. Application of Results

To put our testing results into practice, we constructed two different static electricity discharging fueling pad surfaces at hydrogen stations in Torrance, CA. We applied the conductive paint to the asphalt in front of one of the fueling stations. Two grounding copper bars were embedded in the asphalt and bonded to the conductive paint. After installation, the grounding resistance was measured to be $2.5 \text{ M}\Omega$ (Fig. 10).

At the second station, we installed a concrete fueling pad surface. After installation, the grounding resistance was measured to be $2.3 \text{ M}\Omega$ (Fig. 11).

Because of the low measured resistance values at both hydrogen stations, it is no longer necessary to use the GND cable when fueling the FC test vehicle, or any other fuel cell vehicle meeting the SAE J2578 recommended practice for tire resistance, at these stations.

7. Durability and Other Factors

One downside to using the conductive paint fueling pad surface is that it can be quite slippery when it is wet, or when a user walks on it with wet shoes, so care should be taken when it is raining. Also, after six months of use, we found the paint to be peeling-off in an area where there is a low spot and rain water collects. This demonstrates that the durability of this conductive paint against rain water is insufficient. As mentioned earlier, the paint we used is specified for indoor use. Therefore,



Fig. 10 Conductive paint fueling pad surface in front of hydrogen station



Fig. 11 Concrete fueling pad surface in front of hydrogen station



Fig. 12 Deterioration of conductive paint due to rain water pooling

for this application, a non-slip outdoor spec paint is desired. Of course, in the case of concrete, it is neither slippery when wet, nor does it suffer from any durability issues.

Despite the durability issues with the conductive paint, both the conductive paint surface and concrete surface sustain good grounding resistance values over time, as measurements taken after six months were nearly the same as the initial measurements.

8. Expansion of Research to the Real World

Applying our findings to the two hydrogen stations used in this study has made the fueling process user friendly and safer. However, to benefit the end user and future customers, this practice should be accepted and applied to all hydrogen stations. A tendency in the industry is to be conservative when it comes to safety practices, and our findings show that it is actually safer to ground the vehicle through its tire contacts rather than through a GND cable. Our research and that of others has been studied and considered within code development organizations (CDOs) and standard development organizations (SDOs), as well as industry groups such as the California Fuel Cell Partnership. It is now generally accepted that safe hydrogen fueling can be accomplished by grounding the vehicle through its tires. At stations with concrete fueling pad surfaces, the requirement for connection of the GND cable has, in many cases, been eliminated. Also, in the 2006/07 I-code revisions to the International Code Council (ICC) International Fire Code (IFC), it states, “2209.5.1.1 Vehicle fueling pad. The vehicle fueling pad shall be constructed of a non-coated concrete pavement or shall have a resistivity not exceeding criteria of 1 megohm as measured using the methodology specified in EN 1081.”⁽⁷⁾ With this

addition to the IFC, it will now be a permitting requirement for hydrogen stations to have a conductive fueling pad surface.

9. Conclusion

The aim of our study was to find a way to safely dissipate the static electric charge from the fuel cell vehicle chassis without the use of a GND cable before fueling with hydrogen. To this end, we conducted research on discharging the static electricity through the tires. The results of this research showed that if the grounding resistance of the fuel cell vehicle on the fueling pad surface is less than 100 MΩ, it is possible to safely discharge the static electricity through the tires. The FC test vehicle used in this study has a resistance of 1.7 MΩ on steel plates, 2.3 MΩ on the concrete fueling pad surface, and 2.5 MΩ on the conductive paint fueling pad surface applied onto asphalt. With these highly conductive fueling pad surfaces, the grounding resistance mainly comes from the tires. The resistance of the concrete and the conductive paint fueling pad surfaces are sufficiently small to safely fuel the FC test vehicle, even when surface contaminants of sand, snow, and rain are present. Rain and snow actually reduce the grounding resistance, while dry sand slightly increases the grounding resistance, but not to a level that affects the discharging.

Our research has thus demonstrated that the GND cable connection is unnecessary if the hydrogen station has a concrete or grounded conductive paint fueling pad surface, and the resistance of the tires on the fuel cell vehicle are less than 25 MΩ, in accordance with SAE J2578. As a result, safe and user-friendly hydrogen fueling is now possible. Furthermore, the industry is now recognizing this safe practice and other hydrogen stations are incorporating the use of low resistance fueling pads. With the latest revision to the ICC IFC now specifying both a resistance value and test method for hydrogen fueling pads, the practice of grounding through the vehicle tires will become standard practice at all hydrogen stations in the future.

References

- (1) Handa, K., Mathison, S., Matsuo, S., : An Introduction of Honda's H2 Stations and Fueling Without Grounding Cable, Global Powertrain Congress(2005)
- (2) Ocean Engineering & Energy Systems: <http://www.ocees.com/mainpages/Hydrogen.html>(2007)
- (3) Pidoll, U. v. : REFUELING AUTOMOBILES WITH HYDROGEN, National Institute for Science and Technology(2000)
- (4) Pidoll, U. v. : Avoiding an ignition of Otto-type fuel/air mixtures when refueling automobiles at gas stations, German Scientific Society for oil, natural gas and coal,

- DGMK Research Report 508(1996)
- (5) SAE FCV Safety Working Group : Recommended Practice for General Fuel Cell Vehicle Safety, SAE J2578, Section 4.4.8.4(2002)
 - (6) ACL Inc. : Staticide Diamond Polyurethane Static Dissipative Floor Coating # 4700, http://www.aclstaticide.com/01/info_pages_ind/product_4700.htm(2007)
 - (7) International Code Council : 2007 Supplement to International Fire Code, <http://www.iccsafe.org/cs/codes/2007-08cycle/2007Supplement/IFC07S.pdf> (2007)

■ Author ■



Steve MATHISON



Kiyoshi HANDA



Shiro MATSUO

Development of Ultra-fine Grained Stainless Steel by Nitrogen Absorption Treatment for Gaskets

Tadao NISHIYAMA*

Takashi KATSURAI*

Kazuhiko ADACHI**

ABSTRACT

Desirable attributes for a material used in a cylinder head gasket are the strength required to from a combustion gas seal and sufficient fatigue strength such that the gasket may operate properly during engine operation. The high combustion pressure characteristic of diesel engines in particular creates a severe environment for the gaskets, necessitating the achievement of high levels of strength and fatigue in the material. In order to satisfy these requirements, a method of exploiting the difference in the solubility limit of the nitrogen in the martensite and austenite structures that form the composite structure of SUS301L stainless steel to enable the precipitation of Cr_2N by means of the application of an aging treatment to supersaturated nitrogen was examined. The achievement of high workability and refinement of the grains are effective in increasing fatigue strength. Workability was increased by employing a nitrogen absorption treatment in the intermediate annealing process to produce an austenite structure as the surface structure. In addition, the pinning effect of the precipitated Cr_2N during annealing refined the grains.

These innovations have enabled the development of a gasket displaying approximately 40% higher seal ability and an approximately 20% increase in fatigue limit in fatigue tests than those of a gasket formed from conventional materials.

1. Introduction

As the necessity of reducing the environmental impact of automobiles increases, the impetus towards the reduction of emissions of CO_2 , a leading factor in global warming, is increasing in pace. The achievement of increased fuel economy is an effective method of reducing CO_2 emissions, and sales of vehicles fitted with higher fuel efficiency diesel engines are increasing, in particular in Europe.

One major characteristic of diesel engines is their high combustion pressure. Because of this, the cylinder head gasket ("head gasket" below) which seals the combustion chambers is required to display reliable sealing performance in diesel engines.

As shown in Fig. 1, head gaskets are normally constructed from multiple thin sheets that are 0.2 mm in thickness and feature machined beads. The combustion chambers are sealed by the load reaction force of the beads. High strength is therefore a requirement of gasket materials. In addition, combustion pressure causes the cylinder head to lift when the engine is operating, and a

repeated stress is generated in the beads in response to this lift. High fatigue strength is therefore a further requirement of gasket materials.

The beads are formed in the thin steel plates that make up the gaskets by pressing. As shown in Fig. 2, a localized machining stress is generated in the surface layers of the steel plates during formation, resulting in a reduction of the fatigue strength of the gasket⁽¹⁾. This reduction in fatigue strength is caused by the occurrence of tiny cracks in the grain boundary due to machining stress. Refinement of the grain boundary and the achievement of a high level of workability are therefore effective methods of achieving high fatigue strength.

Based on the discussion above, the characteristics required of head gasket materials can be summarized as follows:

- (1) High strength and high fatigue strength when used in an engine
- (2) High workability when the component is machined

This means that antagonistic characteristics are required during engine operation and during machining.

This paper will discuss research on the further

* Automobile R&D Center

** Sumitomo Metal Industries, Ltd.

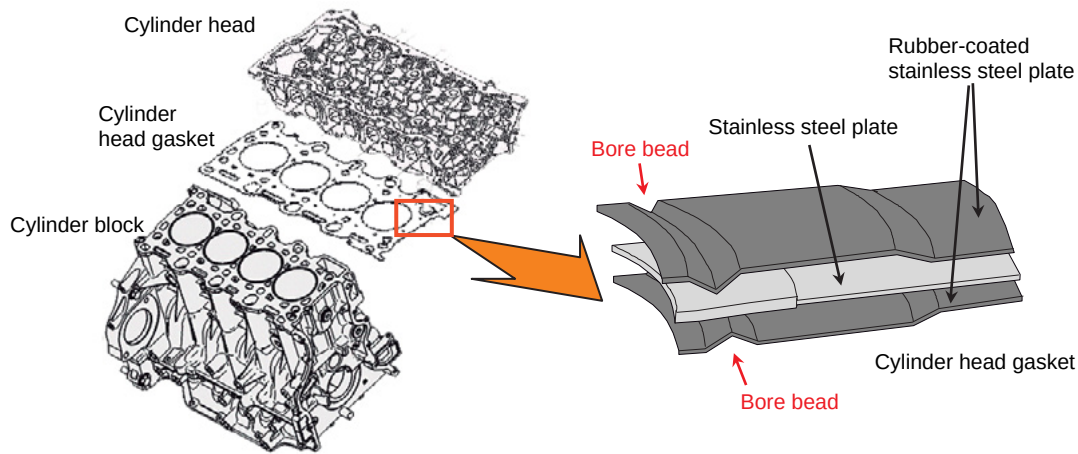


Fig. 1 Illustration of cylinder head gasket

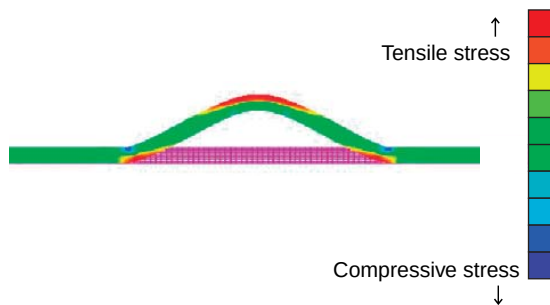


Fig. 2 Distribution of stress in section of bead-formed sheet

refinement of the grain size and the use of heat treatment following machining to increase the strength of the material as methods of reconciling these antagonistic characteristics, and will also discuss the composition and method of manufacture of the materials required to enable this.

2. Research on the Achievement of High Strength and Verification of Effect

2.1. Research on the Achievement of High Strength

Solution hardening, precipitation hardening, work hardening, and transformation hardening are the standard methods of increasing strength. SUS301, a metastable austenite stainless steel, is the main material used in the manufacture of head gaskets. This is a reliable material in which the necessary strength is provided by the transformation of austenite structures into hard, work-induced martensite structures during cold working. The project discussed here studied the possibility of achieving further strength increases by using other hardening methods in combination with this mechanism.

The research focused on the structural change occurring in SUS301L steel. The characteristics of the structures in the steel differ; one specific point of

difference is the difference in the solubility of elements in them. Interstitial solid elements generally display high solubility in austenite structures, which have large spaces in their crystal lattices, and low solubility in martensite structures, which have small spaces in their crystal lattices. This research studied the potential for exploiting this characteristic in order to achieve high strength in the material by aging at low temperatures as a method of promoting the precipitation of the interstitial solid elements that are supersaturated in the martensite structures following cold working.

Carbon (C) and nitrogen (N) are the normal interstitial solid elements present in this steel, but N was selected in this research due to the fact that the precipitation of C in the compound Cr_{23}C_6 would result in the formation of a chromium depletion layer, reducing the required corrosion resistance of the stainless steel.

2.2. Effect of the Aging Precipitation of Cr_2N

The project studied the effect of precipitation in NAR-301L HS1⁽¹⁾, a stainless steel that is employed in the production of gaskets and contains approximately 0.1% nitrogen. Figure 3 shows the change in hardness of NAR-301L HS1 after aging following final cold rolling. At the low temperature of 200°C the material displays a hardness increase of approximately HV40, reaching a hardness of HV520 following the completion of aging. Figure 4 shows the precipitates in the material following dissolution and removal of the parent phase, as observed using a transmission electron microscope (TEM). As Fig. 5 shows, electron beam and EDX analysis show that high quantities of fine Cr_2N are dispersed in the material following aging.

This indicates that the supersaturated N in the work-induced martensite has formed a compound (Cr_2N) with the Cr present in high quantities (approximately 17%) in the material and has precipitated during low-temperature aging hardening. Figure 6 shows the relationship between

the amount of martensite in the material and its hardness following aging. The hardness of the material following aging is proportional to the quantity of martensite. This is thought to be because the area of precipitation of Cr_2N increases with increased martensite content, a result that matched expectations.

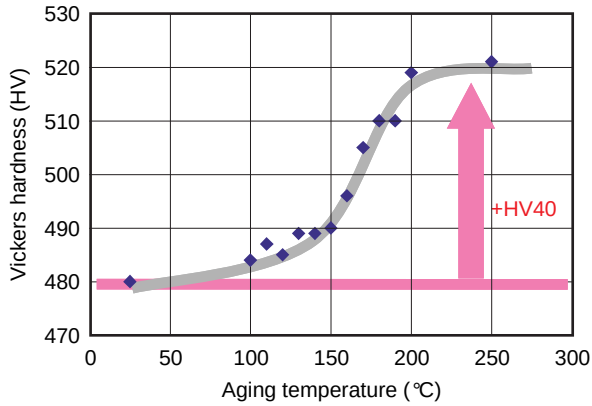


Fig. 3 Relationship between Vickers hardness and aging temperature in NAR-301L HS1

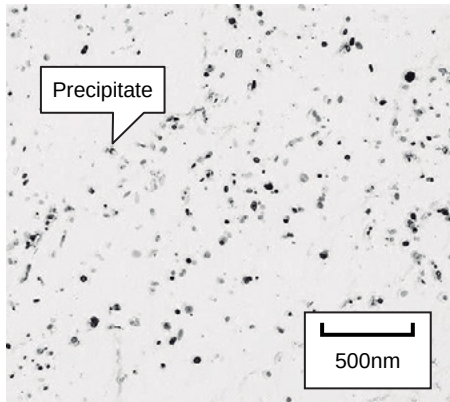


Fig. 4 TEM image of NAR-301L HS1 after aging treatment

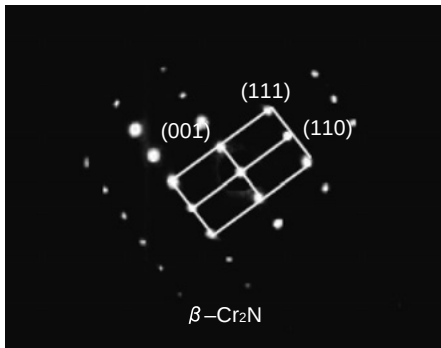


Fig. 5 Identification of precipitates by electron beam diffraction pattern

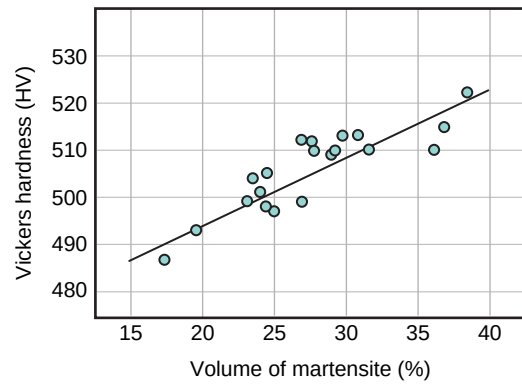


Fig. 6 Relationship between volume of martensite and Vickers hardness after aging treatment

3. Research on the Achievement of Increased Fatigue Strength and Verification of Effect

3.1. Research on the Achievement of Increased Fatigue Strength

As previously indicated, the refinement of the crystal grains in the surface layer of the steel plates used in the manufacture of head gaskets is an effective means of increasing fatigue strength. This method was therefore studied in this research. A method that involves heating the work-induced martensite structures to promote their reverse transformation into austenite and recrystallization⁽²⁾⁻⁽⁴⁾ is available as a method of refining the crystals in SUS301L stainless steel. This method is already applied to the NAR-301L HS1 steel mentioned above⁽¹⁾, and, by optimizing both the rolling conditions prior to final annealing and final annealing conditions, results in the achievement of a grain diameter of approximately $2\text{ }\mu\text{m}$, around one-tenth the average grain diameter of a normal stainless steel. In order to achieve further refinement of the grains, in addition to this method, the research discussed here studied the use of the pinning effect of the precipitated substances to control grain growth during recrystallization.

3.2. Research on Methods of Precipitation

Bright annealing in a non-oxygenated environment is widely used as a technique that enables stainless steels to retain their surface gloss. A mixture of hydrogen and nitrogen is widely used as the ambient gas in this process. Because of this, a large amount of research has been conducted on nitrogen absorption, which is expected to increase corrosion resistance, among other effects^{(5),(6)}.

Figure 7 shows the process of manufacture of NAR-301L HS1. Low temperatures are employed in the final annealing process, compared to the other annealing processes, in order to control grain growth and achieve fine grains. Because the solubility limit of nitrogen in

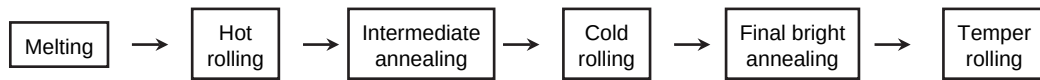


Fig. 7 Production process of NAR-301L HS1

steels is generally proportional to temperature⁽⁷⁾, if the temperature of the intermediate annealing process is set higher than that of the final annealing process, the difference in the solubility limit of nitrogen at each temperature would enable nitrogen precipitation to be exploited. The method selected in this research was therefore to promote precipitation of supersaturated nitrogen during a low-temperature final annealing process following the absorption of high quantities of nitrogen in a high-temperature intermediate annealing process.

3.3. Refinement of Grains Using Nitrogen Absorption and Precipitation and Effect of Aging Precipitation

Based on the research in Section 3.2., a mixture of hydrogen and nitrogen was employed as the environment for the intermediate annealing process. Figure 8 shows the structure of the material following intermediate annealing. Analysis of a cross-section using an optical microscope shows high austenite stability from the surface to a depth of approximately 70 μm . This is due to the absorption of nitrogen, an element that stabilizes austenite, by the surface layer. Abrasive stress has promoted the transformation of the austenite into work-induced martensite in the deeper layers which did not absorb nitrogen. As Fig. 9 shows, analysis using an electron probe micro-analyzer (EPMA) indicates that the austenite structures have absorbed approximately 0.3% nitrogen, three times the amount in the parent material. This figure is close to the solubility limit of nitrogen at the temperature employed in intermediate annealing, and a pinning effect due to the precipitation of Cr_2N in the final annealing process can therefore be expected.

Figure 10 shows the results of study of the area close to the surface layer and the center of the steel plates using transmission electron microscopy. While the average grain diameter at the center of the plates was approximately

2.0 μm , an ultra-fine grain structure was achieved close to the surface layer, with an average grain diameter of 1.2 μm . In addition, a higher amount of precipitation of compounds occurred close to the surface layer. Electron beam and EDX analysis showed the precipitated substances to be Cr_2N compounds as in the case of the aging discussed above.

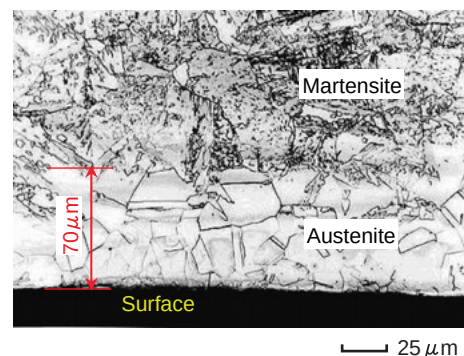


Fig. 8 Optical microscope image of surface structure after intermediate annealing process

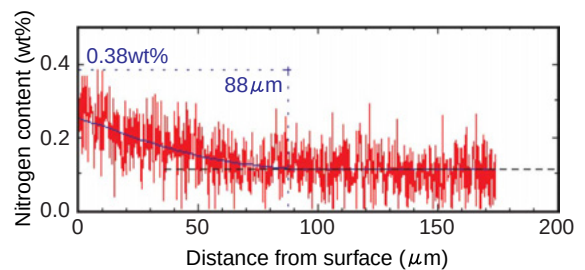


Fig. 9 Result of nitrogen content by EPMA

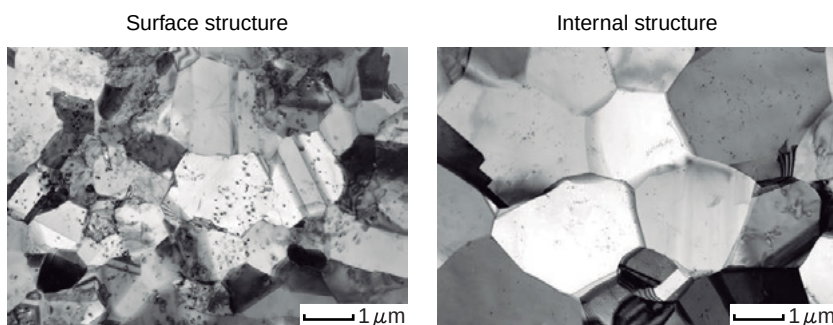


Fig. 10 TEM images of surface and internal structure after final annealing process

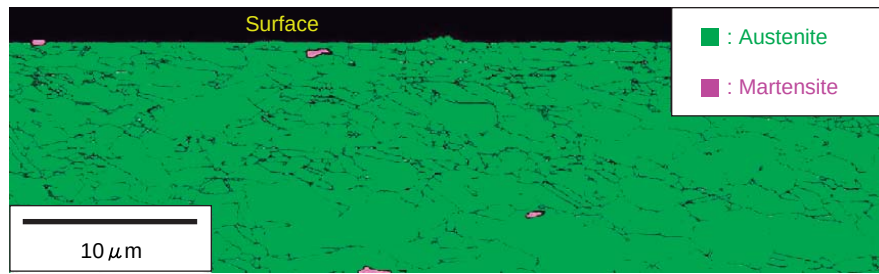


Fig. 11 Phase identification in surface structure after final annealing by EBSD analysis

Figure 11 shows the results of a study of the structure of the material using an electron back scattering pattern (EBSP). The grains in the surface layer are finer than those in the center of the plates, and the grains are almost all in the austenite phase.

This matches the requirement for a gasket material, and indicates that the austenite structure has been stabilized by the absorption of nitrogen, a powerful austenite stabilizer, making it possible that the austenite structures will help ensure that the material maintains superior workability.

4. Verification of Characteristics of Developed Material

4.1. High Strength and High Fatigue Strength

Exploiting the difference in the solubility limit of nitrogen in the austenite and martensite structures that form the composite structure of SUS301L steel, the supersaturated nitrogen in the martensite structures was precipitated as Cr_2N using low-temperature aging as a method of achieving high strength. This resulted in an increase of around HV40 in hardness, representing an increase of approximately 20% in strength.

The absorption of nitrogen into the layers of the plates contiguous to the surface layer during intermediate annealing was employed to achieve high fatigue strength. Reducing the temperature of the final annealing process against the temperature of intermediate annealing enabled the difference in the nitrogen solubility limit to be exploited. Supersaturated nitrogen was precipitated as Cr_2N during the final annealing process, and the pinning effect of this Cr_2N resulted in the refinement of the grains to a diameter of approximately $1.2\ \mu\text{m}$. In addition, nitrogen is a powerful austenite stabilizer, and the fact that the structures in the surface layer are austenite structures helps ensure a high level of workability.

In order to effectively exploit these characteristics, the material was aged following machining of the beads, producing a gasket material that balanced the antagonistic characteristics of high strength and high workability.

4.2. Effect of Employment of Material in Component

Figures 12 and 13 show examples of the results of testing of the sealing performance and fatigue strength of a gasket manufactured using the developed material. Aging was conducted following formation of the beads.

The gasket manufactured using the developed material displayed an increase of approximately 40% in sealing performance against a conventional gasket, and its fracture limit was approximately 20% higher in fatigue tests. In durability tests conducted using an actual diesel engine, the new gasket displayed a high level of sealing performance under conditions of high combustion pressure, in addition to high fatigue strength.

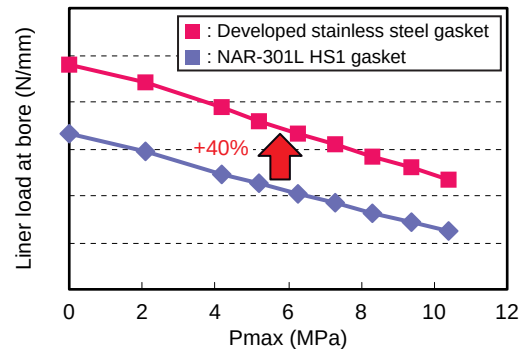


Fig. 12 Gasket sealability

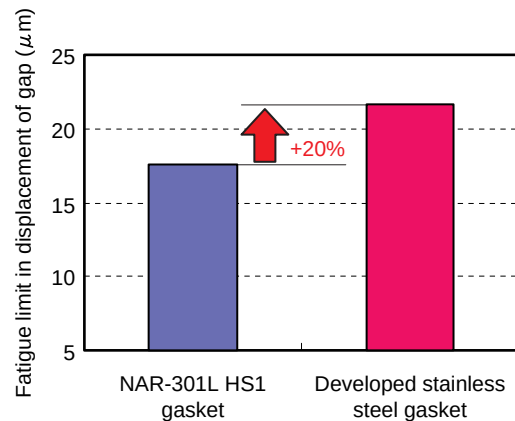


Fig. 13 Result of gasket fatigue test

5. Conclusion

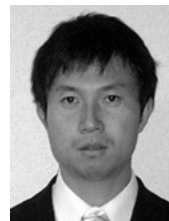
Research was conducted on the use of nitrogen absorption treatment during intermediate annealing and aging precipitation of Cr_2N in SUS301L stainless steel as methods of achieving increased gasket performance. This research produced the following results:

- (1) Nitrogen absorption treatment at high temperatures enabled the achievement of a nitrogen concentration of 0.3% and above from the surface layer of the material to a depth of 70 μm .
- (2) Precipitation of the absorbed nitrogen as Cr_2N during the final annealing process produced a pinning effect. This controlled the growth of crystal grains during recrystallization, resulting in the achievement of ultra-fine grains of approximately 1.2 μm in diameter.
- (3) Aging enabled the dispersion of the supersaturated nitrogen in the martensite as Cr_2N . This precipitation hardening enabled the achievement of high strength.
- (4) A head gasket manufactured using the developed material displayed an increase of approximately 40% in sealing performance and an increase of approximately 20% in fatigue strength against a gasket manufactured using a conventional material.

References

- (1) Katsurai, T.: Development of High Fatigue Strength Ultra-Fine Grained Stainless Steel for Cylinder Head Gasket, HONDA R&D Technical Review, Vol. 12, No. 1, p. 151-159
- (2) Takagi, S.: Reversion of Deformation Induced Martensite to Austenite and Mechanism of Ultra Grain Refining, Tetsu-to-Hagane, Vol. 80, No. 10, N529-535 (1994)
- (3) Takagi, S.: Ultra Grain Refining of Steels, Journal of the Japan Society for Heat Treatment, Vol. 34, No. 5, p. 260-264 (1994)
- (4) Tsuji, N.: Ultrafine Grained Steels, Tetsu-to-Hagane Vol. 88, No. 7, p. 1-11 (2002)
- (5) Hatano, M., Tsuge, S.: Effects of Surface Nitriding on Deformation Microstructure in Cold-Rolled 304 Stainless Steel Sheets with Bright-Annealing, Journal of the Japan Society for Heat Treatment, Vol. 36, No. 6, p. 318-323 (1999)
- (6) Tsuchiyama, T., Takagi, S.: Characteristics of Solution Nitriding and Properties of the High Nitrogen Stainless Steel, ELECTRIC FURNACE STEEL, Vol. 77, No. 2, p. 163-169 (2006)
- (7) Kikuchi, M., Kajihara, M., Frisk, K.: Solubility of nitrogen in austenitic stainless steel, Proc. Int'l. Conf. High Nitrogen Steels, Ed. J. Foct & A. Hendry, p. 63-74 (1989)

■ Author ■



Tadao NISHIYAMA



Takashi KATSURAI



Kazuhiko ADACHI

Development of High-strength Structural Steel for Welding

Masaki SHINKAWA*

Toshiaki OTSUKA*

Yoshikazu UMEMO*

Hiroaki YOSHIDA**

Masanao FUJIWARA**

ABSTRACT

A high-strength structural steel that enables pre-heating and post-heating to be omitted from the welding procedure without the occurrence of weld cracks has been developed. A process has been developed that enables the achievement of an equivalent level of strength and toughness to alloy steels for machine structural use while omitting the quenching process, through the partial application of modified ausforming, in which, immediately following processing during the hot forging process, the material is rapidly quenched at the unrecrystallized austenite temperature just above the A3 transformation temperature.

1. Introduction

Efforts are progressing to reduce CO₂ emissions as a means of controlling global warming. Automobiles account for 18% of CO₂ emissions in Japan, and technological development to reduce CO₂ emissions, including the development of various technologies to increase fuel efficiency and the rationalization of production processes, is active in the country. In the area of body components, efforts are being made to achieve weight savings by increasing the strength and reducing the number of parts, and to reduce sliding resistance and rolling resistance.

The project discussed in this paper focused on a technology to achieve weight savings. It attempted to reduce the number of parts used by enabling direct welding of forged steel parts. These parts have previously been bolted together, because welding has represented a challenge. In order to achieve its goal, the project developed a weldable forged steel without sacrificing strength.

The first issue to be considered during welding is the occurrence of weld cracks. The occurrence of weld cracks is influenced by the chemical composition of the steel, and reduction of the carbon content in particular assists in preventing them. However, the strength of the steel is

influenced by its chemical composition and its microstructure, and reduction of carbon content tends to reduce strength. In high-strength steel plates, control of weld cracks and the achievement of a high level of strength have been achieved by reducing the carbon content and applying a variety of heat treatments to strengthen the microstructure of the material⁽¹⁾. However, forged parts are thicker than steel sheets. Given that it is challenging to control their internal temperature, and from a cost perspective, there are restrictions on the ability to achieve high strength by means of the microstructure of the material. Because of this, the dependence of both weldability and strength on chemical composition is high in forged parts, and the range of choices available to reconcile these parameters is more limited than it is in the case of steel plates. In addition, thick parts tend to be harder on the surface than in the interior. This makes it necessary to increase strength in order to offset this reduction in internal strength, making it more challenging to guarantee weldability.

In order to reconcile surface strength and weldability, the project discussed here addressed these issues through the development of a forged steel displaying a level of hardenability not previously achieved, and which also demonstrated internal strength. At the same time, the project also focused attention on the production process;

* Automobile R&D Center

** Daido Steel Co., Ltd.

the use of the heat of the hot forging process for quenching has enabled the quenching process to be abbreviated, reducing CO₂ emissions during production.

2. Development Concept

2.1. Study of Chemical Composition

One cause of weld cracks is the fact that the hardness of welded areas becomes excessively high in comparison to the surrounding area. The project therefore attempted to determine a chemical composition for the new material that would help prevent this excessive hardness despite welding, and which would produce only a minimal decline in internal hardness.

2.1.1. Controlling weld cracks

Equation (1), specified by the Japan Welding Engineering Society in WES 3001, shows the relationship between the occurrence of weld cracks and chemical composition in terms of the weld crack parameter (Pcm). The symbols in Eq. (1) show the amount of each element added in terms of mass%.

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn}{20} + \frac{Cu}{20} + \frac{Ni}{60} + \frac{Cr}{20} + \frac{Mo}{15} + \frac{V}{10} + 5B \quad (1)$$

Past results indicate that the Pcm should be no greater than 0.29 in order to help prevent weld cracks without preheating or postheating.

2.1.2. Maintaining hardness

It is reported that the potential danger of weld cracks occurring increases if the maximum hardness of the welded area exceeds 400 HV (corresponding to 41 HRC)⁽²⁾. Because the welded areas would be quenched microstructures, the quenching hardness was set at 400 HV or lower. The size of almost all forged parts used in automobiles, in terms of conversion to the diameter of a round rod, is 30 mm or less. Given this, the critical diameter, as specified by JIS G 0201, was set at 30 mm or more.

The following considerations were applied to achieving the highest temper hardness possible. Because machining is the final stage in the process of manufacturing a part from forged steel, a hardness of 38 HRC or less is therefore generally considered desirable from the perspective of tool life. In addition, in order to help prevent the brittleness associated with low-temperature tempering, the tempering temperature should be set at 400°C or higher. This led to the goal of achieving the highest level of hardness possible under 38 HRC at a tempering temperature of 400°C.

Adjustment of the chemical composition on the basis of these conditions produced the formula shown in Table 1. In comparison to conventional steels used in forging, the composition is noteworthy for its low carbon content and the high level of manganese that it contains.

Table 1 Chemical composition of developed steel (mass%)

	C	Si	Mn	P	S	B	Ti
Upper bound	0.15	0.3	2.2	0.03	0.03	0.003	0.07
Lower bound	0.10	-	1.4	-	-	0.001	0.03

2.2. Study of Manufacturing Process Enabling Abbreviation of Quenching Procedure

Direct quenching from forging temperature is a manufacturing method in which the steel is quenched directly after hot forging. This is an effective technique from the perspective of efficient use of heat, but involves quenching from the high temperature (around 1200°C) used in the hot forging procedure, which causes the crystal grains in the material to increase in size, resulting in reduced toughness, compared to normal quench tempering. Modified ausforming⁽³⁾, in which quenching is conducted after forging in the unrecrystallized austenite temperature above the A3 transformation temperature, is known as a method enabling the achievement of high toughness in hot forging, but the low forging temperature employed in the method increases the forging load, resulting in reduced die life. However, it was conjectured that the forging load could be reduced and a high level of toughness achieved in the component by employing modified ausforming only in the sections of the parts where stress concentrated.

3. Test Method

Table 2 shows the heat patterns tested in this project. In Pattern A, the steel was subjected to modified ausforming (water quench [W.Q.] from process Fo2) and tempering following hot forging (process Fo1). Patterns B and C were employed as comparisons. In Pattern B, the steel was quench-tempered following hot forging, while in Pattern C the steel was tempered following forge quenching. Using these heat patterns, the mechanical properties of test pieces formed by forward extrusion, with an area reduction ratio of 30%, and the internal hardness and microstructure of test pieces forged in a die corresponding to a mass production die, were studied. In the case of the forged test pieces for Pattern A, Fo1 and Fo2 were conducted at the same time as weld flash removal, using a hammer forger for the former and a trimming press for the latter. Conducting processes Fo1 and Fo2 on different apparatus helped to ensure that the cooling time between the processes did not affect the tact time for the parts.

Hardenability was studied using the JIS G 0561 Jominy end quench test. In addition, their softening curves

Table 2 Heat pattern

Pattern A	Pattern B	Pattern C

were measured.

Tensile tests using JIS Z 2201 14B tensile test pieces and Charpy impact tests using JIS Z 2202 U-notch Charpy test pieces were conducted in order to study mechanical properties.

To study weldability, strength and fracture position were evaluated using test pieces arc welded to form a lap joint between parallel sections, as shown in Fig. 1. In addition, Vickers hardness tests were conducted to determine the hardness distribution close to the welded sections in the matrix, which had an average hardness of 260 HV. Thirty-five HRC test pieces were formed from steel containing upper limit amounts of the chemical components, which had been quenched at 900°C and tempered at 425°C following sheet rolling to a thickness of 3 mm, with 440 MPa class steel sheets used as the welding rods.

To determine machinability, test pieces of the type shown in Fig. 2 were drilled until the drill broke, and tool wear for the prescribed number of holes was evaluated.

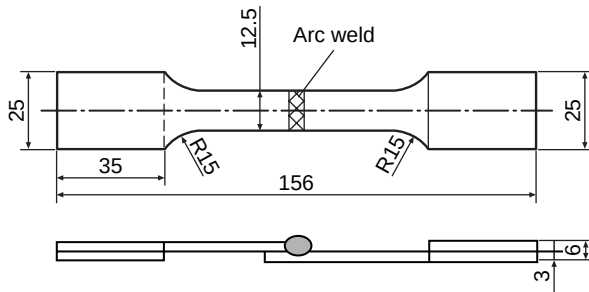


Fig. 1 Weldability test piece

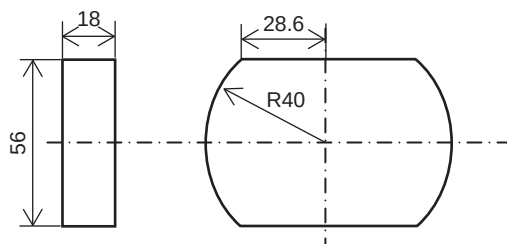


Fig. 2 Machinability test piece

4. Test Results

4.1. Test Results for Test Pieces

4.1.1. Hardenability

The Jominy curve of the developed material is shown in Fig. 3. For comparison, the Jominy curves of a representative carbon steel (S48C) and alloy steel (SCM435H) for machine structural use are also shown. At the lower limit set for chemical components, the steel achieved a maximum hardness of 38 HRC following quenching, and the distance from the quenched end to the point at which the hardness increase of the surface against the interior was halved was 18 mm. Converted to critical diameter⁽⁴⁾, this represents a diameter of more than 70 mm, indicating the achievement of a sufficient level of hardenability.

4.1.2. Temper softening curve

The temper curve of the developed material is shown in Fig. 4. The hardness of the material following tempering at 400°C was 37 HRC at the upper limit for chemical components, and 35 HRC at the lower limit. The material can therefore be used at 37 HRC and below.

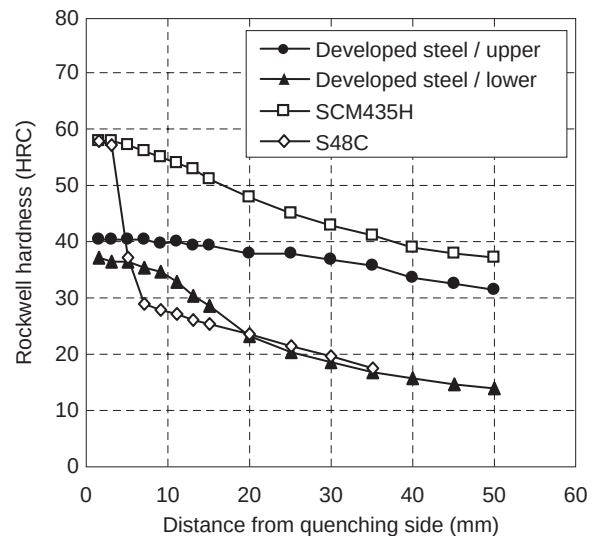
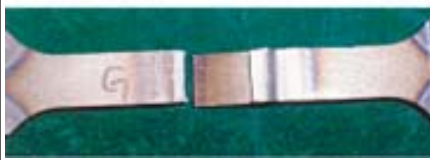


Fig. 3 Jominy curve

Table 3 Mechanical properties of developed steel

	Heat treatment	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Charpy impact value (J/cm ²)
Upper bound	Pattern A	898	941	23.1	220
	Pattern B	876	949	22.0	201
	Pattern C	873	943	21.9	160
Lower bound	Pattern A	880	911	22.8	260
	Pattern B	850	905	22.1	245
	Pattern C	873	932	22.0	230

Table 4 Fracture behavior of tensile test piece containing welding bead

	Appearance after tensile test	Fracture position	Tensile strength (MPa)
Upper bound		HAZ	673
Lower bound		HAZ	520

4.1.3. Mechanical properties

The mechanical properties of the developed material are shown in Table 3. The highest Charpy impact value was obtained for Pattern A. Even in the case of Pattern C, which resulted in a decline in the Charpy impact value, a value of 160 J/cm² or higher was obtained. This is higher than the value for S48C and equivalent to that for SCM435.

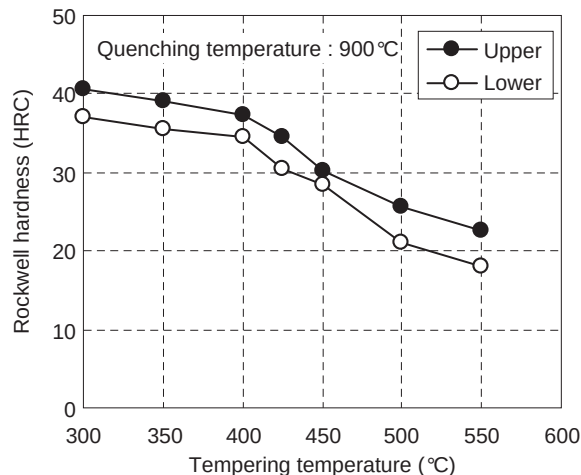


Fig. 4 Temper softening curve

4.1.4. Weldability

Table 4 shows the results of tensile tests on test pieces containing welding beads. The tests showed that fractures occurred in the heat-affected zone (HAZ), and that there was no incidence of welding cracks. X-ray analysis and penetrant inspection also showed no incidence of welding cracks.

The microstructure of the material and the hardness distribution around the welding beads are shown in Fig. 5. While the matrix is tempered martensite, the white corroded section at the boundary of the HAZ exhibits a mixed bainite-ferrite microstructure, with a martensite occurring further into the interior. The hardness of the area in the bainite-ferrite microstructure that shows the maximum decline in hardness is 250 HV, almost identical to the hardness of the matrix.

4.1.5. Machinability

Figure 6 shows changes in levels of tool wear at different levels of hardness, as determined by the drill life test. The graph also contains data for an alloy steel for machine structural use. The results show that the developed steel achieves an equivalent level of machinability to the alloy steel. While the developed material contains a high quantity of manganese, which would tend to reduce machinability because of its effect in increasing working hardness, it is thought that this

effect is offset by the reduction in the content of carbon, which has a greater effect on hardness.

4.2. Result of Tests on Parts

4.2.1. Mechanical properties and internal microstructure

The developed material was evaluated as a rear

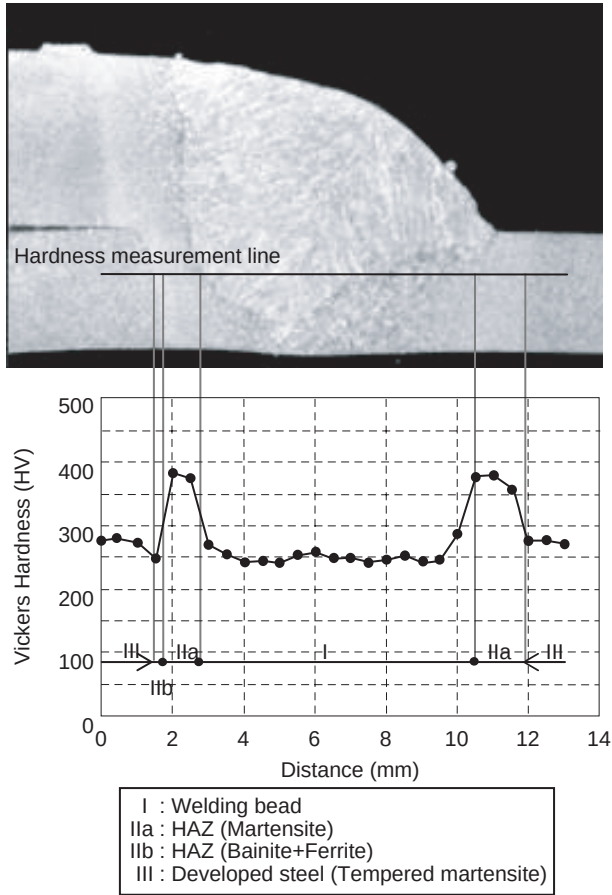


Fig. 5 Microstructure and hardness distribution around welding bead

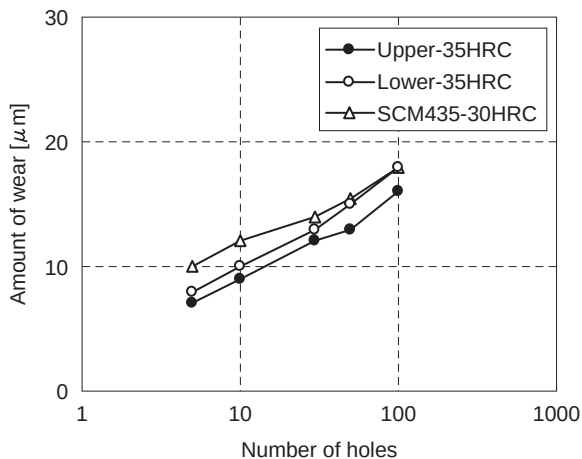


Fig. 6 Relationship between amount of wear of twist drill and hardness

spindle in order to provide an example of its application in a part. Figures 7 and 8, respectively, show the rear spindle and the layout of parts around the rear spindle. This part supports the driven wheels on the axle beam, and therefore should display high levels of both strength and toughness. Figure 9 shows the hardness distribution in the spindles manufactured for the test. There was almost no difference in hardness for the different heating patterns, and the hardness distribution was almost uniform, with only a two-point difference in hardness between the surface and the



Fig. 7 Rear spindle

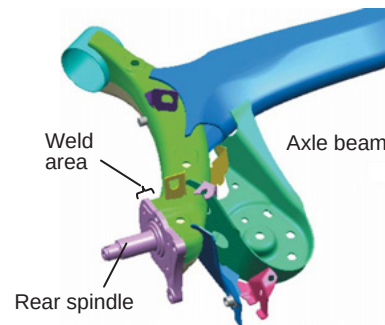


Fig. 8 Parts layout around rear spindle

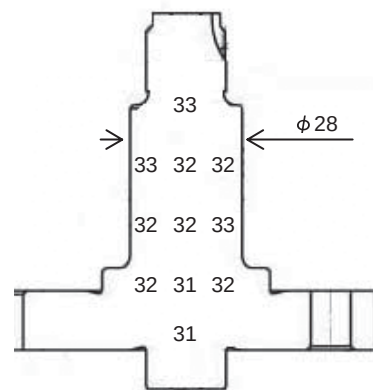


Fig. 9 Hardness distribution of rear spindle

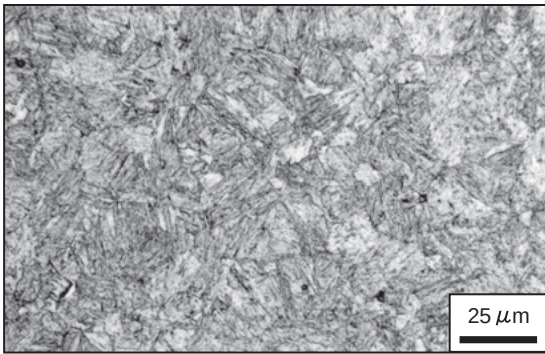


Fig. 10 Microstructure of rear spindle center

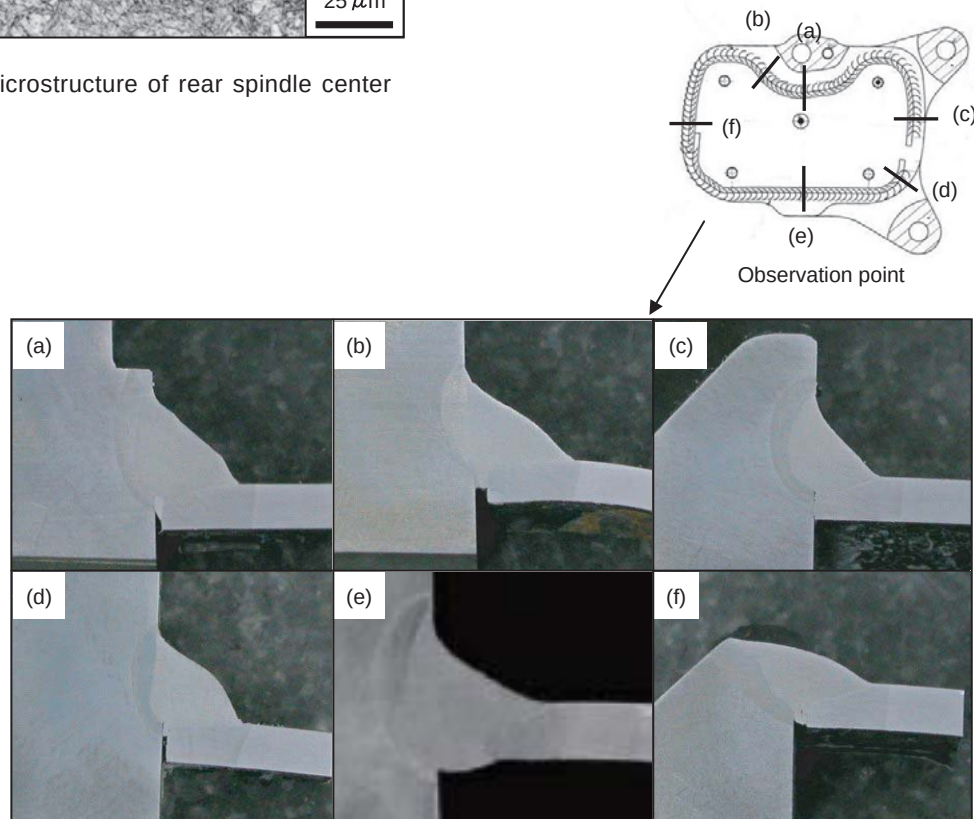


Fig. 11 Microstructures around welding beads of rear spindle

center of the part. Figure 10 shows the microstructure of the center of the spindle. A good tempered martensite microstructure has been achieved up to the center.

4.2.2. Weldability

Figure 11 shows the position and the microstructure of the welding beads between the rear spindle and the axle beam. The axle beam was manufactured from 440 MPa class hot-rolled steel plates, and 440 MPa welding wire was employed. A good bead shape was achieved, with no weld cracks or penetration issues. A variety of strength and durability tests were conducted on the structure, and no failure originated in the welding beads.

5. Conclusion

A weldable high-strength structural steel has been developed. In addition, the application of modified ausforming to sections of parts has enabled the quenching process to be abbreviated during manufacture. The characteristics of the developed steel are as follows:

- (1) The steel can be arc welded without preheating or postheating.
- (2) Quench tempering enables the achievement of a hardness of 37 HRC; the critical diameter for quenching is 70 mm and higher.
- (3) The Charpy impact value of the steel is 160 J/cm² or above.
- (4) The machinability of the steel is equivalent to that of an alloy steel for machine structural use.

References

- (1) Tanae, T., Kaneko, K.: Development of 590 and 780 MPa Grade High-ductility Steel Sheets, Honda R&D Technical Review, Vol. 16, No. 2, p. 183-190
- (2) Inagaki, M., Tanaka, J.: Kouchouryokukou Yousetsu no Jissai, Sampo publications, p. 55 (1984) (in Japanese)
- (3) Maki, M.: Saikin ni okeru Hagane no Kyoujinka, Bulletin of Japan Institute of Metals, Vol. 27, p. 623-630 (1988) (in Japanese)
- (4) Society of Automotive Engineers Handbook, Society of Automotive Engineers, p. 144 (1952)

■ Author ■



Masaki SHINKAWA



Toshiaki OTSUKA



Yoshikazu UMENO



Hiroaki YOSHIDA



Masanao FUJIWARA

Environmentally Friendly Wax for Corrosion Protection

Yasuhisa SHIMIZU*

Takahide MAEDA*

Toshiya NISHINO**

ABSTRACT

A new wax has been developed for the prevention of corrosion in flanges, which are frequently points of origin for corrosion, in order to attempt to ensure 12-year protection against corrosion perforation of the exterior panels employed on vehicle bodies. The wax has been applied to new models. The wax displays reliable penetration into flanges, and hardens by means of oxidative polymerization, enabling the wax film to control corrosion. The properties of the wax help prevent flowing after application. Following application, the vehicle body is heated to enable the wax to penetrate the flanges. When the vehicle body returns to normal temperature, the wax becomes viscous, which helps prevent the material from flowing. In addition, to respond to environmental considerations, no solvents have been used in the wax.

1. Introduction

The increasing use of chemical agents to help prevent ice forming on roads in winter⁽¹⁾ has increased the severity of the threat of corrosion faced by automobiles, necessitating the development of more advanced anti-corrosion technologies.

The Canada Code⁽²⁾ (1.5 years free from exterior corrosion and 5 years free from corrosion perforation) was formulated in 1976 to protect consumers. In 2000, Northern European consumer advocate groups formulated a more stringent set of conditions (5 years free from exterior corrosion and 10 years free from corrosion perforation)⁽³⁾, and there are an increasing number of cases in which the warranty period for corrosion perforation of the vehicle body is set at 12 years in the European market.

The side sills and rear wheel arches of the standard automotive body configuration (the monocoque body) enable the achievement of a balance between low weight and stiffness. Given their effectiveness, the configuration of these parts has become progressively more complex over time. It is challenging to achieve an adequate anti-corrosion coating on the side sills and rear wheel arches, but salt water can easily infiltrate and become trapped in them. These areas should be sufficiently degreased, phosphate treated (pre-treatment) and e-coated to protect them from corrosion.

However, the complexity of the structures prevents the achievement of a sufficient level of flow of the treatment agents, etc. Salt water is prone to be retained and hasten corrosion in the flanges in particular, and this can result in perforation after several years. Guaranteeing corrosion prevention in the flanges is therefore a technological issue.

Responses to corrosion in the areas indicated above should be prioritized. The development of further methods to be used in addition to conventional anti-corrosion coatings is necessary, including increasing the corrosion resistance of the materials used in automotive panels (by employing alloy galvanized steel sheets, etc.) and using sealers and waxes to help prevent water infiltration.

Anti-corrosion waxes shield the vehicle from water and other corrosion-inducing factors, and are able to control corrosion in the flanges, where corrosion resistance cannot be guaranteed by coatings. Automakers employ a variety of different methods to apply wax to the vehicle body following e-coating, including continuous flow nozzles, mist sprays, and immersion of the lower section of the body⁽⁴⁾. In the 1970s, when the automotive industry commenced its battle against corrosion, anti-corrosion wax first made its appearance in liquid form as a vaseline-like agent dissolved in a solvent. The waxes took their present form, a thin film able to effectively prevent corrosion, in the 1980s. The waxes are easy to use and increase corrosion resistance by penetrating into the interior of

* Automobile R&D Center

** HONDA R&D EUROPE (U.K.) LTD.

complex body shapes, but issues remain in terms of ensuring corrosion prevention in flanges. The research focused on in this paper therefore attempted to develop a wax with stable anti-corrosion properties that would effectively penetrate the flanges, which function as points of origin for corrosion. The research focused on a non-solvent-type wax in order to reduce emissions of volatile organic compounds (VOC). This paper will discuss the details of this research.

2. Development Targets

If the solvent is simply removed from a wax as an environmental measure, the viscosity of the wax will increase, resulting in a decline in its level of penetration into the flanges. In order to ensure corrosion resistance performance, it is therefore important to set the viscosity conditions of the wax to enable penetration.

If a low-viscosity wax is employed to ensure penetration, the wax will tend to flow and, accumulating on the floor of the assembly line, etc., will affect work conditions and safety in the workplace. This would necessitate a mechanism to help prevent wax from flowing after application, thus resulting in increased costs.

In addition, there is the possibility that wax flow will affect the commercial appeal of the vehicle by, for example, causing swelling of the plastic components and affecting the appearance of the coating, and it is also necessary to take measures to help prevent wax flow in hot climates. In order to respond to wax flow in the short-term, the research discussed here examined methods of setting and actively controlling the point at which the wax flows. From the perspective of the prevention of wax flow over the longer term, the project examined the potential for the exploitation of the oxidative polymerization reactions of vegetable oils and the formation of a film on the surface of the wax.

This project attempted to control wax flow by means of wax viscosity and temperature, with the following aims:

- (1) Penetration of wax into the flanges
- (2) Prevention of wax flow in later procedures
- (3) Film formation in the flanges

3. Basic Design of Wax and Responses to Environmental Issues

Conventional waxes use organic solvents (mineral spirits, etc.), as diluent solvents in order to achieve low viscosity. The waxes are applied in a spray form, which volatilizes the solvent, increasing viscosity and promoting film formation. Research has been conducted on the possibility of replacing the organic solvent added to reduce viscosity with a low-volatility, high-viscosity oil, but this increased the flow of the wax following application, with the result that the wax film could not be retained under the flow of water from the showers

Table 1 Components of former wax

Function	Main component
Composition of membrane	Calcium sulfonate
	Petrolatums
	Petroleum wax
Rust prevention additive	Metallic salt oxide wax
	Esters
	Sulfanilic acid salts
Solvent	Lubricating oil
	Mineral spirit

Table 2 Comparison of properties of former and developed wax

	Former wax	Developed wax
Appearance	Light brown liquid	Milky white
Density (g/cm ³)	0.85 ± 0.02	0.95 ± 0.03
Viscosity (mPa·s)	3000 ± 2500	900 ± 200
Flash point	35 °C and above	180 °C and above
NV (wt%)	35 – 70	95 and over

Table 3 Components of developed wax

Function	Main component
Composition of membrane	Sulfanilic acid salts
	Petrolatums
	Petroleum wax
Additive for thixotropy	Thixotropy additives
Hardening agent	Vegetable oil
Rust prevention additive	Metallic salt oxide wax
Filler	Calcium carbonate, etc.
Solvent	Low viscosity paraffin
	Vegetable oil

employed in the inspection procedure on the body assembly line. The fact that the waxes which were initially studied were removed in this way by physical force indicated issues in terms of film formation.

In order to develop a solvent-free and low-viscosity wax and to ensure penetration, the research discussed here therefore added low-viscosity lubricating oils (liquid paraffin, etc.) and a hardening agent to a diluent solvent.

Table 1 shows the main components of the former wax, while Table 2 compares the properties of the former and the developed wax. Table 3 and Fig. 1 show the main components of the developed wax.

The addition of the hardening agent promoted an oxidative polymerization reaction at the surface of the wax

(the area exposed to air), enabling the formation of a continuous film. In addition to controlling wax flow, this continuous film hardens, and can therefore also be expected to act as a barrier preventing the infiltration of oxygen, water, and electrolytic substances that promote rust.

Figure 2 shows the effect of the reduction of the solvent content of the developed wax. As a result of using the components discussed above, more than 95wt% of the content of the developed wax is non-volatile, contributing to a reduction in VOC.

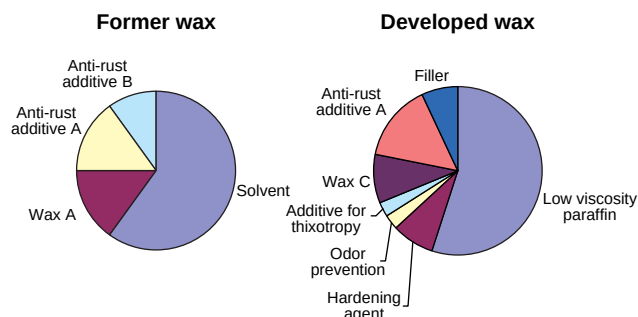


Fig. 1 Composition of former and developed wax

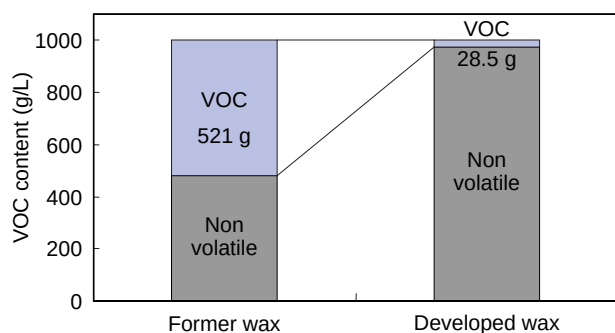


Fig. 2 Effect of reduction of VOC content

4. Characteristics and Basic Performance of Wax

4.1. Wax Viscosity Control: Considerations

There is a correlation between wax viscosity and temperature. Viscosity can also be controlled by the selection of the components of the wax. As a measure to help prevent short-term flow of the wax, the viscosity of the developed wax was controlled by the addition of a heat-activated thixotropic agent⁽⁵⁾ and a new wax component (modified wax).

The addition of the modified wax contributed to the ability to adjust the change in wax viscosity occurring due to changes in temperature. As a result of the addition of the heat-activated thixotropic agent, when the wax is given a thermal history, heat energy causes dislocation of the crystal structure, which forms a reticulated structure

following cooling, increasing the viscosity of the wax. The viscosity of the wax is therefore higher following cooling than it was prior to heating. Control of the viscosity of the wax following application has enabled wax flow to be prevented.

4.2. Wax Viscosity and Penetration

Figure 3 shows the relationship between viscosity and penetration in the former wax. The depth of penetration shown on the vertical axis was measured using the test apparatus shown in Fig. 4, which reproduced a flange. A spacer was used to set a gap of 0.1 mm in the flange. Wax was dripped into the flange, and the depth of penetration was measured visually. The results show that the greatest depth of penetration is achieved at lower viscosity, and that penetration depth decreases with increasing viscosity. The wax to be employed in the flanges needed to penetrate deeply, and to achieve this penetration without the use of solvents. This necessitated study of issues in relation to wax flow.

4.3. Achievement of Penetration and Prevention of Flow by means of Viscosity

This section will discuss the characteristics of the wax to which the heat-activated thixotropic agent had been added to control viscosity. Because the viscosity of the wax differs when measurements are conducted as its temperature increases and as its temperature declines,

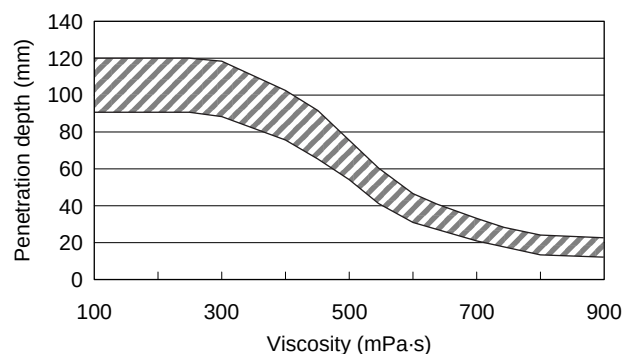


Fig. 3 Relationship between penetration depth and viscosity of former wax

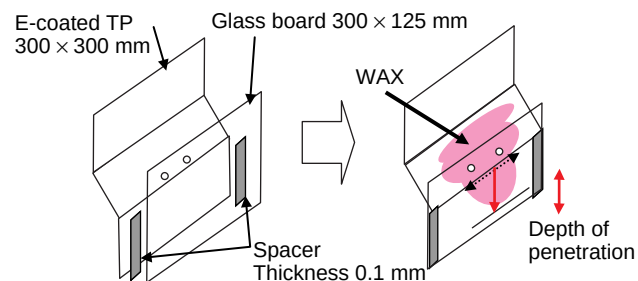


Fig. 4 Reproduced flange for wax penetration test

measurements were conducted under both sets of conditions. The results of viscosity measurements conducted during heating of the wax and during cooling following heating to 70°C are shown in Figs. 5 and 6. Figures 5 and 6 respectively show viscosity measurements prior to and following the addition of the thixotropic agent. The increase in viscosity during cooling following the heating of the wax to 70°C in accordance with the projected heating conditions for the developed wax shows that the target characteristic, an increase in viscosity due to thermal history, has been achieved.

Exploitation of this characteristic to control the viscosity of the developed wax enables wax flow in the short term to be controlled by means of the temperature of the vehicle body.

4.4. Wax Film Properties and Durability

Table 4 shows the basic properties of the former and the developed wax. Penetration was measured using the test apparatus shown in Fig. 4.

The length of the flanges in the side sill, etc., is approximately 15 mm, making it necessary for the wax to achieve a penetration of 20 mm or more. The developed wax meets this requirement.

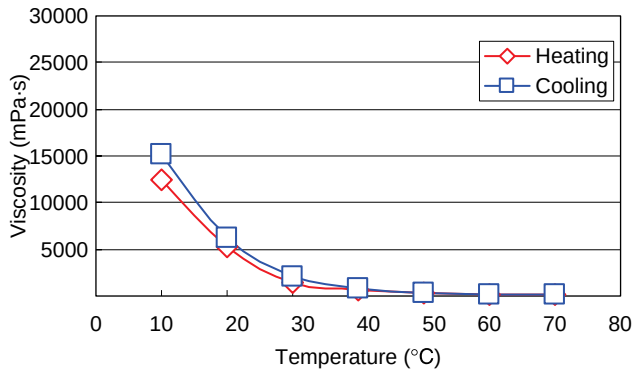


Fig. 5 Heating / Cooling viscosity of developed wax (without thixotropic additive)

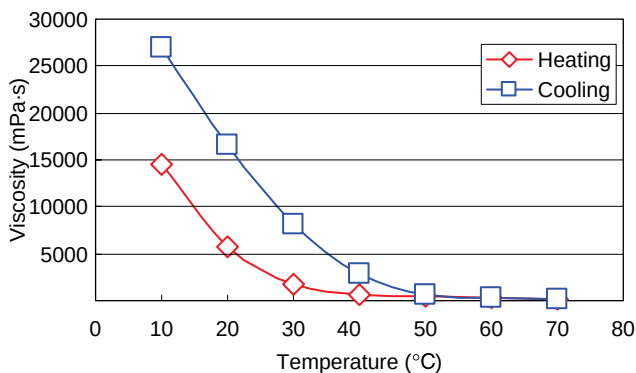


Fig. 6 Heating / Cooling viscosity of developed wax (with thixotropic additive)

Table 4 Basic properties of developed wax

	Conventional wax	Developed wax
Salt spray test	720 Hr red rust area max 10%	Equal to conventional
Cycle corrosion test	No rust from cross cut	Equal to conventional
Humidity	No irregularity	Equal to conventional
Pollution	Lubrication, and expansion	Equal to conventional
Odor	Low odor (no pungent odor)	Strong oil odor (no solvent odor)
Penetration	Good (15mm)	Good (35mm)
Correctivity	Easy to correct	Equal to conventional

Table 5 Endurance test results

Items	Results	
	Former wax	Developed wax
Water resistance 40 °C × 120 Hr DIP	No irregularity	No irregularity
Humidity resistance 50 °C, 95%RH × 120 Hr	No irregularity	No irregularity
Cold bending resistance	No irregularity	No irregularity
Removability	Easily removable	Easily removable
Cyclic heating and cooling resistance	No irregularity	No irregularity
Circulation stability	No change	No change
Stability of storage 40 °C (4 Hr) to −20 °C (4 Hr) Cycle on 240 Hr	Allowable viscosity increase	No problem on visual inspection, Allowable viscosity increase

Table 5 shows the durability of the developed wax. Given the requirement for a stable spray when the wax is employed on the vehicle production line, the test mode assumed circulation of the wax between the wax tank and the spray gun, i.e., a continuous flow between the tank and the spray gun. Looking at viscosity, the results show that application at a stable viscosity has been enabled by the fact that the heat generated during the flow of the wax causes the thixotropic agent to react, ensuring no increase in viscosity. In addition, tests using repeated thermal cycles within the range of temperatures assumed for storage over extended holidays, etc., showed no increase in viscosity.

The effect of application of the developed wax to the left and right side sills of the endurance test vehicle was also tested. Comprehensive durability tests were conducted in a corrosion-promoting environment on a proving ground⁽⁶⁾. Following the running tests the side sills were dismantled and checked for corrosion. Figure 7 shows the inner side of a dismantled outer side sill of the durability test vehicle following testing. The holes represent areas in which the spot welds have been removed to enable the status of corrosion in the flange to be seen. The effect of using wax as compared to using no wax is clearly visible from the status of corrosion. Figure 8 shows a

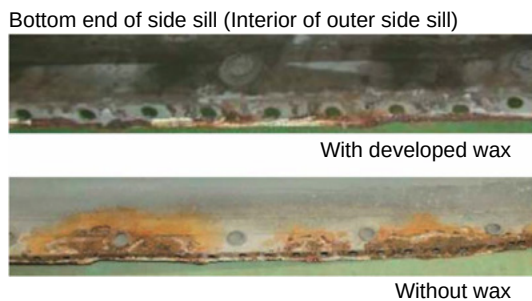


Fig. 7 Dismantled side sill from test vehicle side sill interior

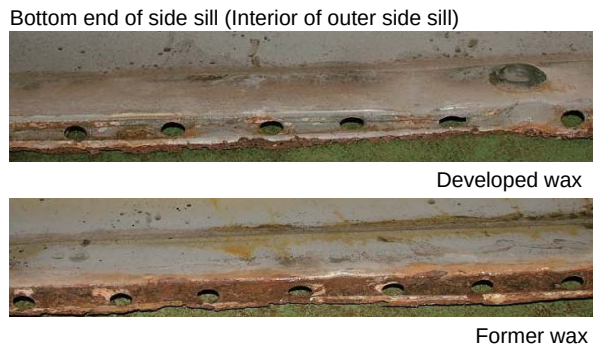


Fig. 8 Results for test vehicle side sill interior (compared to former wax)

comparison of the effect of the developed wax and the former wax. The results indicate that the developed non-solvent, post-heated, high-penetration wax achieves a level of performance equivalent or superior to that of the former wax.

5. Effect on Production Process and Cost

One issue of the developed wax was the fact that it was necessary to heat the vehicle body to a sufficient temperature to enable penetration to be controlled by the temperature of the interior wax. A wrap is therefore used to protect the coating in the drying oven. This has reduced the degree of change required to the conventional assembly line, enabling viscosity control to be used as a measure to help prevent wax flow with only minimal modification of facilities. Figure 9 shows an overview of the line layout. The wax is highly viscous directly after application and does not flow out in the processes between application and baking in the drying oven. Penetration of the wax occurs in the drying oven. A wax catcher is employed to collect the wax that flows out in the drying oven. When the vehicle body returns to a normal temperature, the viscosity of the wax increases, and it ceases to flow. Therefore, there is no need to take measures for wax flow-out in the later procedures. The range of procedures in which the wax flows is determined

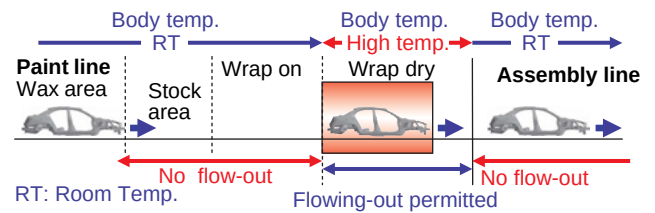


Fig. 9 Line layout (and countermeasures in car paint line)

by the temperature of the vehicle body. The use of the new wax has made the need for measures against wax flow-out such as the use of sealers and drip collectors attached to the bottom of the vehicle unnecessary. This will reduce the labor involved in their removal and the cost of their disposal by dealers, thus reducing expenses.

In addition, the fact that the wax does not employ a solvent reduces its odor and gives it a high flash point, enabling it to be used in environments of 180°C and above (e-coat drying ovens, for example, reach 180°C). The new wax is also not subject to regulations for the prevention of organic solvent poisoning on the production line.

6. Conclusion

- (1) Replacing the former solvent-type wax with a non-solvent type to respond to environmental issues has enabled reduction of VOC.
- (2) In vehicle endurance tests in a corrosion-promoting environment, the developed wax displayed increased corrosion resistance, and showed no functional issues.
- (3) While using no solvent, the developed wax achieves penetration at a low viscosity. As a measure to respond to wax flow, viscosity control is applied to increase the viscosity of the wax after application.
- (4) With only a minor investment in facilities, the use of the developed wax has made the wax flow measures employed when using the former wax unnecessary.

In addition to responding to the demands of the present environmentally-aware era for a reduction in the use of polluting substances, the development discussed here enables Honda to present its customers worldwide with vehicles displaying reliable corrosion resistance. This new post-heated high-penetration wax is being introduced to Honda paint lines around the world, and has already been applied to the 2008 year model in Europe.

References

- (1) Sakauchi, T.: Rust prevention techniques in automobiles, Rust Prevention & Control Japan, Japan Association of Corrosion Control, Vol. 43, No. 3, p. 105-111 (1999)
- (2) Takeuchi, T., Watanabe, H., Watanabe, S.: Automobile Corrosion Problems and Prevention, ISRM90, V-1, p. 187-192 (1990)

- (3) Kume, M.: Corrosion Prevention of Car Vehicle and Electrodeposition Coating, Journal of The Surface Finishing Society of Japan, The Surface Finishing Society of Japan, Vol. 43, No. 6, p. 530-538 (1992)
- (4) Tanaka, T., Masuda, T.: Development of an environment-friendly solventless car body rust prevention wax, Rust prevention & Control Japan, Japan Association of Corrosion Control, Vol. 50, No. 10, p. 390-394 (2006)
- (5) Naganuma, K.: Rensai Suikeigijutsu (1) Suikeitoryouyou Chikusotoropikku zai, Surface Treatment Technology, Japan Coating Technology Association, Vol. 41, No. 11, p. 388-394 (2006) (in Japanese)
- (6) Takeuchi, T., Watanabe, H., Imanaka, T., Shirotani, T.: Automobile Corrosion Problems and Test Method for Corrosion Resistance, Journal of The Surface Finishing Society of Japan, The Surface Finishing Society of Japan, Vol. 43, No. 6, p. 556-561 (1992)

■ Author ■



Yasuhisa SHIMIZU



Takahide MAEDA



Toshiya NISHINO

Development of High-strength Case-hardened Boron Steel

Hitoshi KINOSHITA*

Atsushi MURAKAMI*

Natsuko SOTA*

Toru TAKAYAMA**

Takanari HAMADA***

Yusuke USUI***

ABSTRACT

A high-strength case-hardening steel maintaining good cold forgeability has been developed for use in the manufacture of transmission shafts. The cold forgeability of the steel enables workability to be maintained when the steel is used in the form of wire in a multiple-stage former, as has now become standard. The developed material is also able to match the strength increase that was previously achieved using a special heat treatment (cold quenching) by using a standard carburization quenching (hot quenching). Higher strength represents an impediment to the straightening process that follows carburization, and it was therefore necessary to achieve a balance between high strength and straightenability. In order to do so, flattening of the hardenability curve (Jominy curve) was focused on. Boron was added to a conventional JIS SCr alloy steel and Cr content was adjusted to develop a new steel. During the development process, the mechanism by which the addition of boron causes a decline in the hardenability of the carburized case was clarified, and hardenability was enhanced by the addition of Cr, enabling the achievement of the development goals.

1. Introduction

There is a demand for small, lightweight, high-powered motorcycles, making it desirable to develop a stronger transmission shaft. A sufficient level of strength to resist torsion produced by sudden increases in torque, for example when the bike contacts the ground following a jump, and bending due to gear reaction force is called for, in particular motorcycles used in off-road racing. In addition, the load on the transmission shaft is increasing as motorcycles become smaller, lighter, and more powerful.

Cold forging from a coil offers reliable productivity and is the standard method of manufacturing transmission shafts. A multiple-stage former forges the spline section up to the final shaping procedure. From the perspective of manufacturing costs, it is not acceptable to allow productivity to decline if the strength of the shaft is increased. In addition, the shaft should undergo a process of straightening following carburization. Straightenability and high strength are opposing properties, and it is therefore important to attempt to achieve a balance between them.

Seeking a suitable material for a transmission shaft that reconciled the achievement of high strength with low cost, the project discussed in this paper selected a boron steel in which hardenability could be enhanced by reducing alloying elements. The boron factor (fB) of boron steels is known to be determined by the amount of carbon present in the steel; as carbon content increases, fB decreases⁽¹⁾. During the development process, however, it was shown that the hardenability of the carburized case declined with the addition of boron. Because of this, the project attempted to increase hardenability through the addition of alloy elements.

2. Development Goals

Honda has conventionally employed carburized HSCM420H, a similar steel to JIS Cr-Mo steel, in the transmission shafts of its motorcycles. For models that will be placed under high loads, such as the off-road bikes mentioned above, the oil temperature is reduced during carburization quenching ("cold quenching") in order to increase internal hardness, resulting in increased shaft strength.

* Motorcycle R&D Center

** Sumitomo Metal Industries, Ltd.

*** Sumitomo Metal (Kokura), Ltd.

With the aim of removing special heat treatments of this type in order to develop a high-strength, low-cost shaft, the project discussed here attempted to design a material that would fulfill the following standards:

- (1) The achievement of a level of strength using hot quenching equivalent or superior to that achieved by the present material using cold quenching
- (2) The achievement of an equivalent level of manufacturability to the current material
- (3) Low cost

With regard to standard (1), it was assumed that the treatment would be conducted in a standard gas carburizing furnace, and the design attempted to produce a material that would achieve the level of strength previously achieved using cold quenching (60-80°C) through the use of normal hot quenching (110-130°C).

In addition, when cold quenching is used, there is considerable distortion following carburization, while internal hardness increases to a certain level, which reduces deformation during straightening, generating the issue of a decline in yield during the straightening procedure. The composition design of the developed steel therefore attempted to realize no too-high level increase in internal hardness.

With regard to standard (2), the constraint for manufacturability, because cold forging in a multiple-stage former using steel wire treated with a zinc phosphate coating is the standard manufacturing method in use, the ability to manufacture the developed steel using existing mass production processes was established as a prerequisite.

The removal of Mo, which has increased in cost, from the composition of the developed steel and the removal of the normalization procedure following cold forging were projected as methods of achieving low cost, standard (3).

3. Material Component Design Process

3.1. Quench Curve Design

Prior to the design of the steel composition, the quench curve (Jominy curve) was designed.

In order to satisfy the target of increasing internal hardness and achieving high strength using hot quenching, the hardness of the material was increased in the J7-J15 area. In addition, the hardness of the water quenched end was reduced and the Jominy curve was flattened. The hardness of the water quenched end was reduced in order to help prevent an excessive increase in internal hardness, which would result in reduced straightenability.

In the mass production process, variations in the speed of cooling during carburization quenching cause the internal hardness of the shaft to vary, which in turn causes variation in strength. It is therefore important to flatten the Jominy curve and reduce the level of variation of the internal hardness of the shaft (Fig. 1).

3.2. Basic Composition

Given that the removal of Mo from the material and the achievement of low cost had been established as development guidelines, SCr was selected as the basic composition of the new steel. In order to increase cold workability, Si content was reduced and boron was added, increasing hardenability. In order to flatten the Jominy curve, the carbon content was reduced from 0.20% to reduce the hardness of the water quenched end, and boron, Cr, and Mn were added to increase the hardness of areas further away from the water quenched end.

In addition, Nb was added as a pinning element to control crystal grain growth so that the removal of the normalization process following cold forging did not result in the formation of duplex grains in the carburization quenching process that followed.

3.3. Study of Effect of Boron on Hardenability of Carburized Layer

As discussed above, the boron factor (fB) is determined by carbon content, decreasing with increasing carbon content⁽¹⁾. Considering carburized parts, the fB enhances the hardenability of an internal structure with a carbon content of 0.2%, but does not significantly contribute to increased hardenability in a carburized layer in which carbon content reaches 0.8% during carburization. This is thought to be because the boron forms a compound ($M_{23}(CB)_6$) inside the carburized layer, reducing the amount of dissolved boron necessary to provide good hardenability⁽²⁾. Therefore, the hardenability of the carburized layer in SCr boron steels was evaluated prior to the design of the alloy composition of the developed steel.

First, a steel formed by adding boron to SCr420 (steel A) and the current material, HSCM420H, were compared. The steels were melted using 150 kg vacuum induction melting (VIM), and underwent cogging at 1 250°C and normalization (925°C/1h/A.C.). Test pieces ($\phi 25 \times 40$ mm) were prepared and carburized in mass production furnaces, after which the quality of the heat treatment was

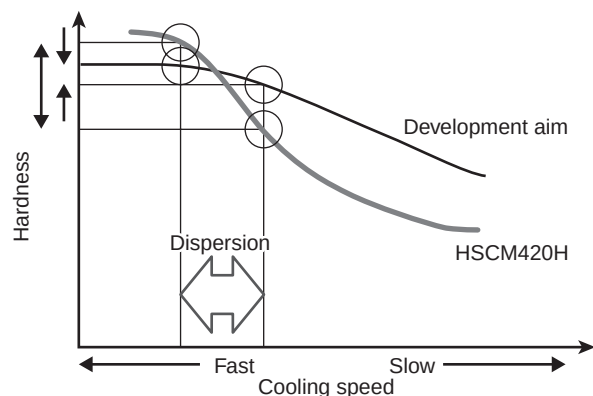


Fig. 1 Flattening quenching curve

examined. Quenching temperatures of 125°C (corresponding to hot quenching) and 80°C (corresponding to cold quenching) were used. Measured cross-sectional hardness distribution is shown in Fig. 2.

As Fig. 2 shows, when steel A is cold quenched, the hardness of the carburized layer is equivalent to that achieved using SCM420, but when hot quenched, the hardness of the surface of the carburized layer is lower than that of the current material, and insufficient hardenability of the carburized layer is achieved.

Next, in order to study the effect of the addition of boron on the hardenability of the carburized layer, steel A as shown in Table 1 was used as a base, and the carbon content was set to 0.8% to correspond to the figure following carburization. Hardenability was then studied with and without the addition of boron (Table 2).

As in the previous study, Jominy tests were conducted following cogging and normalization of the steels. The heating pattern used in the Jominy tests was based on the carburization heating pattern. Following heating at 930°C for 30 min, the steels were heated at 840°C for 20 min, after which they were quenched.

The test results are shown in Fig. 3. Hardness declined in the boron additive steel from the J15-J25 positions.

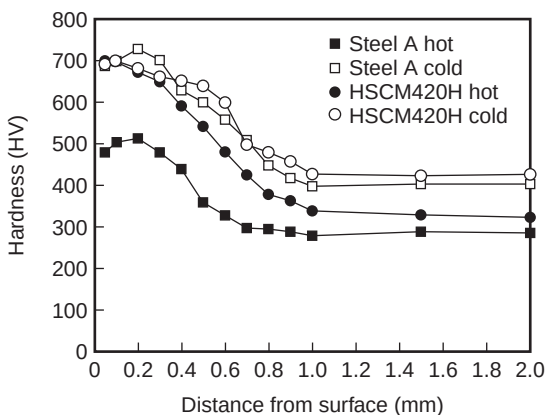


Fig. 2 Cross-sectional hardness distribution

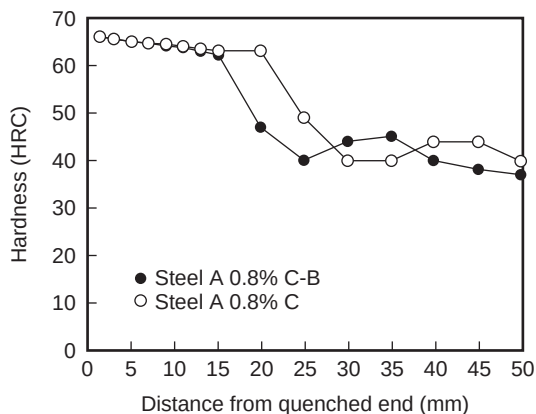


Fig. 3 Hardening-related test results

Table 1 Chemical composition and measured DI value

	(mass%) (in)							
	C	Si	Mn	Cr	Mo	Nb	Ti	B
Steel A	0.20	0.03	0.60	1.06	—	0.031	0.031	0.0012
HSCM420H	0.20	0.20	0.70	1.10	0.10	—	—	—
								2.52
								2.50

Table 2 Chemical composition

	(mass%)							
	C	Si	Mn	Cr	Mo	Nb	Ti	B
Steel A 0.8%C-B	0.79	0.05	0.75	1.06	—	0.036	0.028	0.0017
Steel A 0.8%C	0.79	0.05	0.75	1.06	—	0.036	0.028	—

Detailed study of the structure of the steel following quenching using an optical microscope showed the presence of troostite, a material lower in hardness than martensite, at a greater distance from the water quenched end than the area in which the decline in hardness occurred. At a shorter distance, i.e., closer to the quenched end where sufficiently rapid cooling had taken place, the steel displayed either a full martensite structure or a structure with low troostite content.

Observation of the area at a greater distance from the quenched end where a decline in hardness occurred using a field emission scanning electron microscope (FE-SEM) showed the presence of comparatively large precipitates (several μm in width), surrounded by troostite.

Microanalysis using an auger electron spectroscopy (AES) was conducted in order to determine the status of boron segregation in these relatively large precipitates. Figure 4 shows AES element mapping images of the

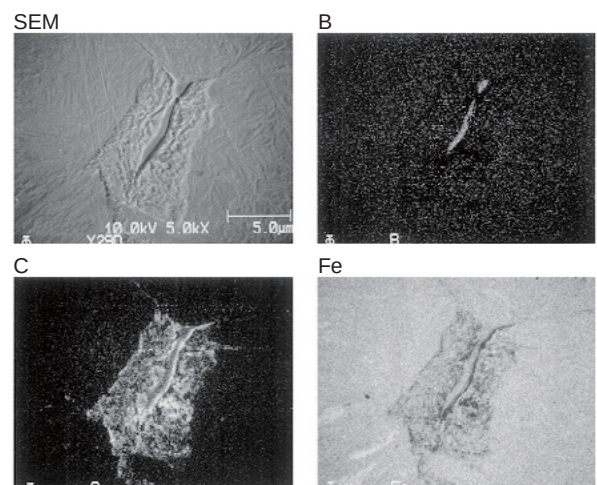


Fig. 4 Boron compound (AES mapping) separated at grain boundary in steel A 0.8%C-B

troostite areas formed close to the grain boundary in steel A (0.8% C-B). These results suggested the possibility of the presence of boron carbide.

A line analysis using an electron probe microanalyzer (EPMA) was conducted next in order to determine the level of variation in element concentration around the boron carbide. The results are shown in Fig. 5. It was considered that the low level of boron content in the precipitates would make line analysis challenging, and therefore it was not used to study boron. Cr content was approximately 17%, and there was an approximately 3 μm area of Cr depletion, at levels lower than the matrix. Areas of slightly depleted Mo and Mn were observed, but were not clear. No area of depleted C was observed. Electron diffraction analysis using transmission electron microscopy / energy dispersive X-ray spectrometry (TEM/EDS) was employed to identify the crystal structure of the precipitated boron carbide. The precipitate was judged to be $\text{M}_{23}(\text{CB})_6$. Figure 6 shows TEM images and electron diffraction patterns.

From these results, it is conjectured that hardness declines in Cr boron additive steel (steel A: 0.8% C-B) because: (a) the boron carbide $\text{M}_{23}(\text{CB})_6$, containing Cr, forms at the grain boundaries; (b) a Cr depletion layer forms around this compound; (c) during cooling, troostite forms from this Cr depleted layer; (d) resulting in a structure that contains troostite. From the perspective of carburizing conditions, it was not necessary to consider this phenomenon while employing cold quenching, in which the cooling speed is rapid, but the insufficient hardenability of the carburized layer becomes an issue

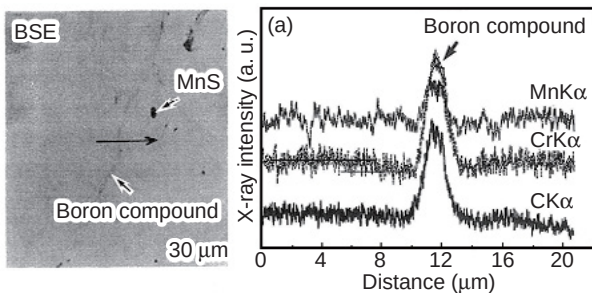


Fig. 5 Effect of boron compound vicinity in EPMA line analysis

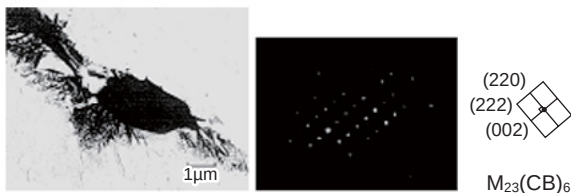


Fig. 6 TEM image of steel A 0.8%C-B steel and electron diffraction pattern

when using hot quenching, in which the speed of cooling is slower. Given the fact that hot quenching is the standard method in use today in the carburizing process in mass production, and that distortion should be avoided when using this method, this is an important issue to be considered when using SCr boron additive steels.

3.4. Method of Evaluation of Hardenability of Carburized Layer

The use of a “carburized Jominy test” (a Jominy test conducted following carburization of the material) was examined as a method of evaluating the hardenability of the carburized layer when designing the composition of the steel under development.

The test method involved the formation of test pieces of similar specifications to JIS G 0561 test pieces ($\phi 25 \times 100$ mm), which were then carburized. The test pieces were heated at 930°C for 30 minutes and at 840°C for 20 minutes after which they were quenched using the JIS method. A Vickers hardness tester was used to measure hardness from the surface of the test pieces to a depth of 0.1 mm.

Figure 7 shows a carburized Jominy curve for steel A. Steel A clearly shows insufficient hardenability in comparison to the current material. The achievement of a level of hardenability greater than that of the current material, as indicated by the Jominy curve, was therefore established as a target of the composition design of the new steel. From the perspective of the substitution of the developed steel for the current material, if the developed steel demonstrated an equivalent or higher level of hardenability to the current material in this test, evaluating the hardenability of the carburized case for different component shapes and under different cooling conditions during carburization would not be necessary, making the test an effective method of evaluating the hardenability of the carburized case during the process of material development.

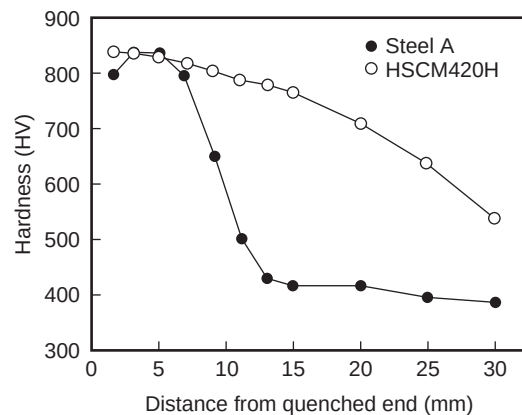


Fig. 7 Carburization Jominy curve

Table 3 Chemical composition

	(mass%)							
	C	Si	Mn	Cr	Mo	Nb	Ti	B
1.6% Cr	0.14	0.05	0.50	1.60	—	0.028	0.025	0.0016
1.8% Cr	0.14	0.05	0.50	1.80	—	0.028	0.025	0.0016
2.0% Cr	0.14	0.03	0.49	1.99	—	0.028	0.024	0.0015
HSCM420H	0.20	0.20	0.70	1.10	0.10	—	—	—

3.5. Establishment of the Material Composition

The composition of the material was established on the basis of the tests and studies conducted to this point. Mn and Cr were candidates for use as an additive element to enable hardenability to be increased, but because the ferrite intention index of Mn is higher than that of Cr, considerations of cold forgeability led to the optimization of Cr content.

Steels were formulated with varying Cr content, as shown in Table 3. The hardenability of the steels was evaluated in carburized Jominy tests and the quality of the heat treatment was checked following carburization

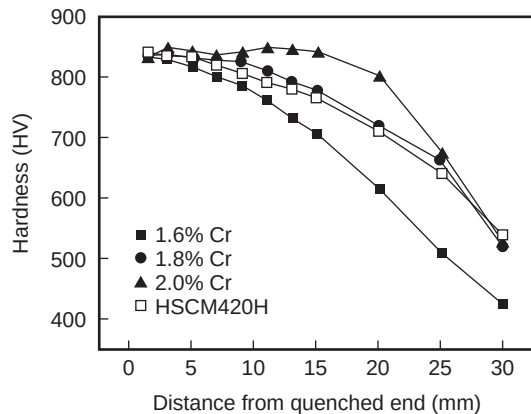


Fig. 8 Carburization Jominy test results

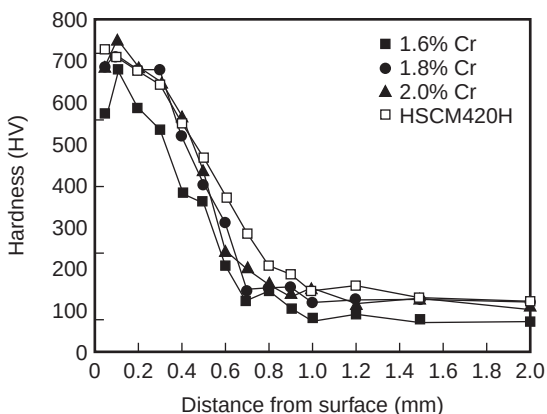


Fig. 9 Cross-sectional hardness analysis

Table 4 Chemical composition of developed steel

	(mass%)							
	C	Si	Mn	Cr	Mo	B	Ti	Nb
Developed steel	0.16	0.05	0.55	1.93	—	0.0015	0.040	0.040
HSCM420H	0.20	0.20	0.70	1.10	0.10	—	—	—

quenching (hot quenching) in furnaces used in the mass production process in order to establish the quantity of Cr to be added.

The results of these tests showed that a Cr content of 1.8% or higher would enable the achievement of a level of hardenability of the interior of the component and the carburized case equivalent or superior to that achieved using the current material (Figs. 8 and 9). Table 4 shows the composition of the developed steel.

4. Manufacturability of the Developed Steel

The conditions used in the coating and machining processes were modified to enable the developed steel to be manufactured using the same processes as the current material.

4.1. Coating Process

Steel wire to which a zinc phosphate treatment has been applied is employed in cold forging using a multiple stage former. The zinc phosphate treatment involves acid pickling to remove scale, dipping in a zinc phosphate solution, and drying. It was found that the conditions used in the acid pickling process can have a negative effect on the adhesion of the coating. Figure 10 shows the difference in the amount of coating that results from different acid pickling conditions. One set of conditions resulted in an insufficient coating in a short period, and cracking

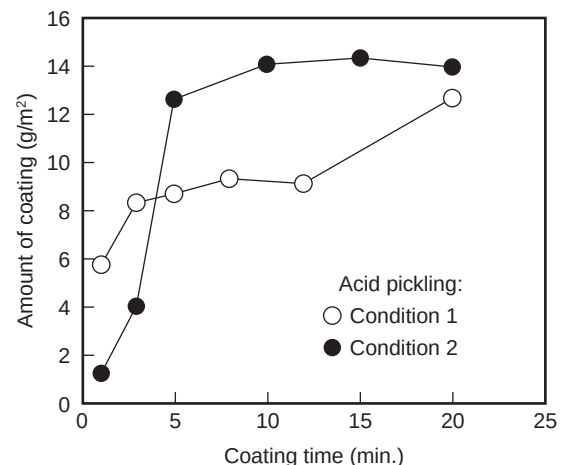


Fig. 10 Amount of coating in different acid pickling

occurred in this coating during cold forging (Fig. 11). Because it has a high Cr content, by contrast with the current material, there is a high concentration of Cr directly underneath the scale layer following rolling in the developed steel. It was hypothesized that, depending on the acid pickling conditions, this Cr layer and the corrosion residue (smut) from acid pickling affected the formation of the coating.

4.2. Change in Dimensions following Carburization

Grooves for the clips that are used to hold the gears in position are machined into transmission shafts. These grooves are cut following cold forging, and the positioning of the grooves during machining takes into consideration the change in dimensions that will occur after carburization.

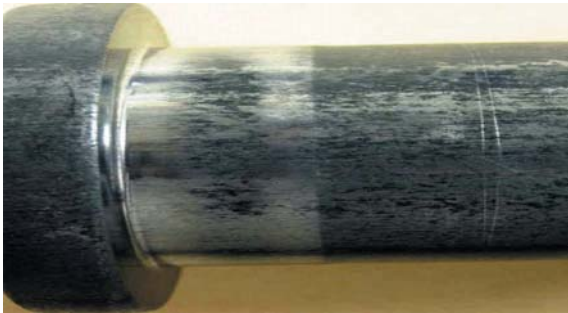


Fig. 11 Cracking of anodic oxide coating

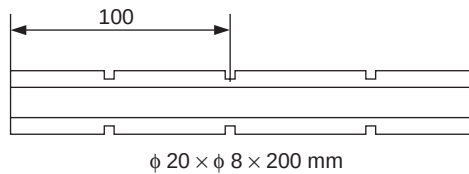


Fig. 12 Test piece

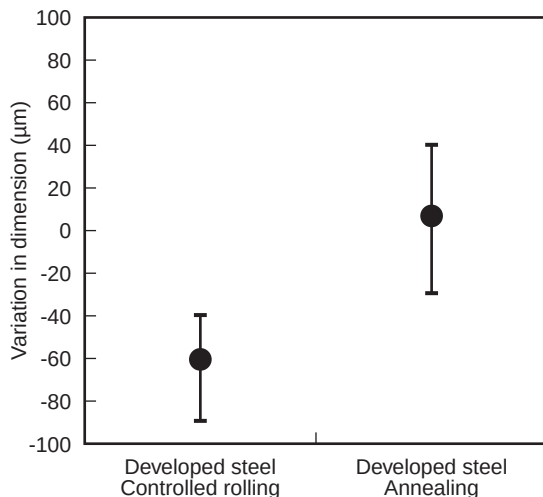


Fig. 13 Change in dimension

The change in dimensions after carburization in the developed steel differed from that of the current material, and the positioning of the grooves was therefore reset. The developed steel demonstrated a different tendency in terms of dimensional change when it was used to produce steel wire by controlled rolling and when the wire was produced by rolling followed by annealing. As part of the study conducted of the change in dimensions of the material, test pieces of the type shown in Fig. 12 were produced from each type of wire. Figure 13 shows an example of the change in dimensions of the test pieces following carburization.

The variation in dimensions was greater in the controlled rolled rods than in the annealed rods. Because it resulted in a lower level of dimensional change, the use of annealing would be better suited to achieving dimensional accuracy in components, and this method was therefore selected for use in the mass production process.

5. Characteristics of Transmission Shaft

5.1. Torsional Strength

Prototype countershafts for 1100 cc engines were produced and torsional strength was compared. Both hot quenched and cold quenched shafts were produced using the current material. Figure 14 shows test results. Considering the results in terms of internal hardness and the torque factor when cracking occurred, strength can be seen to have increased as internal hardness increased. The results for the developed steel fall on the higher-strength side of the line, and the increased grain boundary strength achieved by the use of boron is thought to have contributed to this result⁽³⁾.

In addition, straightenability has been enhanced by controlling internal hardness to a lower level than that of the cold quenched steel.

5.2. Manufacturing Cost

The use of the developed steel has enabled the removal of the normalization process following cold forging, the

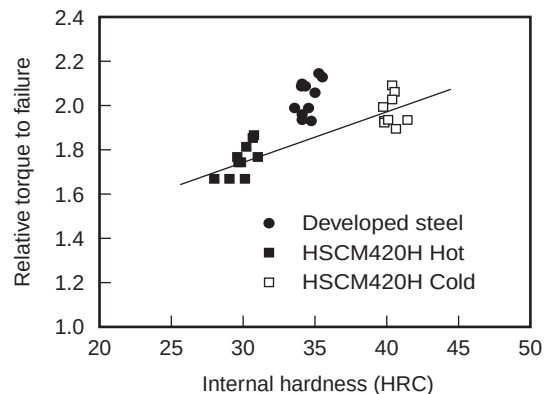


Fig. 14 Relationship between shaft torsional strength and internal hardness

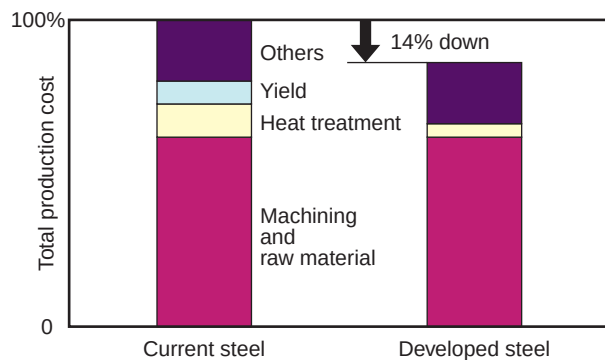


Fig. 15 Comparison of total production cost

removal of the use of cold quenching, and the achievement of an increased yield rate during straightening, resulting in a 14% reduction in the cost of transmission shafts (Fig. 15).

The developed steel has been employed in the transmission shaft of the 2008 CRF250R off-road racing motorcycle.

6. Conclusion

A high-strength, low-cost case-hardening boron steel has been developed. The main points of this development are as follows:

- (1) The addition of boron to JIS SCr420 steel resulted in a decline in the hardenability of the carburized layer. This occurred because a boron carbide containing Cr was formed at the grain boundary, and troosite formed from a Cr depletion layer around this boron carbide compound, causing a decline in hardness.
- (2) The addition of 1.8% Cr to SCr boron steel enables the achievement of a level of hardenability of the carburized case equivalent or superior to that of SCM420.
- (3) "Carburized Jominy" is an effective method of evaluating the hardenability of the carburized case.
- (4) When the developed steel is used to manufacture transmission shafts, the conditions employed in the coating and machining processes should be modified, but the shafts can be mass-produced using existing manufacturing facilities.
- (5) The composition of the developed steel has enabled torsional strength to be maintained and straightenability to be enhanced despite the use of hot quenching in place of cold quenching.

References

- (1) Rahrer, G. D., Armstrong, C. D.: The effect of carbon content on the hardenability of boron steels, "Trans ASM", Vol. 40, p. 1099 (1948)
- (2) Yamashita, T., Matsuzaki, A., Takajou, S.: Effect of B

on the Spheroidizing Behavior of Cementite in Fe-0.8 mass% C alloy, The journal of the Iron and Steel Institute of Japan, Vol. 85, No. 6, p. 486-491 (1999)

- (3) Kinoshita, H., Murakami, A., Takayama, T., Hamada, T.: Development of High Strength and Low Cost Motorcycle Transmission Shafts, Small Engine Technology Conference, 2007-32-0087 (2007)

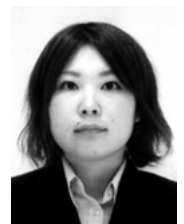
■ Author ■



Hitoshi KINOSHITA



Atsushi MURAKAMI



Natsuko SOTA



Toru TAKAYAMA



Takanari HAMADA



Yusuke USUI

Study of “LONG” Lighting System for Enhanced Motorcycle Conspicuity

Yojiro TSUTSUMI*

Kazuyuki MARUYAMA*

ABSTRACT

The Longitudinal Oriented Normative time Gap compensation (LONG) lighting system is proposed to enhance conspicuity with regards to the evaluation of motorcycle distance and speed. This system positions motorcycle lamps over a wider range in the vertical direction. Conspicuity was evaluated by measuring the critical time gap (CTG) with an oncoming motorcycle in an automobile waiting for a right turn (in left-hand traffic countries). The results showed that a motorcycle equipped with the LONG lighting system can have approximately the equivalent conspicuity as an automobile.

1. Introduction

Reported analysis of motorcycle traffic collisions in the United Kingdom has shown that, at times, it is not easy for other road users to detect motorcycles⁽¹⁾. For this reason, the United States commenced efforts to promote headlamp use in daytime from around the end of the 1960s to enhance motorcycle detectability during the daytime. Japan mandated daytime headlamp use in 1998, and since then the practice has also gained widespread acceptance in Europe. These measures aim to enhance the “detectability” element of conspicuity, and do not have the

main purpose of enhancing the “evaluation of distance and speed,” which is another element. The data for fatal motorcycle traffic collisions (in which an automobile driver is the party at fault) were analyzed from traffic collision statistics for fiscal year 2003⁽²⁾. The results showed that the main causes of traffic collisions are “misperception of distance or speed” and “oversight” of motorcycles on the part of automobile drivers (Fig. 1). In addition, research by Donne indicates that “misperception of distance or speed” also accounts for a relatively high percentage of traffic collisions in the United Kingdom⁽¹⁾. A lighting system that enhances conspicuity with regards to the evaluation of motorcycle distance and speed in order to reduce this misperception has been proposed.

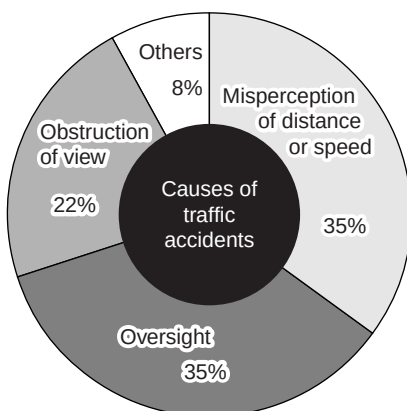


Fig. 1 Analysis of motorcycle traffic accidents in Japan (ITARDA 2003)

2. Fundamental Concept

Previous research showed the possibility of standardizing the conspicuity of various vehicle types using lighting systems⁽³⁾. Some vehicles have high conspicuity, which means that the relative conspicuity of other vehicles may decrease as a result, so this study was conducted to correct this difference. It is thought that the conspicuity of motorcycles should be approximately equal to that of automobiles. However, motorcycles have a more complex body contour than automobiles, which makes it difficult to recognize the vehicle size and shape. Therefore, in particular, the headlamp and front position

* Motorcycle R&D Center

lamps stand out when viewed from the front, and are thought to be used as a reference for recognizing distance and speed.

As the height of an object within the visual field subject to perception separates from the horizon, the object is felt to be closer. This is a type of perspective effect⁽⁴⁾⁻⁽⁶⁾. In addition, evidence supporting the theory that people judge the distance from objects using angular declination by the horizon has also been reported⁽⁷⁾. Ordinary motorcycles have the headlamp and front position lamps in relatively high positions, and there is nothing noticeable near the road surface, so these motorcycles may be perceived as farther away than the actual distance. Therefore, lamps were placed on the lower front fork to emphasize a low position near the road surface. This can be expected to help reduce the effect that motorcycles are felt to be farther away than the actual distance (Figs. 2 and 4).

On the other hand, when a vehicle has a small visual size, the amount by which the image on the retina is magnified as it approaches is also small, making it difficult to sense the speed of approach. Previous research has reported that when an approaching vehicle has a large visual size, the approach speed can be recognized at a farther distance⁽⁸⁾. Most ordinary motorcycles arrange the headlamp and front position lamps within a narrow range that results in a small image on the retina, so it may be difficult to recognize the speed. Ordinary motorcycles have a relatively large body height dimension compared to a small body width dimension. Therefore, lamps are placed in low and high positions on the vehicle body, for example on the lower front fork and the front side of the rear view mirrors, to emphasize the vertical length of the vehicle body. This helps prevent the visual size from being recognized as smaller than the actual size, and makes it easier to recognize the speed (Fig. 3). Furthermore, a large visual size also affects distance recognition, and it has

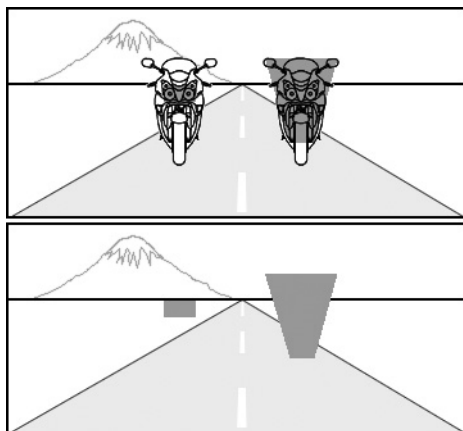


Fig. 2 Principle of enhancing sense of distance

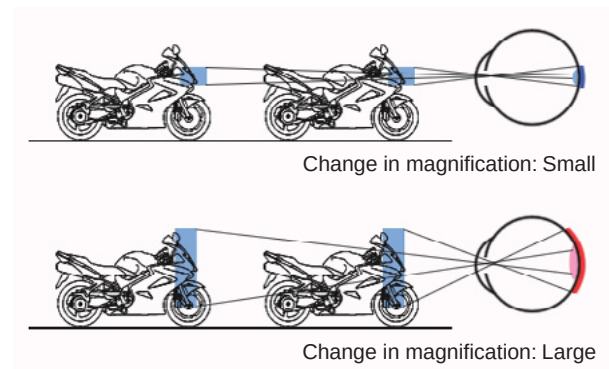


Fig. 3 Principle of enhancing sense of speed, effect of visual size difference projected on retina

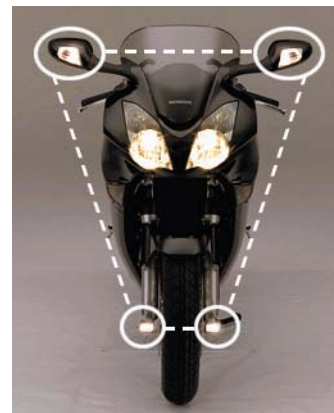


Fig. 4 LONG lighting system

been reported that the distance to objects with a large visual size is felt to be closer⁽⁹⁾ (Fig. 2).

This paper proposes the Longitudinal Oriented Normative time Gap compensation (LONG) lighting system that positions lamps in a reverse trapezoidal shape (Fig. 4). This method makes use of the above-mentioned concepts to enhance conspicuity with regards to the evaluation of motorcycle distance and speed to approximately an equivalent level as that of an automobile.

3. Evaluation Methodology

3.1. Critical Time Gap (CTG)

When making a right turn across traffic (in left-hand traffic countries), the driver is thought to make the decision to start the right turn based on a comprehensive judgment of the distance and speed of approaching oncoming vehicles, the driver's own speed, the road width, and other factors. This series of behaviors is called the gap acceptance behavior in right-turn across path scenario. In addition, the time from when the driver decides not to make the right turn because an oncoming

vehicle is too close until the vehicle passes the right turn start point is called the critical time gap (CTG)⁽¹⁰⁾. Comparing this CTG for various vehicles enables quantitative comparison of the conspicuity of these vehicles with regards to the evaluation of distance and speed. Therefore, the LONG lighting system was quantitatively evaluated by measuring the CTG in the right-turn across path scenario.

Figure 5 shows the vehicle arrangement for CTG measurement. The experimental subjects were instructed that, "You are waiting to make a right turn at an intersection. Press the brake pedal as soon as you judge that you will have to forego the right turn if the approaching oncoming vehicle comes any closer." The speed of the approaching oncoming vehicle used as the stimulus was set at 60 km/h, which is the speed limit on major Japanese roads. In order to regulate the stimulus to the experimental subjects, observation of the stimulus was started when the approaching oncoming vehicle passed the position 150 m from the experimental subject. Specifically, experimental subjects were told to face downward so that they were not looking forward at first, and then to observe the forward direction when they heard the beep from the vehicle passage sensor. In addition, observation was stopped by having experimental subjects face downward again immediately after pressing the brake pedal in order to minimize the learning effect. The vehicle in which the experimental subjects sat had a millimeter wave radar unit installed in the front grill that measured the speed and distance of the stimulus vehicle at a 0.1 s

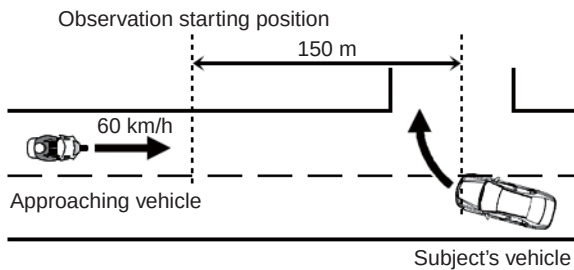


Fig. 5 Schematic plan of right-turn across path scenario, as used in the study

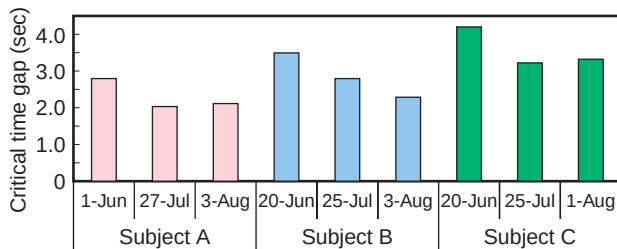


Fig. 6 CTG of ordinary motorcycle in nighttime

cycle. The CTG was calculated from the speed and distance of the stimulus vehicle at the instant the experimental subjects pressed the brake pedal. The CTG was measured five consecutive times for the same stimulus vehicle, and the mean was used as the value for that stimulus vehicle.

3.2. CTG Ratio

Figure 6 shows an example of the CTG measurement results for an ordinary motorcycle in nighttime. This is the data for three people, and shows the values for experiments conducted on three different days using the same motorcycle for each subject. The coefficients of variation were obtained by dividing the standard deviations of the CTG for experimental subjects A, B, and C by each mean, and were 0.25, 0.30, and 0.21, respectively. Even though these results are for the same subject using the same stimulus vehicle, there is variation depending on the measurement day. CTG variation was also indicated in past research⁽¹¹⁾, and it is thought that the CTG lacks sufficient reliability to be employed directly as a variable expressing conspicuity. Therefore, this research focused on the fact that the CTG of automobiles measured on the same day varied in the same manner as that of motorcycles. Figure 7 shows the CTG ratio of motorcycles compared to that of automobiles, which is expressed as a percentage obtained by dividing the motorcycle CTG by the automobile CTG. The coefficients of variation were obtained by dividing the standard deviations of the CTG ratio for experimental subjects A, B, and C by each mean, and were 0.06, 0.02, and 0.10, respectively. This shows a clear decrease in value variation by measurement day. That is to say, variance by measurement day can be suppressed, and conspicuity can be evaluated in a stable manner by using the CTG of an automobile measured on the same day as a reference. The LONG lighting system aims to make the conspicuity of a motorcycle approximately equivalent to that of an automobile, so comparison with automobiles also matches this goal. Therefore, this research used the CTG ratio of an automobile measured on the same day as the variable for evaluating conspicuity with regards to evaluating distance and speed.

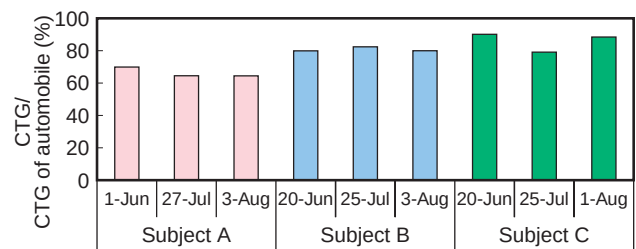


Fig. 7 CTG ratio of ordinary motorcycle compared to automobile

4. Conspicuity Enhancement Effects

4.1. Vehicles Used for Measurement

The conspicuity enhancement effects of the LONG lighting system were evaluated by measuring the CTG using actual vehicles. Figure 8 shows a photograph of the stimulus motorcycle used for measurement. This vehicle is an on-road type motorcycle (Honda XR250 Motard) with a displacement of 250 cm³, and uses 17-inch tires for both the front and rear tires. The LONG lighting system was mounted on the front of this vehicle using stays. In addition, the LONG lighting system used large turn-signal lamps (for the CB1300SF) on the upper side, and small turn-signal lamps (for the XR250) on the lower side. However, the lenses of these lamps were changed from amber to clear in order to emit white light. The lower lamp height (H) was 225 mm, and the distance in the horizontal direction was 300 mm. The upper lamp height was set so that the distance (S) from the lower lamps was 950 mm, and the distance in the horizontal direction was 750 mm. In addition, a pulse width modulation (PWM) dimmer circuit was mounted that enables the maximum luminous intensity of the LONG

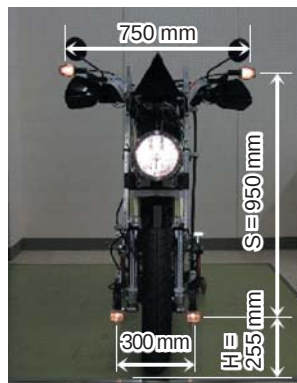


Fig. 8 Motorcycle used for measurement of enhanced conspicuity



Fig. 9 Automobile used for measurement of enhanced conspicuity

lighting system to be freely changed. This motorcycle had special stays that enabled the headlamp and height of various vehicle types on the market to be reproduced, and a single-bulb type multi-reflector headlamp (55/60 W, for the CB1300SF) was mounted at a height of 825 mm. Figure 9 shows a photograph of the stimulus automobile used for measurement. This vehicle is a Japanese minivan type passenger car (Honda STEPWGN) with a displacement of 2 000 m³ and a body color of white. In addition, the vehicle body width is 1 695 mm, the vehicle body height is 1 770 mm, the headlamp height is 800 mm, and the distance between the headlamps is 1 350 mm.

4.2. Enhancement Effects in Nighttime

Figure 10 shows the mean nighttime CTG ratio with an automobile of an ordinary motorcycle (MC) and a motorcycle equipped with the LONG lighting system (LONG MC). The experimental subjects were 21 people (18 men, 3 women, age 23 to 52) who drive an automobile on a daily basis. The error bars show the maximum and minimum values. The maximum luminous intensity of each of the four lamps comprising the LONG lighting system was adjusted to 16 cd. This value is the luminous intensity of ordinary motorcycle position lights. All measured stimulus vehicles were driven with the low-beam headlamps lit at a speed of 60 km/h. In addition, the course over which the measurements were performed was illuminated by streetlights, and the illuminance at the road surface was approximately 6 lx. The MC CTG ratio was 81.8%, which was approximately 18% smaller than that of the automobile. The mean automobile CTG in these measurements was 4.0 s, so this reduction in CTG corresponds to 0.72 s. In addition, the minimum MC CTG ratio was approximately 65%, and this CTG reduction of 35% corresponds to approximately 1.4 s. This showed quantitatively that an ordinary motorcycle may be perceived as being farther away and slower than an automobile in nighttime. In contrast, the LONG MC CTG ratio shows a value of 98.9%, which indicates that the sense of distance and speed is approximately equivalent to that of an automobile.

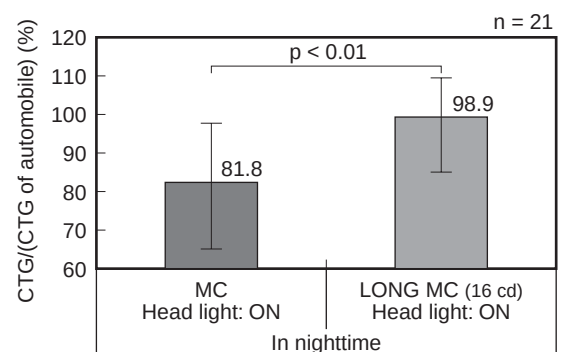


Fig. 10 Enhanced conspicuity in nighttime

4.3. Enhancement Effects in Daytime

Figure 11 shows the mean MC and LONG MC CTG ratios with an automobile for all experimental subjects in daytime. The experimental subjects were 14 people (12 men, 2 women, age 23 to 52) who drive an automobile on a daily basis. The error bars show the maximum and minimum values. The MC CTG was measured under the two conditions with the low-beam headlamp off (Head light: OFF) and on (Head light: ON). In addition, The LONG MC CTG was measured with the headlamp off, and the maximum luminous intensity of each of the four LONG lighting system lamps adjusted to 121 cd. This value is the maximum luminous intensity of ordinary motorcycle turn-signal lamps. All measured stimulus vehicles were driven at the same speed of 60 km/h as the nighttime measurements. The illuminance from the unobstructed sky of the course over which the measurements were performed was 4 410 lx to 33 500 lx. These measurements were performed over a five-day period, so there was variation in the illuminance from the unobstructed sky. The headlamps of the automobile measured to obtain the CTG ratio were off. The MC CTG ratio with the headlamp off was 86.5%, which means that the MC (Head light: OFF) CTG is 13.5% smaller than that of the automobile. This showed quantitatively that even in daytime, an ordinary motorcycle may be perceived as being farther away and slower than an automobile. In contrast, the MC CTG ratio with the headlamp on was 93%, which is an increase of 6.5% over the MC with the headlamp off. This indicates that turning on the headlamp enhances the sense of distance and speed. However, this CTG is still approximately 7% smaller than that of an automobile, which means that the equivalent conspicuity of an automobile for the evaluation of distance and speed cannot be obtained simply by turning on the headlamp. On the other hand, the LONG MC CTG is 99%, which is approximately equivalent to that of an automobile. This showed that even during the daytime, the LONG lighting system can enhance conspicuity with regards to the

evaluation of motorcycle distance and speed to approximately the equivalent level as that of an automobile. For reference, the mean automobile CTG for all experimental subjects during the daytime was 4.0 s, which is approximately equivalent to the nighttime mean of 4.1 s for these same experimental subjects.

5. Dependence on Lamp Layout

5.1. Measurement Conditions

The dependence of the conspicuity enhancement effects in nighttime on the lamp layout was measured. The distance (S) in the vertical direction between the upper lamps and the lower lamps, and the lower lamp height (H) from the ground surface were used as the lamp layout parameters. In addition, the distance in the horizontal direction was fixed at 750 mm between the upper lamps, and at 300 mm between the lower lamps (Fig. 8). The maximum luminous intensity of each of the four lamps was adjusted to 16 cd. All measured stimulus vehicles were driven with the low-beam headlamps lit at a speed of 60 km/h. The course used for the measurements was illuminated by streetlights, and the illuminance at the road surface was approximately 6 lx.

5.2. Dependence on height(H) of lower lamps

Figure 12 shows the CTG ratio dependence on H. The H values used for measurement were the three levels of 125 mm, 225 mm, and 325 mm, and the parameter S was fixed to 950 mm. The experimental subjects were 16 people (14 men, 2 women, age 23 to 52) who drive an automobile on a daily basis. The error bars show the maximum and minimum values. The results show that there was little CTG ratio dependence on H over the measured H range. The mean automobile CTG measured at the same time was 4.0 s, and the mean CTG of a motorcycle equipped with the LONG lighting system was 3.92 s, 3.94 s, and 3.90 s when H was 125 mm, 225 mm, and 335 mm, respectively.

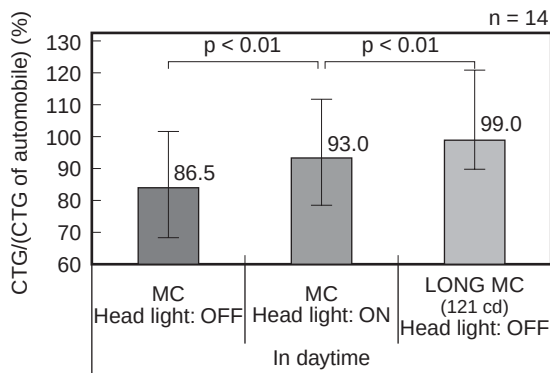


Fig. 11 Enhanced conspicuity in daytime

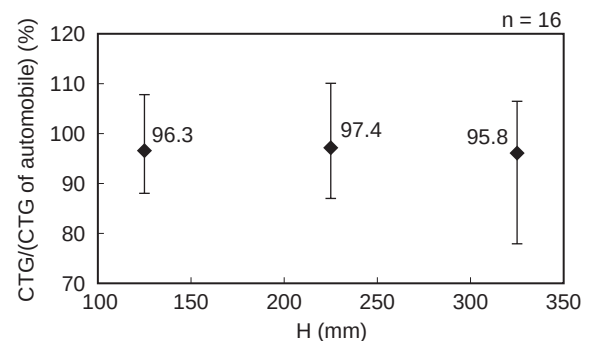


Fig. 12 CTG ratio dependence on height (H) of lower lamps in nighttime

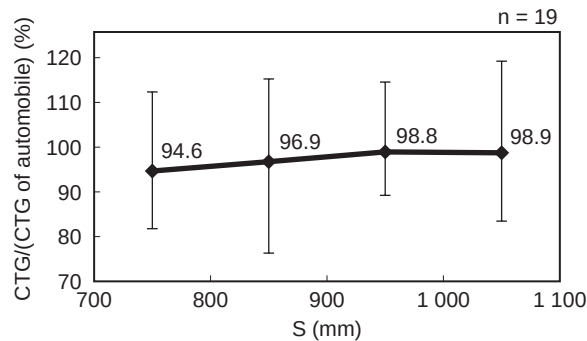


Fig. 13 CGT ratio dependence on space (S) between upper lamps and lower lamps in nighttime

5.3. Dependence on distance(S) between upper lamps and lower lamps

Next, Fig. 13 shows the CTG ratio dependence on S. The S values used for measurement were the four levels of 750 mm, 850 mm, 950 mm, and 1 050 mm, and the parameter H was fixed to 225 mm. The experimental subjects were 19 people (17 men, 2 women, age 23 to 52) who drive an automobile on a daily basis. The error bars show the maximum and minimum values. The results show that the CTG ratio increased with S over the S range from 750 mm to 950 mm. The fundamental concept of the LONG lighting system is that increasing the visual size increases the accuracy of speed and distance evaluation, which is predicted to increase the CTG ratio. The measurement results match this premise.

From these results, it can be inferred that drivers mainly use the size of the noticeable portions of vehicles to evaluate the distance and speed of a single approaching vehicle when making a right turn across traffic.

6. Dependence on Lamp Luminous Intensity

The dependence of the conspicuity enhancement effects in nighttime on the lamp luminous intensity was measured. The lamp layout was set at H = 225 mm and S = 950 mm. The luminous intensities of the lamps used for measurement were the three levels of 16 cd, 34 cd,

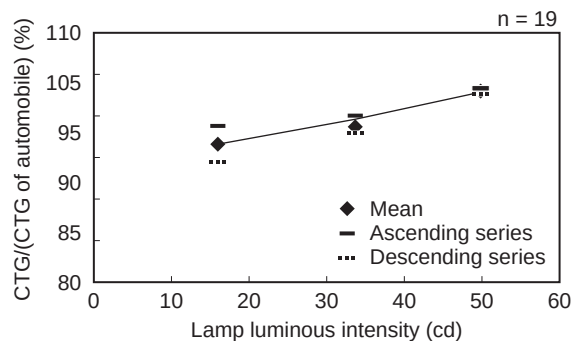


Fig. 14 CTG ratio dependence on lamp luminous intensity in nighttime

and 50 cd. All measured stimulus vehicles were driven with the low-beam headlamps lit at a speed of 60 km/h. The course used for the measurements was illuminated by streetlights, and the illuminance at the road surface was approximately 6 lx. The experimental subjects were 19 people (17 men, 2 women, age 23 to 52) who drive an automobile on a daily basis. Preliminary experiments showed sequential effects with regards to level. Therefore, each experimental subject was measured both in ascending series (16 cd → 34 cd → 50 cd) and descending series (50 cd → 34 cd → 16 cd) of luminous intensity, and the mean of the values for the same levels were used as the typical values in order to minimize these effects. Figure 14 shows the CTG ratio dependence on lamp luminous intensity. These results show that the CTG ratio increases with the lamp luminous intensity. In addition, when the lamp luminous intensity is zero cd in nighttime, the CTG ratio is literally the same as that of a motorcycle that is not equipped with the LONG lighting system, so the CTG ratio in this case is thought to be approximately 81.8% from Fig. 10. In the lamp luminous intensity range below 16 cd, the CTG ratio is presumed to decrease rapidly as the lamp luminous intensity approaches zero cd.

7. Conclusion

The LONG lighting system was proposed as a method of enhancing conspicuity with regards to the evaluation of motorcycle distance and speed to approximately an equivalent level as that of an automobile.

- (1) Experimental results showed that the conspicuity of a motorcycle can be increased to approximately an equivalent level as that of an automobile by making the distance in the vertical direction between the lower and upper lamps 950 mm.
- (2) The lower lamp height has no effect on the enhancement effects, but increasing the distance between the lower lamps and upper lamps increases the enhancement effects in nighttime.
- (3) The enhancement effects increase with the lamp luminous intensity in nighttime.

A remaining issue is the need to research how the effects of lamp layout change when the lamp luminous intensity changes. This and other issues will be further examined and researched in the future.

References

- (1) Donne, G. L.: Research into Motorcycles Conspicuity and its Implementation, Proceedings: International Congress and Exposition, SAE Paper 900749 (1990)
- (2) Annual Traffic Accident Report in 2003, Institute for Traffic Accident Research and Data Analysis of Japan (ITARDA), 403p. (2003)
- (3) Maruyama, K., Uematsu, I., Tsutsumi, Y., Sakamoto, M., Kushida, K.: A Study of New Lighting System for

- Better Conspicuity of Motorcycle, Review of Automotive Engineering, Vol. 27, No. 4, p. 571-577 (2006)
- (4) Gibson, J. J.: The Perception of the Visual World, Houghton Mifflin, 247p. (1950)
 - (5) Dunn, B. E.: Relative height on the picture plane and depth perception, Perceptual and Motor Skills, Vol. 21, p. 227-236 (1965)
 - (6) Epstein, W.: Perceived depth as a function of relative height under three background conditions, Journal of Experimental Psychology, Vol. 72, p. 335-338 (1966)
 - (7) Ooi, T. L., Wo, B., He, Z. J.: Distance determined by the angular declination below the horizon, Nature 414, p. 197-200 (2001)
 - (8) Maruyama, K., Tsutsumi, K., Kushida, K.: A Study of New Lighting System for Better Conspicuity of Motorcycle, Journal of Society of Automotive Engineers of Japan, Vol. 37, No. 5, p. 137-142 (2006)
 - (9) Gogel, W. C.: The absolute and relative size cues to distance, American Journal of Psychology, Vol. 82, p. 228-234 (1969)
 - (10) Miura, T.: A preliminary study of gap acceptance behavior and its perceptual factors, Bulletin of the Faculty of Human Sciences, Osaka University, Vol. 6, p. 37-41 (1980)
 - (11) Ueno, H., Maeda, K., Ochiai, K.: Analysis of Driving Behavior in Right Turns, Journal of Society of Automotive Engineers of Japan, Vol. 46, No. 9 (1992)

■ Author ■



Yojiro TSUTSUMI



Kazuyuki MARUYAMA

Method for Objectively Evaluating Power Steering Pump Noise and its Correlation with Subjective Vehicle Feeling Judgment

Jinghong Yu* Drew Ritchie*

ABSTRACT

It is challenging to evaluate the source noise characteristics of a power steering pump unit by the current one-pressure method. In this research, an effective evaluation system and a single indicator are developed, based on fluid dynamics in a pipe and 3-point pressure pulsation measurement. The value of the evaluation indicator, which is obtained from pump's source flow ripples measured by the new evaluation system, is well correlated with the noise performance of power steering system in an actual vehicle. It is shown that the new evaluation system and indicator are valuable tools for investigating the pulsation characteristics of pump units, objective scaling of the source noise properties of steering systems and developing quiet power steering pumps and systems.

1. Introduction

Power steering noise is one of the issues that affect vehicle overall NVH (noise, vibration and harshness) quality. Fluidborne noise (FBN) is one type of noise that can be noticed in an automotive hydraulic power steering system. In the system, the power steering pump is the fluidborne noise source that generates fluctuating flow, i.e., flow ripples, to the system. The flow ripples of the pump interact with the connected hose, pipes and steering gearbox unit to generate pressure pulsations. The pressure pulsations are transmitted through the fluid to everywhere in the system and may excite annoying mechanical vibrations and high levels of airborne noise. In order to reduce the level of fluidborne noise and develop quiet power steering systems, it is important to effectively evaluate and monitor the noise source characteristics.

Currently, the conventional method to judge the source fluidborne noise characteristics of power steering pumps is to measure actual pressure pulsation levels at one location in a given pump-hose-valve bench system, which is named as the "One Pressure" method, as illustrated in Fig. 1. In this method, the pump is connected to the power steering hose assembly and then connected to a simple loading valve. The fluidborne noise level of the pump is evaluated by examining the pressure pulsation levels at either the hose outlet or the hose inlet. There are

several technical disadvantages with the current method that may affect the effectiveness of the evaluation. Firstly, the results obtained from this method are dependent on the entire measurement system. That is, slight changes to the dimensions of connection pipes and/or the characteristics of the loading valve will yield different results. This makes it difficult to compare test results obtained in different geographical places. Figure 2 shows an example of the pulsation results for an identical pump obtained by using the "One Pressure" method separately from the measurement systems at two different places. This example shows that the difference between the results from the two systems can be as big as 20 dB. Secondly, the results obtained may not reflect actual noise levels or trends when the pump is installed in an actual power steering system because the impedance characteristics of the bench loading valve are different from those of a

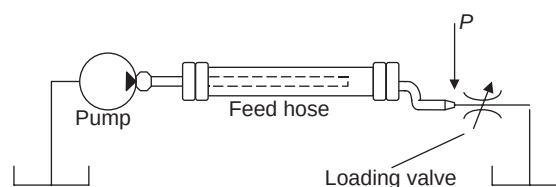


Fig. 1 Basic system of "One Pressure" method

* HONDA R&D AMERICAS, INC.

power steering gearbox, as shown in Fig. 3. Finally, measurement results are the combined effect of the entire measurement system and cannot be used as objective scaling for the inherent fluidborne noise properties of the pump. Therefore, it is necessary to establish a new method to evaluate the independent source characteristics of the pump unit.

The source fluidborne noise characteristics of a power steering pump which represents the pump's potential to excite FBN can be fully described by the following two parameters: source flow ripple (Q_s) and internal impedance (Z_s). Some existing efforts have been given to the development of experimental methods for evaluating the values of source flow ripple and internal impedance. Due to the system dependence of pressure pulsations, in most of the proposed methods, the characteristics of every component of the measurement circuit should be measured or established analytically first⁽¹⁾⁻⁽⁵⁾, or another (secondary) pulsation source is needed⁽⁶⁾⁻⁽⁸⁾. This makes the test circuit and measurement procedure complicated. One of the simplest and most accurate methods is the “2 Pressures/2 Systems” method proposed by Kojima⁽⁹⁾ and used by Kojima and one of the authors for hydraulic piston pumps⁽¹⁰⁾. This method can evaluate the source flow ripple and internal impedance of the pump by measuring only

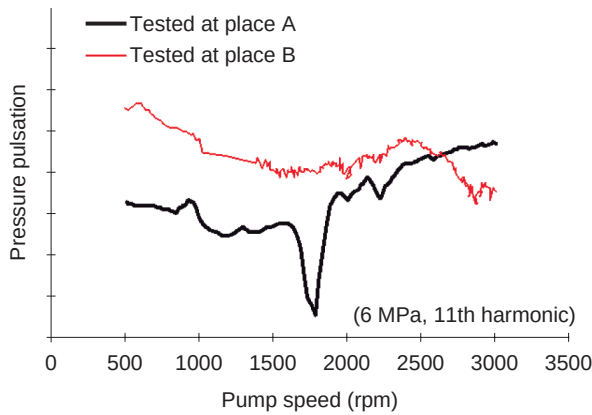


Fig. 2 Pulsations of pump measured at different places by using “One Pressure” method

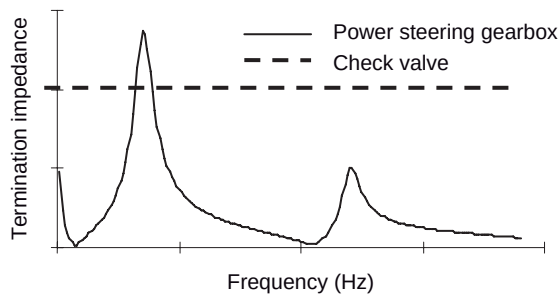


Fig. 3 Impedance characteristics of power steering gearbox and check valve

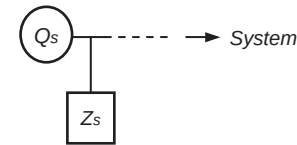
the wave propagation characteristics of pressure ripple generated by the test pump itself in a specific reference pipe. Based on this method, the “3 Pressures/2 Systems” method was proposed by one of the authors⁽¹¹⁾. This new method integrates exclusively an on-line measurement technique for the speed of sound in the fluid and a technique for eliminating flow disturbance effect on pressure sensors into the basic principle used in the existing “2 Pressures/2 Systems” method. The new method has an inherent potential to yield results with higher accuracy and higher confidence.

The work to be presented in this paper is directed toward an evaluation system and evaluation indicator for the source fluidborne noise characteristics of a power steering pump, by applying the theory of the “3 pressures/2 systems” method. After the validation on the system accuracy and repeatability, a single indicator for the source pulsation level is defined as the total pulsation energy of a pump. Then, the correlation between pump data and vehicle noise performance is presented.

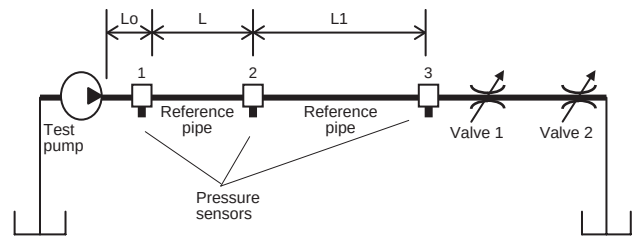
2. Theoretical approach and test system

2.1. Theoretical approach

By the standard “Norton” representation, the source fluidborne noise characteristics of the pump can be modeled as a source flow ripple, Q_s , connected in parallel with a internal impedance, Z_s , as shown in Fig. 4(a). Consider a test hydraulic circuit consisting of a test pump, a rigid pipe (hereafter referred to as the reference pipe), a connection pipe and then two loading valves separated by proper distance, as shown in Fig. 4(b). Alternative use of Valve 1 and Valve 2 allows a change to the standing wave in the circuit. On the reference pipe, there are three dynamic pressure sensors separated from the pump exit and from each other by distances of L_0 , L and L_1



(a) Pump model



(b) Measurement hydraulic circuit

Fig. 4 Pump model and basic hydraulic circuit of “3 Pressures/2 Systems” method

respectively. The circuit is called as System 1 and System 2 separately when Valve 1 and Valve 2 is used to load the system.

Consider unstable, two-dimensional, laminar viscous flow in the circuit. Based on fluid dynamics in the pipes, the source flow ripple and source impedance of the pump can be related to the pressure pulsations P_1 and P_2 from Sensors 1 and 2, as expressed by Eqs. (1) and (2), where the prime signs indicate the signals taken from System 2 with respect to the same pump rotational reference position as used in System 1. This constitutes the basic theory of the “3 Pressures/2 Systems” method⁽¹¹⁾.

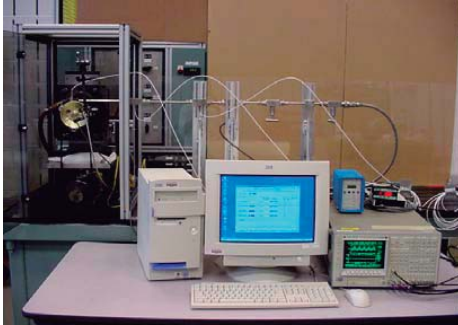
$$Q_s = \frac{j}{Z_c} \frac{P_1 P_2' - P_1' P_2}{(P_1 - P_1') \sin[\beta(L + L_0)] - (P_2 - P_2') \sin(\beta L_0)} \quad (1)$$

$$Z_s = -jZ_c \frac{(P_1 - P_1') \sin[\beta(L + L_0)] - (P_2 - P_2') \sin(\beta L_0)}{(P_1 - P_1') \cos[\beta(L + L_0)] - (P_2 - P_2') \cos(\beta L_0)} \quad (2)$$

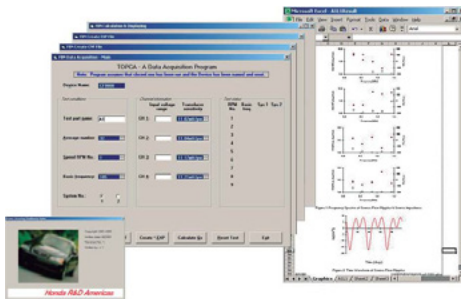
$$\text{where, } \beta = -j \frac{s \xi(\omega)}{c}$$

$$Z_c = \frac{\rho c \xi(\omega)}{\pi r^2}$$

$$\xi(\omega) = 1 + \sqrt{\frac{\nu}{2r^2\omega}} - j \left[\sqrt{\frac{\nu}{2r^2\omega}} + \frac{\nu}{r^2\omega} \right]$$



(a) System hardware



(b) System software

Fig. 5 New evaluation system

In Eqs. (1) and (2), $j = \sqrt{-1}$, s is the Laplace operator, ω angular frequency ($\omega = 2\pi f$, f is frequency), ρ the fluid density, ν the kinematic viscosity of the fluid, r the inside radius of the reference pipe, c the speed of sound in the fluid. The value of c can be on-line derived from pressure signals at sensors 1, 2 and 3, based on Eq. (3) by means of the “Three Transducer” method⁽¹²⁾⁻⁽¹⁴⁾.

$$\frac{P_1}{P_2} \sin \left[\frac{\xi(\omega)\omega}{c} L_1 \right] + \frac{P_3}{P_2} \sin \left[\frac{\xi(\omega)\omega}{c} L \right] - \sin \left[\frac{\xi(\omega)\omega}{c} (L + L_1) \right] = 0 \quad (3)$$

2.2. Experimental system

Figure 5 (a) shows the hydraulic test circuit and data acquisition system for measuring the source flow ripple and internal impedance of fluid power pumps by using the theoretical approach described above.

The lengths of the reference pipe between sensors 1 and 2, the extension pipe between valves 1 and 2, and the reference pipe between sensors 2 and 3 are appropriately selected for the frequency range of interest, 0 – 1000 Hz. The data acquisition system consists of a personal computer and a four-channel Fast Fourier Transform (FFT) analyzer. The sampling of the pressure ripple signals in the FFT analyzer is triggered externally by a photoelectric sensor detecting a fixed position of the pump driveshaft. The computer is used to control the FFT analyzer for data acquisition and to perform data processing, with a general-purpose software package shown in Fig. 5(b) developed with MS Visual Basic for the interface, Fortran for the data analysis and MS Excel Macro for report generation.

3. Validation of evaluation system

3.1. Measurement accuracy

The measurement accuracy is validated by two ways. In the first way, the evaluation system is verified by comparing the predicted results of pressure ripples, based on the determined source flow ripple and internal impedance, with the measured results of pressure ripples in a pump-pipe-valve circuit. The source flow ripple and internal impedance, Q_s and Z_s , of a power steering pump is measured by the evaluation system described in the preceding section. The termination impedance, Z_t , of the valve is measured by means of two pressure signals. Then, the pressure ripple at any locations of the confirmation system can be predicted, based on the measured data of Q_s , Z_s and Z_t as well as theoretical models of fluid dynamics in pipes. Figure 6 presents an example of the comparison of the predicted and measured pressure pulsations at one location on the pipe. Similar comparison results are obtained for other points along the pipe. It is shown that there is a very good agreement between the predicted and measured results in a wide order range of the pump's flow ripple. This

indirectly verifies that the evaluation system can yield evaluation results with good accuracy.

In the second way, the length of the connection pipes of the test system is changed on purpose so that the independence of measurement results on pipe dimensions can be verified. Two different lengths, 320mm and 750mm, are randomly selected for the connection pipe between sensor 3 and valve 1. Figure 7 shows the measured source flow ripples obtained by using the connection pipes with different lengths. The figure indicates that the change to connection pipe length has little influence on the measurement results. Variations at high orders likely result from unstable motor speed and unstable internal operation conditions of the pump.

3.2. Repeatability of evaluation system

It is very important to make sure that the evaluation system can provide repeatable results before the system is used for actual application. To minimize the influence of possible internal operating uncertainty of pump, a constant displacement power steering pump is used to perform repeatability test. The pump is tested nine times on the evaluation system. To maintain similar operation conditions to the pump during each test, the driving motor is stopped and turned on again before starting each test, and all other test conditions are kept the same. Figure 8

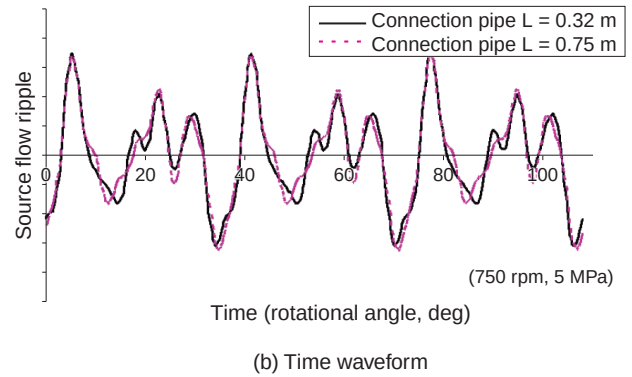
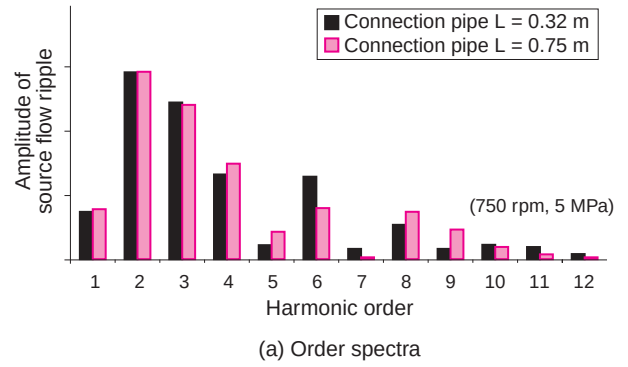


Fig. 7 Measured results of source flow ripple of pump with respect to different connection pipe lengths

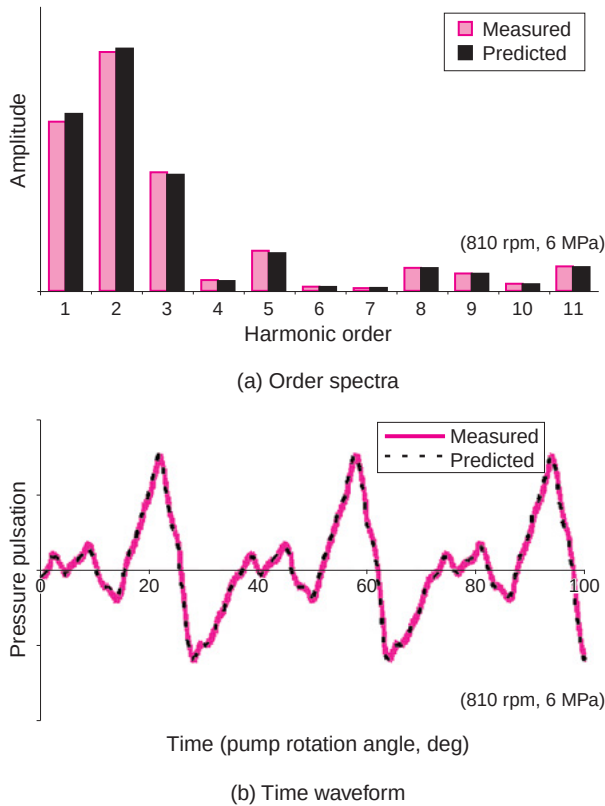


Fig. 6 Predicted and measured pressure pulsations at one location on feed pipe of pump-pipe-valve system

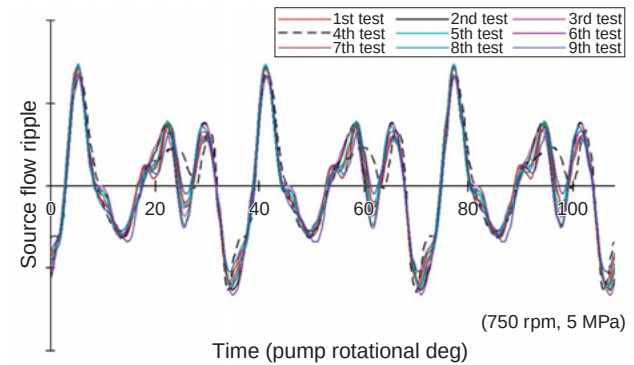


Fig. 8 Measured levels of source flow ripple of same pump from nine different tests

illustrates the time waveforms of the evaluation results for the nine tests. The results show that the evaluation system and the test pump have acceptable repeatability for practical use.

4. New evaluation indicator

Now that we can measure the source flow ripple and internal impedance of a power steering pump by using the

evaluation system based on Eqs. (1) and (2), the effect of each harmonic component on the source characteristics of the pump can be readily examined and evaluated directly from the harmonic spectra and resultant time waveform of source flow ripple. Beyond the harmonic analysis, it is also important to be able to judge the pump overall pulsation level by using a single indicator.

The source fluidborne noise characteristics are fully represented by the two parameters, that is, source flow ripple and internal impedance. The value of internal impedance is normally determined by the fluid compressibility and fluid wave propagation inside the pump discharge passageway. For a given design of pump, the layout and size of discharge passageway is fixed, and hence the internal impedance is theoretically fixed if same test fluid and temperature condition are maintained. This implies that source flow ripple is the key parameter to be considered while evaluating the source pulsation level for a certain type of pump.

A single evaluation indicator is defined here for evaluating the overall level of source pulsation level of a pump, by Eq. (4).

$$L_k = 20 \log_{10} \sqrt{\sum_{i=1}^k Q_i^2 / Q_{ref}^2} \quad (\text{dB}) \quad (4)$$

where Q_i is the i -th harmonic order of measured source flow ripple and Q_{ref} a reference value of $10^{-6} \text{ m}^3/\text{s}$.

The evaluation indicator represents physically the total power of the harmonic spectral components of source flow ripple up to the upper order of the harmonic range of interest. Since the source flow ripple is directly related to the pressure pulsations in power steering systems and the pressure pulsations are related to the system vibrations and noise, L_k is an indicator reflecting the potential of a pump to cause pulsation-induced noise in a power steering system.

In addition, an A-weighting filter can be easily included in Eq. (4), if necessary.

5. Correlation between pump data and vehicle performance

According to source-path-receiver noise transferring manner, in an actual vehicle, if the power steering hose and gearbox are fixed and the vehicle sound treatment package is kept the same, the power steering noise heard in cabin should be correlated to the source, that is, the pump's characteristics.

A correlation test between pump data and vehicle performance is performed on a vehicle. Four pumps with basically same design but different levels of source flow ripple are specially made for this test. Those pumps are firstly evaluated in terms of the total power of source flow

Table 1 10-point rating scale for subjective judgment

Rating	Judgment
10	Excellent
9	Very good
8	Good
7	Acceptable
6	Marginally acceptable
5	Borderline unacceptable
4	Unacceptable
3	Poor
2	Very poor
1	Extremely poor

ripple by using the evaluation system under the following two sets of test conditions: (1) fluid pressure of 1 MPa and pump speed of 750 rpm; (2) fluid pressure of 5 MPa and pump speed of 750 rpm and 1100 rpm.

As the evaluation of vehicle performance, in-car power steering noise is subjectively judged separately for the four different pumps by several technical experts under the following two different conditions corresponding to those used in bench test: (1) no or small steering input and idle engine speed; (2) steering input of partial loading and full lock, and engine speeds of idle and 1200 rpm. The subjective judgments are made based on a 10-point ranking system, as shown in Table 1.

Figure 9 shows the test results for the correlation of the test pumps and the vehicle noise performance with pump's total power of source flow ripple in x-axis and subjective judgment of vehicle noise in y-axis. It is shown that there is a very good correlation between the pump data and vehicle performance. This indicates that the fluidborne noise characteristics of power steering pump can be evaluated by the total power of source flow ripple.

From the correlation data, the fluidborne noise

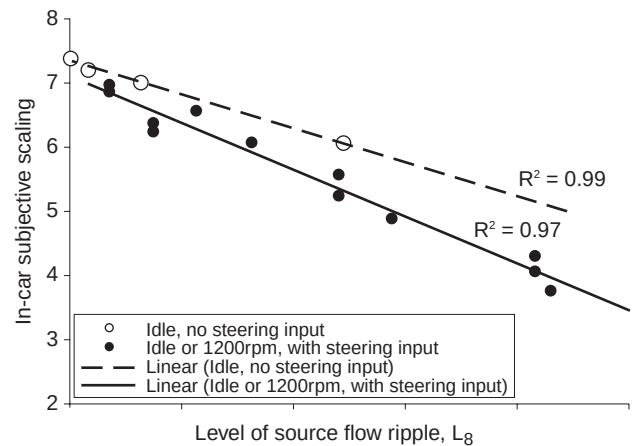


Fig. 9 Correlation of pump unit data and vehicle noise performance

(pressure pulsation) specifications of pump can be specified easily based on the flow ripple level at the cross points of correlation lines and the minimum requirement line of vehicle performance.

6. Application examples

As one application example, the new evaluation system and indicator are used to benchmark Civic-class competitor's pumps. Six pumps on different small-size cars in the North American market are selected for the benchmarking test. (For confidentiality purpose, the manufacturers information are not disclosed here.)

The pumps are tested under two different conditions which duplicate the operation status of interest for power steering noise concerns. Condition 1 is set to replicate the idle engine speed without or with very little steering input, while Condition 2 is set to replicate idle engine speed with continuous steering turning input.

Figure 10(a) shows the source fluidborne noise levels with a cutoff order of 6 under Condition 1, and Fig. 10(b) shows the results under Condition 2. It is revealed that those pumps have quite different source characteristics, and some are good for no or small steering input while

the others are good for continuous steering input. Among them, Pump 5 has the best balance for both conditions.

7. Conclusions

A new system for evaluating fluidborne noise characteristics of automotive power steering pump units has been developed, by using the "3 Pressures/ 2 Systems" method. A single evaluation indicator in terms of the total power of pump's flow ripple harmonic components was proposed for the level of source fluidborne noise of power steering pumps. The value of the indicator can be easily calculated from the harmonic spectral results obtained by the evaluation system. For the first time, the fluidborne noise level of pumps was correlated with the noise performance of power steering systems in an actual vehicle, and a high degree of correlation achieved. From the correlation data, the pulsation specifications of a pump unit can be easily and logically established.

It has been shown that the evaluation system is effective for obtaining objective data and the new, single indicator is valuable for providing objective scaling for the inherent noise characteristics of a power steering pump unit. They can be useful tools for developing quiet power steering pumps and hence quiet power steering systems.

References

- (1) Davidson, L. C.: The Internal Impedance of Positive Displacement Pumps (Experimental Determination and Effect on System Noise), Proceedings of the 32nd National Conference on Fluid Power, p.99-100 (1976)
- (2) O'Neal, D. L., Maroney, G. E.: Measuring Pump Fluid-Borne Noise Generation Potential, The BFPR Journal, Vol.11, p.235-242 (1978)
- (3) Szerlag, S. F.: Rating Pump Fluid-Borne Noise, SAE Technical Paper, 750830 (1975)
- (4) Kojima, E., Nagakura, H.: Characteristics of Fluid-Borne Noise Generated by Fluid Power Pumps, 1st Report, Mechanism of Generation of Pressure Pulsation in Axial Piston Pump, Bulletin of the JSME, Vol.25, p.46-53 (1982)
- (5) Edge, K. A., Wing, T. J.: The Measurement of the Fluid-Borne Pressure Ripple Characteristics of Hydraulic Components, Proc. Instn. Mech. Engrs, Part B, Vol.197, p.247-254 (1983)
- (6) Edge, K. A., Johnston, D. N.: The "Secondary Source" Method for the Measurement of Pump Pressure Ripple Characteristics, Part A: Description of Method, Proc. Instn. Mech. Engrs, Part A, Vol.204, p.33-40 (1990)
- (7) Edge, K. A., Johnston, D. N.: The "Secondary Source" Method for the Measurement of Pump Pressure Ripple Characteristics, Part B: Experimental Results, Proc. Instn. Mech. Engrs, Part A, Vol.204, p.41-46 (1990)
- (8) Hydraulic fluid power - Method for determining pressure ripple levels generated in systems and components - Part

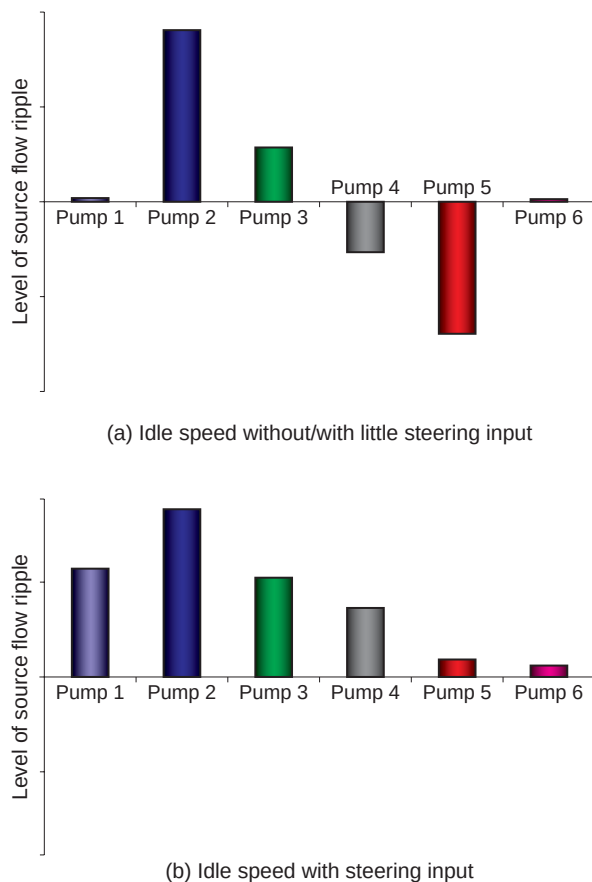


Fig. 10 Benchmarking results of Civic-class competitor's pumps

- 1: Precision method for pumps, ISO10767-1 (1996)
- (9) Kojima, E.: A New Method for the Experimental Determination of Pump Fluid-Borne Noise Characteristics, Proceedings of the 5th Bath International Fluid Power Workshop, Circuit, Component and System Design, p.111-135 (1992)
 - (10) Kojima, E., Yu, J.: Experimental Determining and Theoretical Predicting of Source Flow Ripple Generated by Fluid Power Piston Pumps, SAE Technical Paper, 2000-01-2617 (2000)
 - (11) Yu, J.: Determining Source Fluidborne Noise Characteristics of Automotive Fluid Power Pumps, SAE Technical Paper, 2001-01-1612 (2001)
 - (12) Yu, J., Kojima, E.: Methods for Measuring the Speed of Sound in the Fluid in Fluid Transmission Pipes, SAE Technical Paper, 2000-01-2618 (2000)
 - (13) Johnston, D. N., Edge, K. A.: In-Situ Measurement of the Wavespeed and Bulk Modulus in Hydraulic Lines, Proc. Instn. Mech. Engrs, Part I, Vol.205, p.191-197 (1991)
 - (14) Hydraulic Fluid Power – Determination of the Fluid Borne Noise Characteristics of Components and Systems, Part 1: Measurement of the Speed of Sound in a Fluid, ISO/CD15086-2
 - (15) Kojima, E., Ogura, S., Wan, C., Ando, K.: Reducing the Fluid-Borne Noise of Variable-Displacement Vane Pump for Automotive Hydraulic Power Steering System, Transactions of the Japan Fluid Power System Society, Vol.33, p.124-131 (2002)

■ Author ■



Jinghong Yu



Drew Ritchie

Enhancement of Vibration Analysis Accuracy Using FE Model Applied by Three-dimensional Measurement Technology

Naoki KAMIMURA*

ABSTRACT

The influence of shape differences between the experimental part and the CAD shape, which is thought to be an error factor in the finite element method, was verified. Three-dimensional shape measurement and modeling technologies were applied to power train structural parts that have a complex shape, and a finite element model was created that reproduces the real shape. The shape error between the real shape and the CAD shape of a prototype transmission case was clarified, and the vibration characteristics of a model created from the CAD and a model created from the real shape were compared and verified. The results confirmed that shape error has a noticeable influence, particularly in the high frequency mode shape. These results clearly showed the importance of shape reproducibility in a finite element model, and proved that real shape measurement technology can be used as an accurate modeling tool for the finite element method.

1. Introduction

Recently demands to reduce individual part weights, to enhance the environmental performance of automobiles, have been increasing. On the other hand, conventional structural measures for enhancing vibration and noise performance often involve weight increases, so there are demands for structures that can simultaneously achieve both lighter weight and low vibration and noise.

Vibration analysis that uses the finite element method (FEM) is performed as an effective means of investigating the power train structure. However, the frequency range to be investigated is expanding into the high frequency range, which is making it more challenging to maintain accuracy.

The high frequency range has a complex vibration mode shape, so highly accurate FE models should be created.

Three-dimensional CAD models are becoming more common, and it has become possible to create FE models from three-dimensional CAD shapes. However, when compared with the vibration characteristics (eigen frequency, vibration mode shape, frequency response

function (FRF)) obtained by experiments, the accuracy is sometimes insufficient. Therefore, analysis error factors should be clarified and methods established to enhance accuracy.

The model update method⁽¹⁾ revises the plate thickness, material properties and other factors so that the model matches the experimental results, and has conventionally been used as a method for enhancing vibration analysis accuracy. When using a solid element model the material properties are used as the change parameters. However, this method has various issues, such as that experimental modal analysis is required so analysis takes a long time, and revised material properties are not necessarily physically correct values and may lack general applicability.

The accuracy of vibration analysis for individual power train structural parts is thought to depend on the following three factors.

- (1) Shape
- (2) Material properties (Young's modulus, Poisson's ratio, mass density)
- (3) Element size

Shape error has conventionally been assumed to have

* Automobile R&D Center

an influence, but there were no detailed three-dimensional CAD models for power train structural parts with complex shapes, three-dimensional shape measurement technology was insufficient for parts with complex shapes, and calculation environment limitations made it challenging to execute calculations with FE models that accurately reproduce shapes. For these and other reasons, the influence of shape error has not been sufficiently investigated.

Recent advances in three-dimensional CAD modeling, shape measurement technology, application technology, and calculation capabilities have established the necessary environment for verifying the degree of influence of shape. Examples of use for CAE that applies three-dimensional shape measurement technology have also been reported^{(2),(3)}, but so far there are no reports of verifying the influence of shape differences in vibration analysis.

This paper reports the application of three-dimensional shape measurement and data processing technologies to power train structural parts with complex shapes, and the creation of FE models that reproduce real shapes. This clarified the influence of shape and proved that accurate analysis is possible.

2. Shape Measurement Methods

2.1. X-ray CT Scanner

Given recent advances in three-dimensional shape measurement technology, optical scanners and X-ray CT scanners are becoming widely used as means of verifying CAD models.

X-ray CT scanners are particularly advantageous in that they allow non-destructive measurement of parts with hollow or internal structures. This makes them suitable for evaluating the shape of power train structural parts with complex shapes.

Fast and accurate CT scanners that use high energy X-rays with high transmissive performance have also been developed, and there are reports of use even for large parts such as cylinder blocks^{(2) - (4)}.

In order to use the CT image information of evaluation subject parts for shape evaluation, equal pixel value surfaces that serve as component boundaries are extracted from layered three-dimensional images to create a polygon model⁽⁵⁾. This processing provides the same data structure as that from an optical scanner.

2.2. Equipment Used and Scanning Conditions

Table 1 shows the X-ray CT scanner used and the scanning conditions.

2.3. Shape Measurement Accuracy

Figure 1 shows the artifact used for verification. Verification was performed using a polygon model created from a three-dimensional CT image obtained under the

Table 1 Equipment and conditions for CT scanning

X-ray CT scanner	HITACHI HiXCT-1M
Energy of X-ray	0.95 MeV
Permeation	Aluminum 330 mm
Scanning mode	Rotate-rotate mode
Slice thickness	1.0 mm
Slice pitch	0.5 mm
Image size	1500 x 1500
Pixel size	0.4 x 0.4 mm

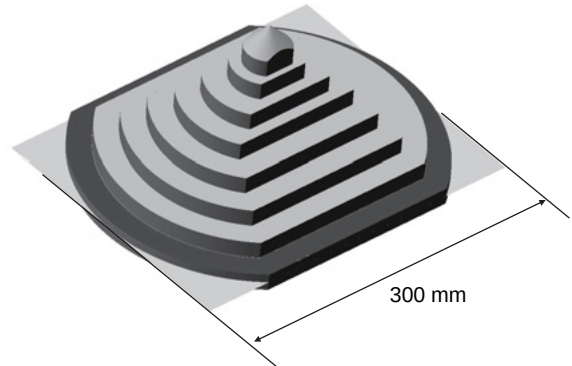


Fig. 1 Artifact used for verification

conditions in Table 1, and the results showed an accuracy of approximately ± 0.15 mm for general surfaces. This level of accuracy enables use for evaluation of the non-machined area shapes of cast parts.

3. FE Modeling Method

Polygon models created from CT images are comprised of millions to tens of millions of minute surfaces. Therefore, directly creating solid elements inside the model results in a number of degrees of freedom, and is unrealistic given current processing environments.

FE modeling methods that allow calculations can be broadly classified into two methods.

3.1. FE Modeling Method via CAD Surface

This method creates an approximate free curve surface based on a polygon model, and then uses this as the CAD surface to create a FE model using an ordinary mesh generator.

Various design application software is also available on the market as technology for creating CAD surfaces, but these have the issue that it is difficult and time consuming to generate the feature lines needed for FE modeling. However, recently, there have also been reports of research on technology for creating surface models with feature lines⁽⁶⁾.

3.2. FE Modeling Method by Mesh Reduction

This method reduces the number of meshes of the polygon model to a mesh number that can be applied to FEM.

This method also has a number of issues. For example, clear edges cannot be created in polygon models generated from X-ray CT scanner images; image noise often causes minute unevenness, which makes it unlikely to sufficiently express shape features when the number of meshes is reduced; the element quality is low, and the like. A mesh generation system (MRR mesh generator) that uses multi resolution representation (MRR) has been reported as one technology for addressing these issues⁽⁷⁾.

This method extracts the surfaces, ridgelines, and other feature information in the large-scale polygon model stage where there is little shape error, and provides this information as attribute information in order to maintain a shape accuracy close to the large-scale polygon model. At the same time, the element quality is enhanced to create the FE model.

3.3. Selection of FE Modeling Method

CAD surfaces are useful in that they can be used for various applications, but in terms of reproducibility during FE modeling, they are thought to be same as the MRR mesh generator. Therefore, this study tried the MRR mesh generator, which is expected to be better in terms of modeling process time.

4. Shape Measurement Results

4.1. Subject Part

A sand mold cast transmission case in the prototype stage was selected as a part that experience has shown is often challenging to create an accurate FE model from the CAD shape.

Figure 2 shows the CAD shape, Fig. 3 shows the three-dimensional rendition of 455 CT images obtained under the above-mentioned conditions, and Fig. 4 shows the polygon model created from the CT images.

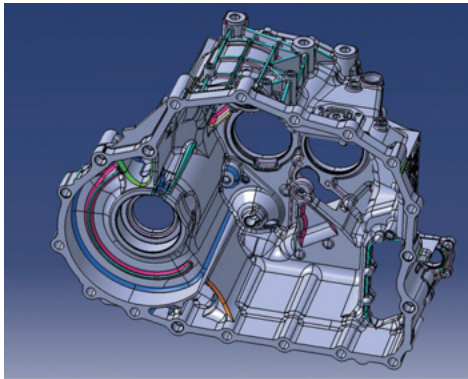


Fig. 2 3D-CAD model of subject part

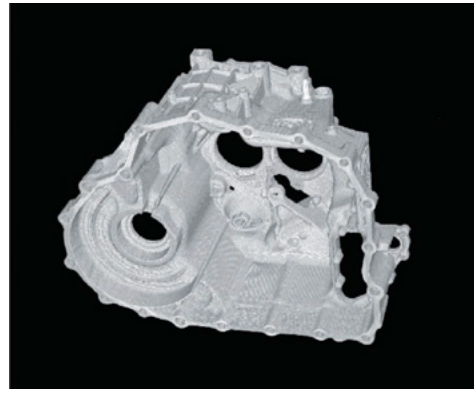


Fig. 3 3D-CT image

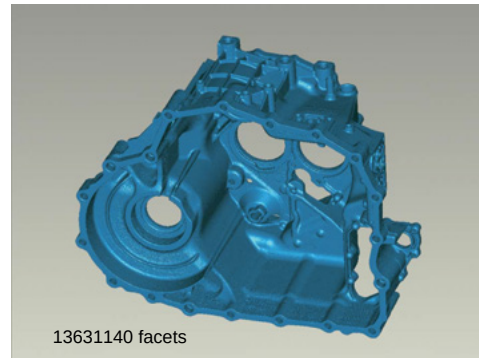
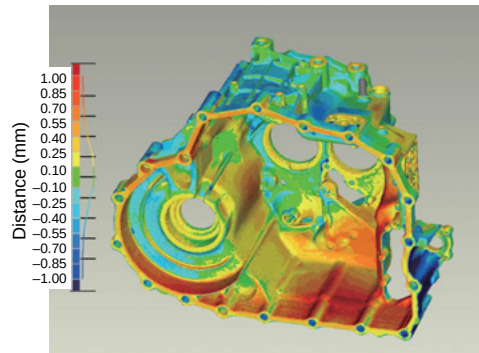
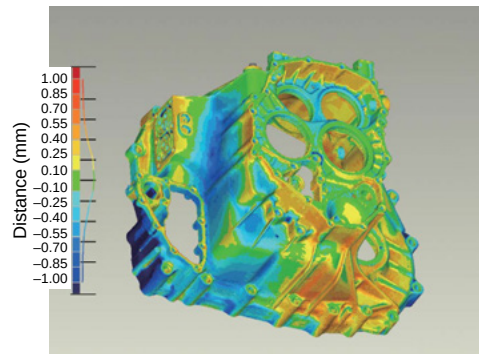


Fig. 4 Polygon model made from CT image

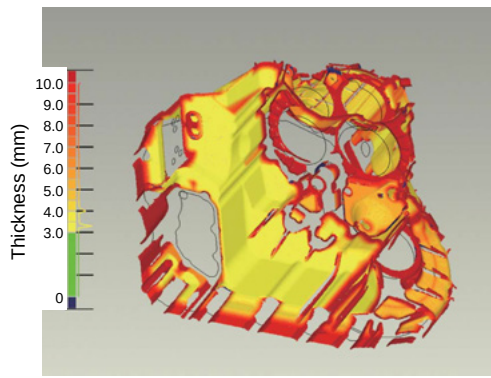


(a) View A

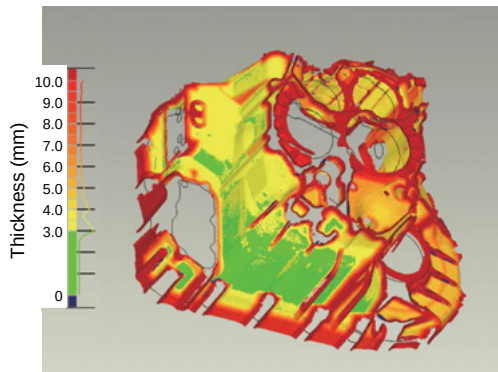


(b) View B

Fig. 5 Difference between CAD and polygon model



(a) CAD model



(b) Polygon model

Fig. 6 Wall thickness

4.2. CAD Shape Verification Results

Figure 5 shows the shape differences between the polygon model and the CAD shape. The difference is defined as positive (+) when the CAD surface is outside, and negative (-) when inside the polygon model surface.

In addition, Fig. 6 shows the results of evaluating the wall thickness as the distance from the inner surface to the outer surface of the transmission case.

These results show that there is strain overall, and that the bottom and side surfaces are approximately 0.5 mm thinner compared to the CAD shape.

5. FE Models

5.1. FE Model Based on CT Scanning (CT base model)

The large-scale polygon model (13 631 140 facets) created from the CT images posed an issue for the calculation capacity of the MRR mesh generator, so a polygon model with reduction processing performed (1 466 387 facets) was used.

Figure 7 shows the created FE model. This model is comprised of 2nd order tetrahedral elements.

Figure 8 shows the shape differences between the FE model and the polygon model. The difference is defined as positive (+) when the FE model surface is outside, and negative (-) when inside the polygon model surface. Some difference was seen in the fillet areas due to the influence

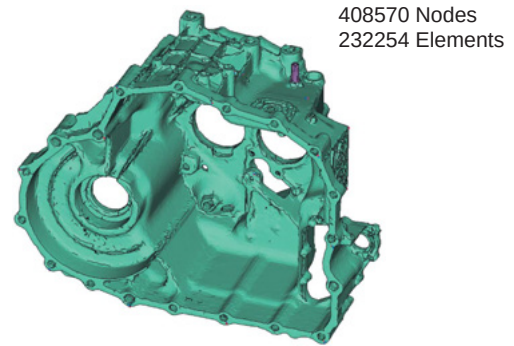


Fig. 7 FE model based on CT scanning

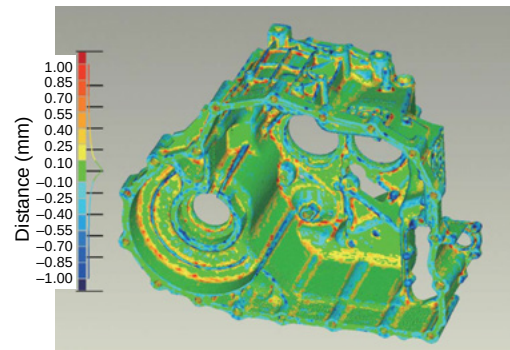


Fig. 8 Difference between FE model and polygon model



Fig. 9 FE model based on CAD

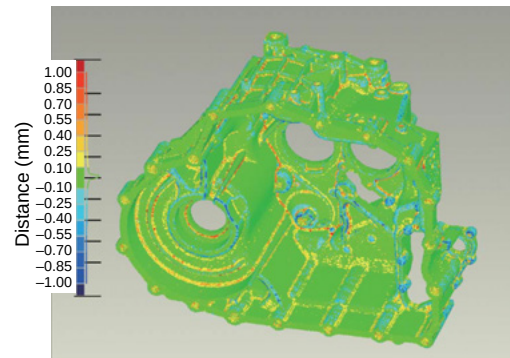


Fig. 10 Difference between FE model and CAD

Table 2 Material properties

Young's modulus	7.2e10 Pa
Poisson's ratio	0.33
Mass density	2.74e3 kg/m ³

Table 3 Comparison of mass

	Mass (kg)	Error ratio (%)
Measurement	8.24	–
CT base model	8.32	+0.96
CAD base model	8.43	+2.20

of the set element length, but it was confirmed that overall the shape is maintained well. Therefore, it is thought that this FE model can be used to evaluate the influence of differences between the CAD shapes shown in Figs. 5 and 6 and the real object.

The time needed for FE modeling in this case was approximately 3 hours using an ordinary PC (32-bit Windows XP, 2.5 GHz, 2 GB memory, single CPU processing), which confirmed that a practical process time can be achieved. The work time for the series of operations from CT scanning was approximately 3 days.

5.2. FE Model Based on CAD (CAD base model)

Figure 9 shows the FE model comprised of 2nd order tetrahedral elements that was created from the CAD shape as a comparison subject. Shape reproducibility was provided by setting a shorter element length, so the model scale is larger.

Figure 10 shows the shape differences between the FE model and the CAD shape. The difference is defined as positive (+) when the FE model surface is outside, and negative (-) when inside the CAD surface. These results show that this model has high CAD shape reproducibility.

5.3. Material Properties

To help eliminate error due to the material properties, the material properties were measured using a test piece cut from a part in the same lot as the subject part.

The Young's modulus and Poisson's ratio were obtained using the resonance method⁽⁸⁾, and the mass density was obtained using the Archimedes method. Table 2 shows the material properties.

5.4. Comparison of FE Model Mass (Comparison with Actual Measured Value)

Table 3 shows the results of comparing shape differences using the real shape model mass.

These results show that shape differences between the FE models and the real object appear as mass differences, and that there is 2.2% error even when the CAD shape is accurately reproduced. In contrast, the error for the CT base model is within 1%.

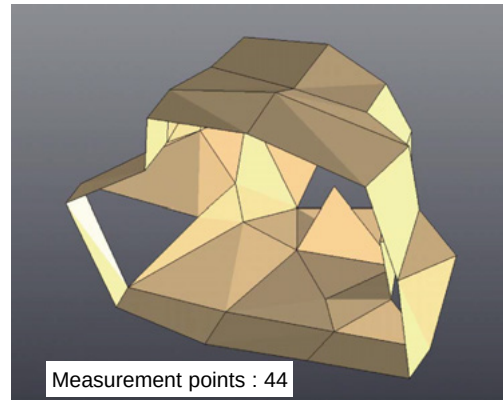


Fig. 11 Measurement points for EMA

6. Experimental Verification Method

This study performed verification by comparing experimental modal analysis (EMA) with FEM eigenvalue analysis and frequency response analysis.

Experimental analysis is used to verify the high frequency range, so high accuracy is also demanded.

The hammering excitation method was used as the excitation method, due to the high subject frequencies, and in order to help eliminate the influence of the excitation machine support. In addition, experimental error was minimized by adding weights with the same mass as the sensors to the measurement points, and by switching around the sensors and weights for each measurement in order to reduce the influence of changes in the sensor mass distribution when FRF measurements are divided into multiple times, etc.

The measurement points shown in Fig. 11 were selected to enable expression of high-order, complex vibration mode shapes.

The model was made equivalent to the FE model by reflecting the sensor mass as added mass.

7. FEM Accuracy Verification Results

7.1. FEM Vibration Analysis

The FEM solver used MSC/NASTRAN 2005 eigenvalue analysis (SOL 103) and frequency response analysis (SOL 111).

7.2. Comparison of Eigen Frequencies

The frequencies subject to comparison were up to 2.5 kHz (24th order mode) from the viewpoint of experiment reliability.

Figure 12 compares the eigen frequency for each mode, and Fig. 13 shows the eigen frequency error ratio compared to EMA.

Table 4 shows the average error ratio and maximum error ratio compared to EMA. Here, the average value of

Table 4 Eigen frequency error ratio

	Average error ratio (%)	Maximum error ratio (%)
CT base model	0.36	-1.67
CAD base model	1.55	-5.52

the absolute error ratio values was used as the average error ratio.

Experimental comparison of eigen frequencies showed that the CT base model had an average error ratio of 0.36% and maximum error ratio of -1.67%, indicating that this is an accurate simulation.

On the other hand, the CAD base model had larger error than the CT base model, with an average error ratio of 1.55% and maximum error ratio of -5.52%.

7.3. Comparison of Vibration Mode Shape Correlation

The EMA and FEM vibration mode shapes were compared and evaluated using mode assurance criterion (MAC)⁽⁹⁾. Figure 14 shows the results.

When using the CT base model shown in Fig. 14(a), a high correlation could be obtained up to the high order vibration mode shapes. In contrast, when using the CAD base model shown in Fig. 14(b), the correlation drops

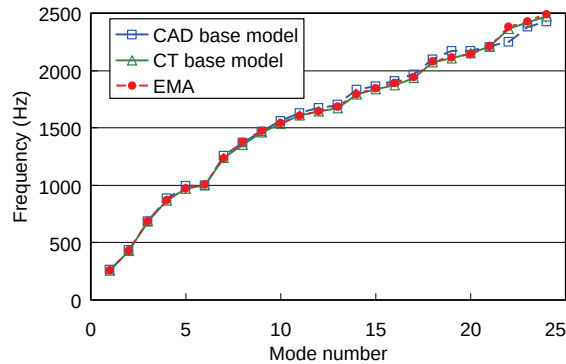


Fig. 12 Eigen frequency to mode number

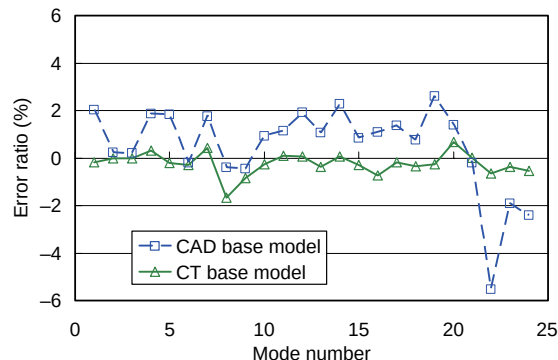


Fig. 13 Error ratio to mode number

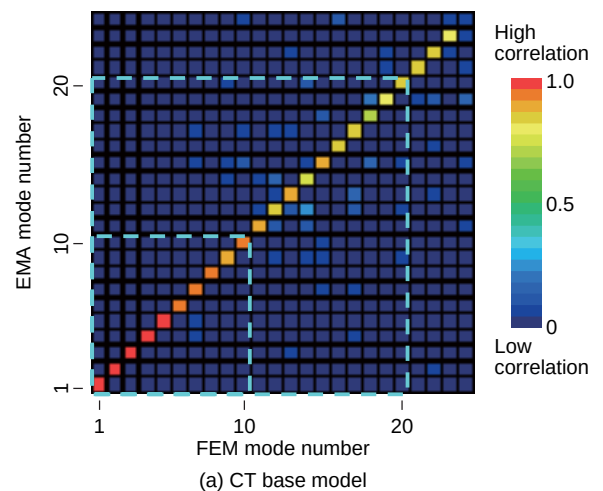
even for relatively low order vibration mode shapes such as those of 5th and 6th order, and the correlation is low for 12th order and higher order vibration mode shapes.

7.4. Comparison of Element Strain Energy

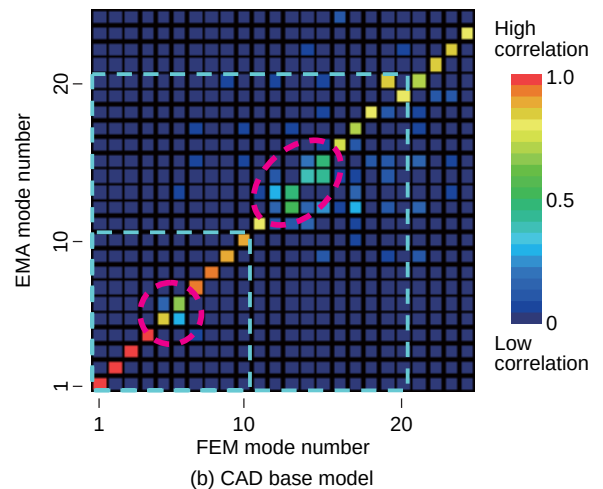
Figure 15 shows the results obtained by FEM eigenvalue analysis of both the CT base model and the CAD base model for the 6th order vibration mode shape, which shows a difference in the FEM and EMA vibration mode shape correlation. The color scale indicates the element strain energy.

Based on the correlation height obtained by MAC, the element strain energy distribution of the CT base model is thought to accurately express the status in an actual part.

The vibration mode shape for the CT base model exhibits large deformation in the upper part of the openings. In contrast, the vibration mode shape for the CAD base model differs in that it also exhibits large deformation in the lower part of the openings, and has



(a) CT base model



(b) CAD base model

Fig. 14 Comparison of MAC

areas with high element strain energy in both the upper and lower parts of the openings. This is thought to be caused by a difference of approximately 0.5 mm in the bottom and side wall thickness as shown in Fig. 6.

Measures for vibration issues generally consist of investigating countermeasure structures by considering the vibration mode shape for the frequency in question and the element strain energy which represents the rigidity sensitivity. These results indicate the possibility of investigating different measures for different vibration mode shapes.

7.5. Comparison of Frequency Response Function (FRF)

The average value of the modal damping ratio obtained from the experimental modal analysis results was applied to FEM, and the FRF was calculated.

Figure 16 compares the FRF of both models with the experimental results. The CT base model obtained accurate results for both peak frequency and response level up to 2.5 kHz. In contrast, the CAD base model exhibited increased FRF error at a frequency of 2 kHz or higher due to the influence of eigen frequency error as described in section 7.2 and vibration mode shape differences as described in section 7.3.

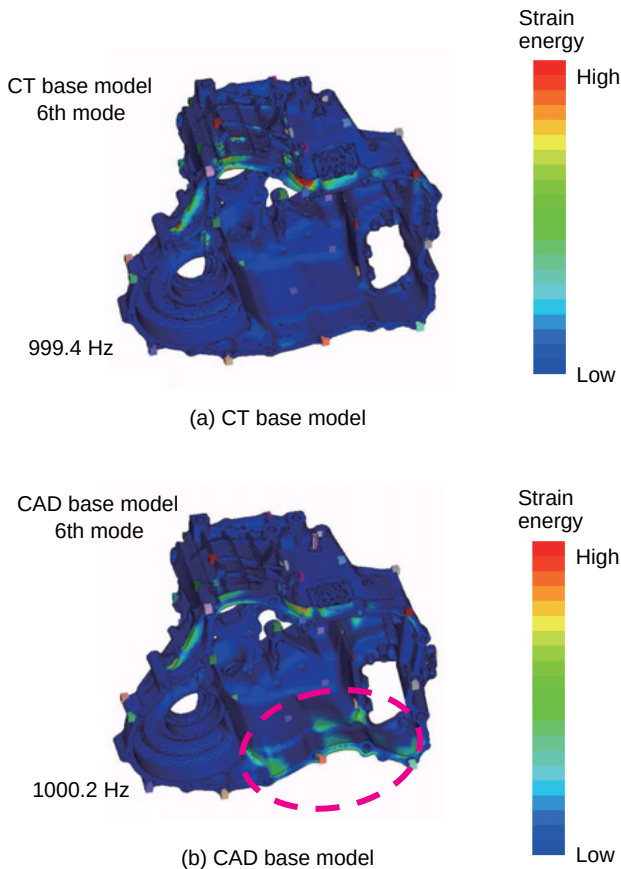
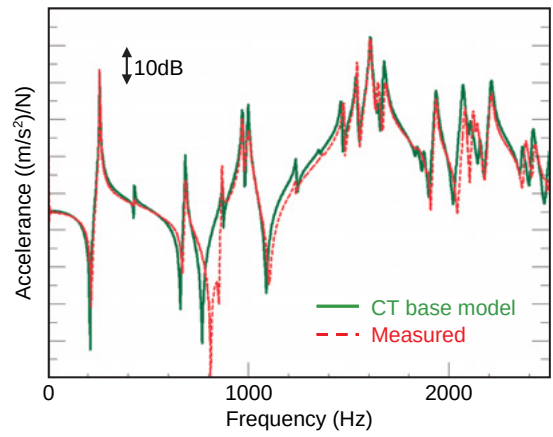
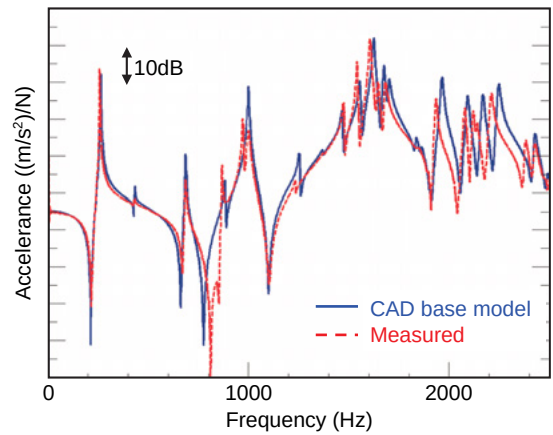


Fig. 15 Strain energy of 6th mode



(a) CT base model



(b) CAD base model

Fig. 16 Comparison of FRF

8. Conclusion

Three-dimensional shape measurement and modeling technologies were applied to power train structural parts that have a complex shape as a means of enhancing vibration analysis accuracy. The results verified the efficiency of the method for creating a FE model that reproduces the real shape.

- (1) It was clearly shown that using a model that reproduces the real shape allows accurate FEM vibration analysis up to the high frequency range.
- (2) The influence of shape differences, which is an error factor for FE models of complex-shaped parts that could not be clearly evaluated thus far, was clarified.
- (3) FE modeling can be performed using only physical measurement data, which proved that this is a widely applicable method for enhancing accuracy.

References

- (1) Sakai, T., Terada, M., Ono, S., Kamimura, N.:

- Development of Procedure for Interior Noise Estimation by Virtual Vehicle Analysis, Honda R&D Technical Review, Vol. 13, No. 2, p. 195-204
- (2) Miyake, T., Murata, M., Yoshida, T., Shimoyama, H., Fujii, H., Yamashita, K.: Introduction of X-Ray CT Scanner and Application Examples, Mazda Technical Review, No. 22, p. 167-172 (2004)
 - (3) Sadaoka, N.: Xsenn CT wo katsuyousita Degital Engineering, 2004 Japanese Society for Precision Engineering Annual Congress, Symposium Proceedings, p. 69-76(2004) (in Japanese)
 - (4) Okada, T., Miwata, Y., Ishii, H.: Three-Dimensional Shape Measurement with X-Ray CT-Scan, SAE Paper, 2003-01-1033, p. 1-5 (2003)
 - (5) Lorensen, W., Cline, H.: Marching Cubes : A High Resolution 3D Surface Construction Algorithm, ACM SIGGRAPH 1987 Proceedings of the 14th annual conference on Computer graphics and interactive techniques, p. 163-169 (1987)
 - (6) Matsuzaki, K., Suzuki, H., Soma, A., Sadaoka, N.: Research into fully automatic generation of CAD models from measured_data(First Report), 2007 JSAE Annual Congress Proceedings, No. 122-07, p. 9-12 (2007)
 - (7) Date, H., Kanai, S., Kishinami, T., Nishigaki, I., Dohi, T.: High Quality and Property Controlled Finite Element Mesh Generation from Triangular Meshes Using Multiresolution Technique, ASME Journal of Computing and Information Science in Engineering, Vol. 5, Issue 4, p. 266-276 (2005)
 - (8) Japan Society of Mechanical Engineering: Danseikeisuu no Sokuteihou, The Modulus of Elasticity of Metals and Alloys, Japan Society of Mechanical Engineering, p. 7(1980) (in Japanese)
 - (9) Yoshimura, T.: Modal assurance criterion, Modal Analysis Handbook, Corona Publishing Co., Ltd, p. 128 (2000)

■ Author ■



Naoki KAMIMURA

Modelling Carpet for Use in Occupant Crash Simulations

Dylan Thomas*

ABSTRACT

Predictions of occupant injury using explicit finite element crash simulations may be enhanced by including numerical representation of materials that are not normally included within the structural model. Intuitively, it makes sense that the carpet would be useful to predict the tibia index during frontal crash events; however, there appears to be little published on the topic. The tibia index is an injury criteria that needs to be predicted during the Insurance Institute for Highway Safety (IIHS) frontal offset occupant simulations, but may also be looked at during unbelted Federal Motor Vehicle Safety Standard (FMVSS) 208 simulations. Since carpet behaves quite differently during compressive and tensile loading, a numerical representation that can stably capture both regimes during occupant modelling is needed.

This paper outlines a method to model the carpet using a specific meshing method and two material models. Shell elements in combination with a piecewise linear plasticity material model are used to model the tensile load carrying capacity of the carpet, while brick elements and a foam material model are used to represent the compressibility of the carpet. Validation of using this modelling method with test data is presented, as well as the application of the carpet model in larger occupant models.

1. Introduction

Frontal occupant simulations typically require a wide variety of materials to be defined when creating a finite element model of the vehicle interior. The carpet supports the occupant's heels at the beginning of the event and may absorb crash energy if sufficient backing material is present. Since the carpet supports the feet during the beginning of the simulation, its presence in the finite element model can affect the kinematics of the occupant's legs, which ultimately determines the loads they can experience during a crash event.

Previous occupant models did not have a representation of the carpet. In these models the occupant's feet were left to interact directly with the sheet metal of the vehicle floor. Based on previous development experience it was felt that the simulation models could be improved if a representation of the carpet could be included within the occupant simulation models.

This work highlights the steps taken to include a representation of the carpet within a finite element crash model. Samples of carpet were physically tested by cyclically loading both in tension and compression. Shell

elements are used in combination with a piecewise linear plasticity material model to represent the majority of the tensile load carrying capacity of the carpet. Brick elements combined with a foam material model are used to represent the compressibility of the carpet.

2. Material testing

Physical tests were undertaken on the carpet material using a 25 kN Instron 5866 testing machine. For the purposes of this work, the tensile loading direction is defined as being in the plane of the carpet as shown in Fig. 1. The compressive loading direction is defined as being normal to the plane of the carpet, which is also shown in Fig. 1.

To gain an understanding of the tensile loading and unloading characteristics of the carpet, one sample was loaded monotonically in tension to failure, while five samples of the carpet were cyclically loaded and unloaded in tension. Figure 2 shows a sampling of these tensile loading tests. During these cyclic loading tests, each specimen was loaded to 5 percent engineering strain, then unloaded and loaded 5 times to generate the first

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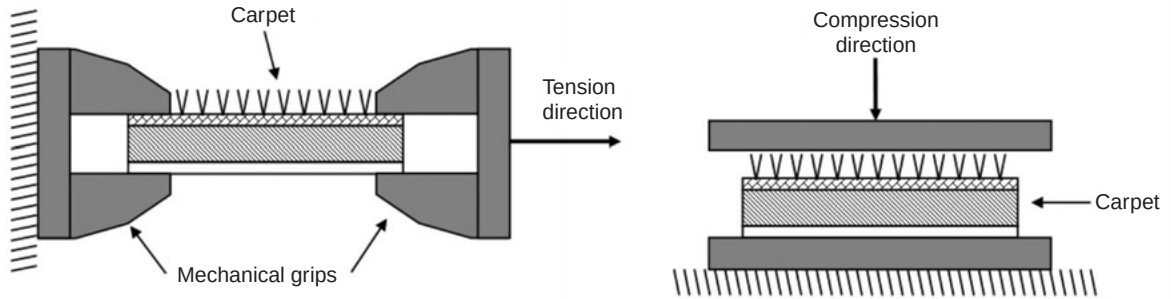


Fig. 1 Tensile and compressive loading directions that were adopted for this work.

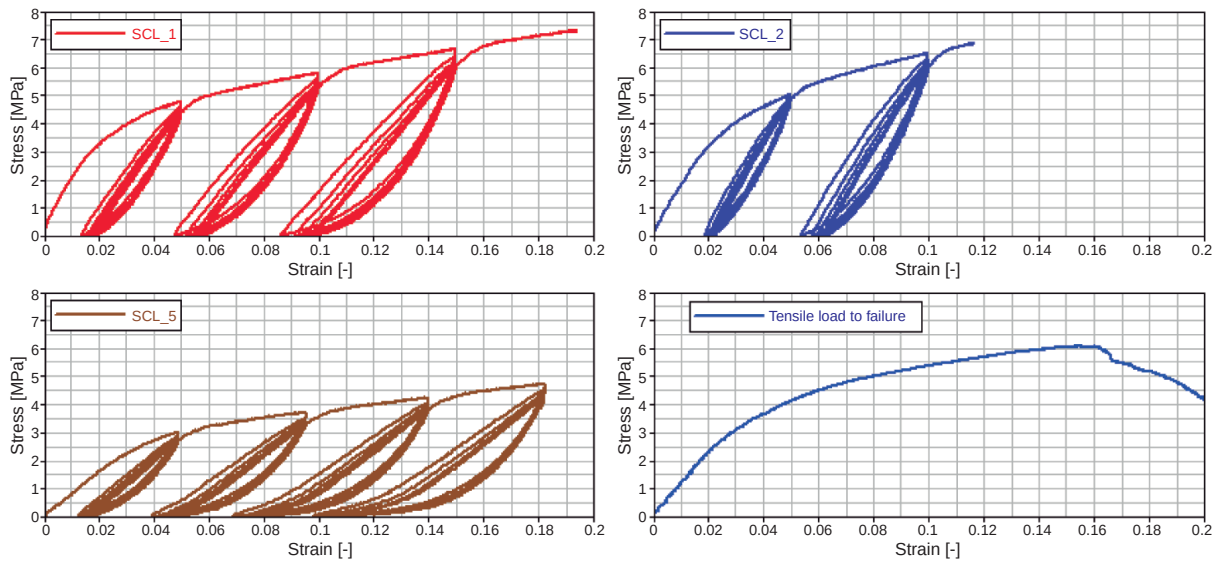


Fig. 2 Tensile loading and unloading test data

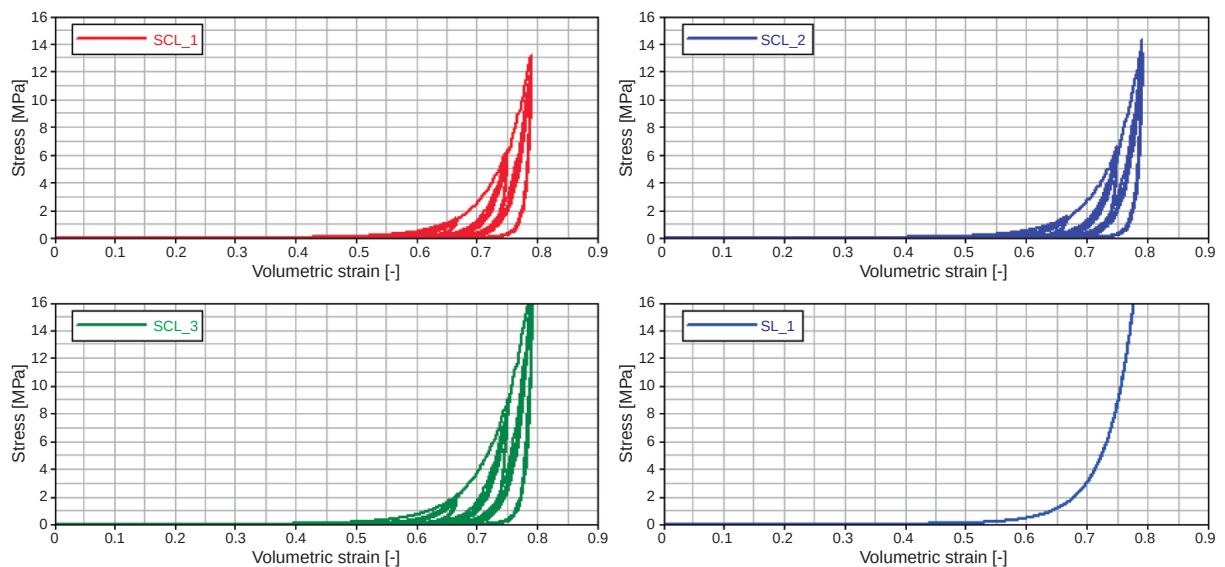


Fig. 3 Compressive loading and unloading test data

hysteresis loop shown in Fig. 2. Tensile loading then continued to 10% engineering strain, and 5 loading / unloading cycles were repeated. This sequence was continued at 5% increments in strain until the specimen broke.

The compressive tests were performed in a similar manner as shown in Fig. 3. One sample was loaded monotonically in compression until the limit of the machine was reached. Three samples were loaded cyclically in compression to generate both compressive loading and unloading curves. During these cyclic compression tests, the carpet was compressed to increasing compressive strains of 50%, 66%, 75% and 79%. For each strain level, five load and unload cycles were performed before proceeding to the next strain level.

Figures 2 and 3 highlight the difference in tensile and compressive loading behaviour of the carpet. Figure 2 shows that there are fairly large variations in the carpet tensile strength and failure strain as each of the four samples were cut from the same piece of carpet. The variability of compressive strength is less noticeable, but still present, as shown in Fig. 3.

3. Finite Element Material Model Creation

From analysis of Figs. 2 and 3, one can see that the carpet behaves quite differently during tensile and compressive loading. During a frontal crash event, the carpet can be both in tension, and compression. For example, inertial loads placed on the carpet creates tension that must be reacted internally (by the carpet), towards the attachment points of the carpet to the vehicle. In other regions, such as underneath the feet of the occupants, the carpet can be compressed during the crash event.

In order to match this behaviour a unique approach was created that allows both the tensile and compressive behaviour of the carpet to be modelled. Figure 4 shows a cross section of a typical carpet construction used in vehicles. From inspection of the carpet samples it was

felt that the majority of tensile strength came from the outer layers, while the majority of compressive compliance came from the pile and middle layer. The pile layer is comprised of upstanding yarn fibres and a woven backing. The woven backing is strong in tension, while the upstanding yarn fibres are weak both in the compression and tension directions. The height of these fibres do, however contribute to the overall thickness dimension of the carpet.

For the current work, it was assumed that the contribution of the upstanding yarn portion of the pile layer was negligible. This necessitated that the thickness of the carpet used in the models to be adjusted to not include the upstanding yarn portion, but allows the carpet to be modelled using a simple, three ply construction. When constructed this way, the outer layers provide the majority of the tensile stiffness and the middle layer provides the compressive compliance.

In this manner, the behaviour of the carpet could be matched during different loading regimes. The tensile behaviour of the carpet shown in Fig. 2 appears to yield, but carries an increasing amount of load prior to failure. This material flow behaviour is similar to metals, which are represented in many of the commercially available finite element solvers using linear plasticity material models. For the current work, LS-DYNA⁽¹⁾ was used as the general finite element solver, so the *MAT_PIECEWISE_LINEAR_PLASTICITY⁽²⁾ material model was chosen to represent the outer layers. The compressive loading behaviour of the carpet looked similar to that of typical foams, so the LS-DYNA *MAT_FU_CHANG_FOAM⁽³⁾ material model was chosen to represent the middle layer. Similar material models are available for use in the other commercially available finite element solvers.

Figure 5 shows the manner in which the carpet should be meshed for this method to work. For the carpet that was tested, 2 mm thick shell elements were used for the top and bottom layers, while a 10 mm thick layer of brick

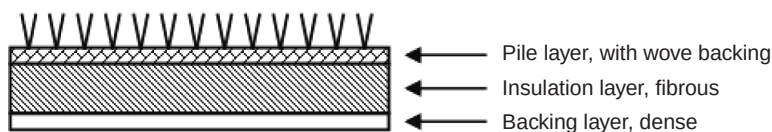


Fig. 4 Construction of typical automotive carpet

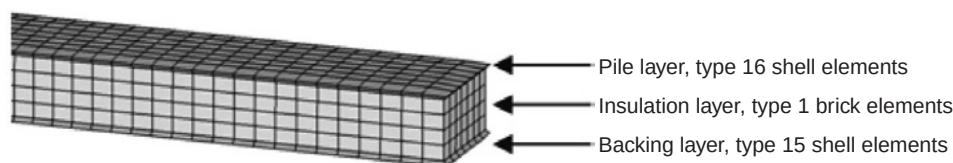


Fig. 5 Finite element meshing method chosen for the Carpet

elements are used for the middle. For clarity, in Fig. 5 the shells are shown with the LS-PRE/POST⁽⁴⁾ thickness option, so they appear as brick elements.

The data from each cyclic tensile test was post processed using linear regression to find average Young's modulus values for the initial loading and each hysteresis loop portion of the test. An average Tangent modulus was also calculated from the appropriate post-yield portion of the data. Figure 6 shows these moduli for the first cyclic tensile test. In Fig. 6, E0 represents Young's modulus, E1, E2 and E3 represent the average loading and unloading modulus for the first, second and third hysteresis loops, and ETan represents the tangent modulus.

The averaged Young's and Tangent modulus values were used to create a simple *MAT_PIECEWISE_LINEAR_PLASTICITY LS-DYNA material model which matched the average tensile strength of the carpet. This material model is prescribed to the two outer shell layers of the carpet shown in Fig. 5.

The compressive test data shown in Fig. 3 looked similar to foam materials, consequently the test data was post-processed to create a *MAT_FU_CHANG_FOAM

material model. In LS-DYNA, this material model has the capability to model rate - sensitive loading and unloading, but since rate sensitivity was not tested, just one loading and one unloading curve was used. The monotonic loading curve was calculated for each compression test by taking the cyclic compressive test data and removing the unloading and intermediate reloading portions. These resulting monotonic loading curves were then averaged and smoothed to create a single monotonically increasing loading curve that represented the compression characteristics of the carpet. The same procedure was used to create an averaged unloading curve, but the loading portions, and intermediate unloading portions were removed. The resulting averaged test loading and unloading curves are shown in Fig. 7 with a very small stress scale on the ordinate axis.

During testing, a 25 kN load cell was used to obtain accurate load measurements during the initial compression of the carpet, which limits the amount of force that can be applied. For our compression test specimen size, the corresponding stress levels were less than 20 MPa. During occupant simulations, the carpet can be in contact

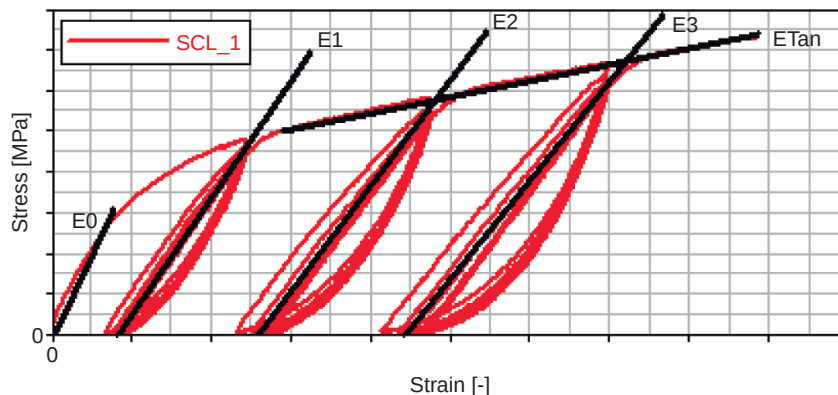


Fig. 6 Average elastic moduli that were calculated for each portion of the cyclic tensile test data

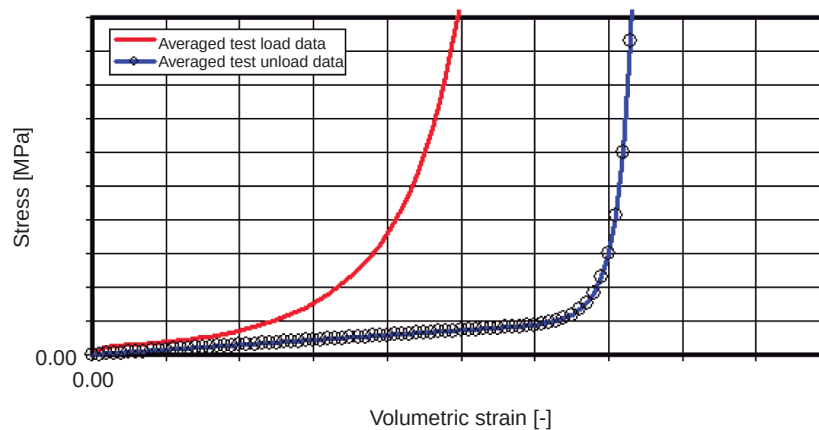


Fig. 7 Averaged and smoothed loading and unloading curves from compression test data primarily representing deformation of upstanding yarn position

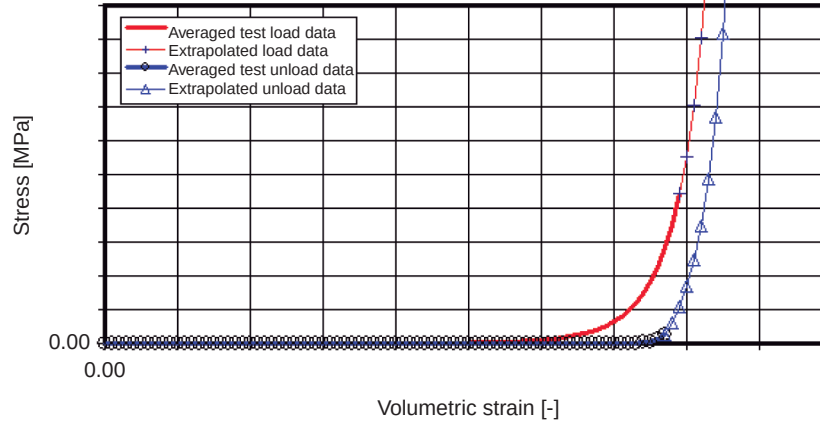


Fig. 8 Averaged, smoothed and extrapolated compression test data showing loading and unloading curves at intermediate stress levels

with other materials that have much higher yield strengths, and localized compressive stresses may become quite large. Thus, for numerical stability the curves should be extrapolated to create a more robust material model. Both the loading and unloading curves were extrapolated to 99% volumetric strain using a Hyperbolic function to smoothly extend the data. This technique, suggested by Du Bois⁽⁵⁾ relates the rate of change of yield strength with respect to strain:

$$\left. \frac{\partial \sigma}{\partial \varepsilon} \right|_i = \left(\left. \frac{\partial \sigma}{\partial \varepsilon} \right|_{\varepsilon_0} \right) \left(\frac{1.0 - \varepsilon_0}{1.0 - \varepsilon_i} \right)^n \quad (1)$$

where ε_0 is the strain value from which the extrapolation starts. The exponent n should be calculated from the test data for strain points just below ε_0 to get an idea of what the value should be. The extrapolated yield strength values are given by:

$$\sigma_{i+1} = \sigma_i + \left. \frac{\partial \sigma}{\partial \varepsilon} \right|_i \Delta \varepsilon \quad (2)$$

Using this method, extrapolated compressive load and unload curves for the material model were calculated, as shown in Fig. 8, along with the original test data shown in Fig. 7. Note that averaged test load and unload curves in Fig. 8 are the same as in Fig. 7, however the scale on the ordinate axis in Fig. 8 is 500 times larger, which allows us to present both the measured and extrapolated data. This material model is prescribed for the inner brick layer of the carpet shown in Fig. 5. It should be mentioned that the *MAT_FU_CHANG_FOAM material model also requires an Elastic modulus to be prescribed in the case of tensile loading. For the current study, a value of 5.0 MPa was used. This value was chosen by running several of the simulation models described in the next section to determine the minimum value that was numerically stable. Unfortunately, this value also

introduces error when the carpet is pulled in the tensile direction, however since the carpet does not yield during occupant simulations, the level of error was deemed acceptable. Nonetheless, it was decided to apply a correction factor to the tangent modulus that was calculated in the previous section for the tensile direction, which mitigated the error.

4. Finite Element Material Model Validation

A simple LS-DYNA simulation model was created that tested the resulting material models in both tension and compression. Figure 9 shows the simulation model. As described earlier, the meshes of both the tensile and compressive sample are created by extruding brick elements between two shell meshes. The shell meshes have a thickness of 2 mm and the thickness of the bricks is 10 mm. Prescribed motion is used to pull the tensile sample in the same manner as the cyclic tensile tests, although only one unload and re-load cycle was performed

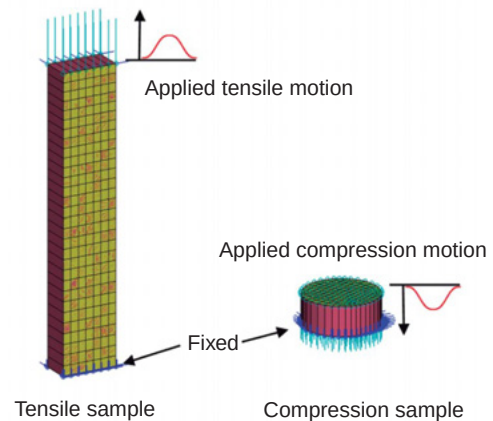


Fig. 9 Finite element simulation validation models

at 5%, 10%, 15% and 20% engineering strain. The compression sample is also simulated in the same manner as the compression tests, with prescribed motion compressing and then unloading the sample to the increasing compressive strain levels of 50%, 66%, 75% and 79%. As with the tensile simulations, only one load and unload cycle was performed at each compressive strain level.

Figure 10 shows the behaviour of the combined carpet model for the tensile sample. The simulation results are shown as a dotted line, while the test results are shown as a solid red line. From Fig. 10, it can be said that the simulation model is capturing the loading and unloading characteristics of the carpet when pulled in tension.

Figure 11 shows the behaviour of the carpet model for the compressive loading and unloading cycles, along with one of the cyclic compressive tests previously shown in Fig. 2. The test curve is shown in green and while the simulation is shown as black points. From Fig. 11, it can be said that the general loading and unloading characteristics of the carpet has been matched in compression.

5. Application in Occupant Crash Models

For a model of the carpet to be included within the occupant crash models, several steps should be taken. The carpet should be meshed as described previously, with a layer of shell elements sandwiching one or more layers of brick elements. Contact of the occupant with the carpet should be allowed to initialize prior to the crash event. This can be performed by allowing the dummy to settle under gravity, or by prescribed motion of the occupant to its equilibrium or initial position. Figure 12 shows an example of the carpet in an unbelted occupant simulation model. This simulation model represents the unbelted 40 km/hour United States Government crash test specified in the Code of Federal Regulations⁽⁶⁾. Also shown in this model is the floor mat which lies on top of the carpet. In these models, the floor mat was modelled in the exact same manner, using the same properties as the carpet. This simulation model was run twice, once with the carpet and floor mat and once without to show the importance of simulating the carpet when predicting lower leg injury. This study focused on improving the lower left Tibia

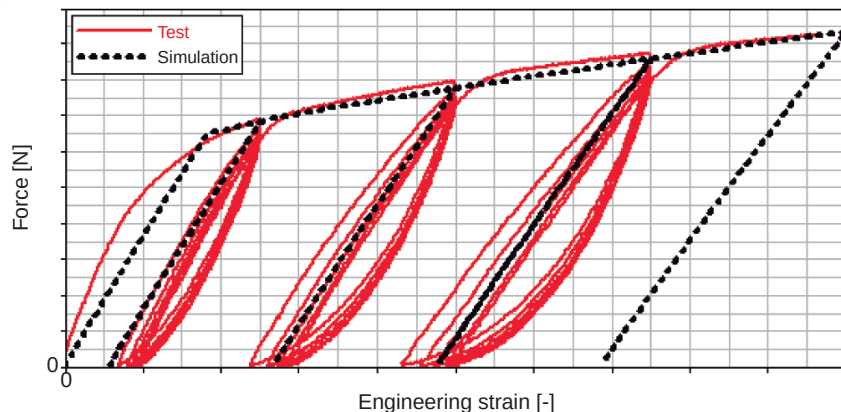


Fig. 10 Comparison of finite element simulation to one of the tests during tensile loading and unloading

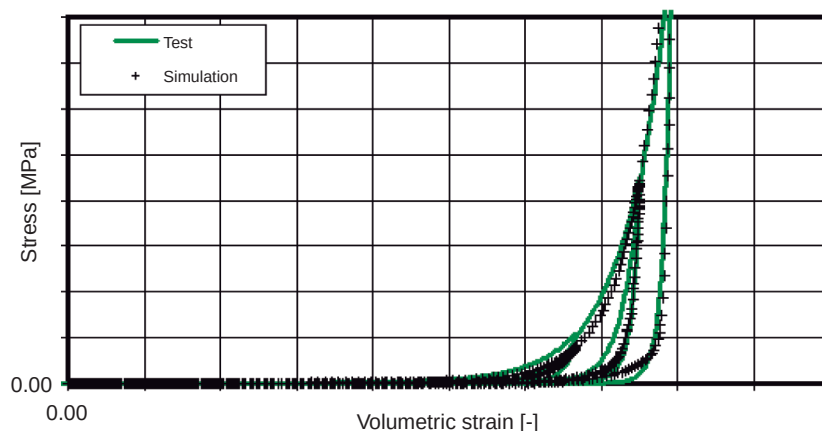


Fig. 11 Comparison of finite element simulation to test data during compressive loading

Index predictions within the finite element models. A future study will focus on improving the lower right Tibia Index, which has additional influences such as the accelerator pedal.

Figure 13 shows the lower left Tibia Index of the occupant for these two simulations compared to test data. The Tibia Index is a function of the axial load and resultant bending moments that the lower leg experiences during a crash test. From Fig. 13, one can see that the Tibia Index prediction from the simulation model with the carpet and floor mat was considerably closer to the actual test than the simulation model without the carpet. Figure 14 shows the left foot and tibia of dummy at key points during the simulations, both with and without the carpet. The key points labelled in Fig. 13 correspond to the

pictures in Fig. 14.

Analysis of the occupant models showed that the simulation model without the carpet predicted two additional peaks in the Tibia Index at the points 1A and 3A labelled in Fig. 13. These peaks occurred when the left heel first came to a stop against the foot rest (Fig. 14-1A), and also when the heel contacted the floor (Fig. 14-3A). In the simulation model without the carpet, higher tibia axial loads were predicted at these times, which caused the peaks to occur. In the simulation model with the carpet, the heel did not contact the foot rest as sharply (Fig. 14-1B) nor did it bottom out against the floor (Fig. 14-3B).

It is felt that the main reason for the improvement in Tibia Index prediction was because the carpet is in contact

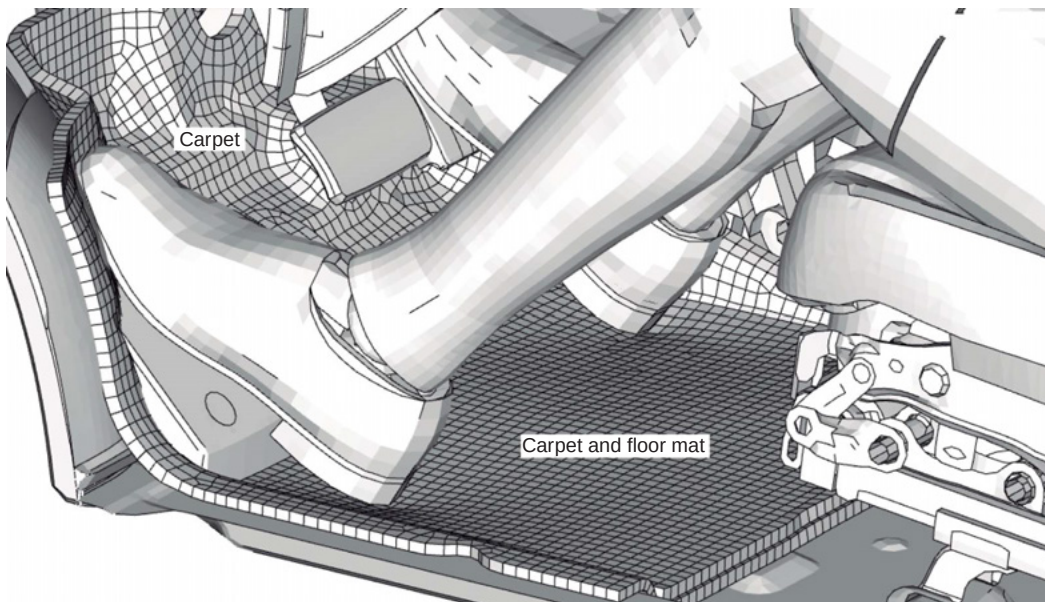


Fig. 12 Carpet and floor mat being modelled within an unbelted occupant sled model

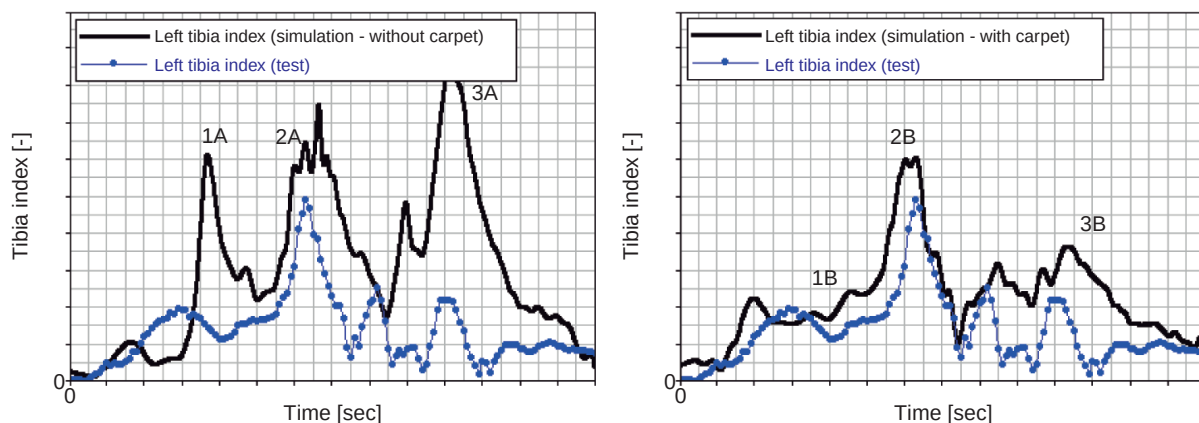


Fig. 13 Left tibia index predictions without carpet model and with carpet model

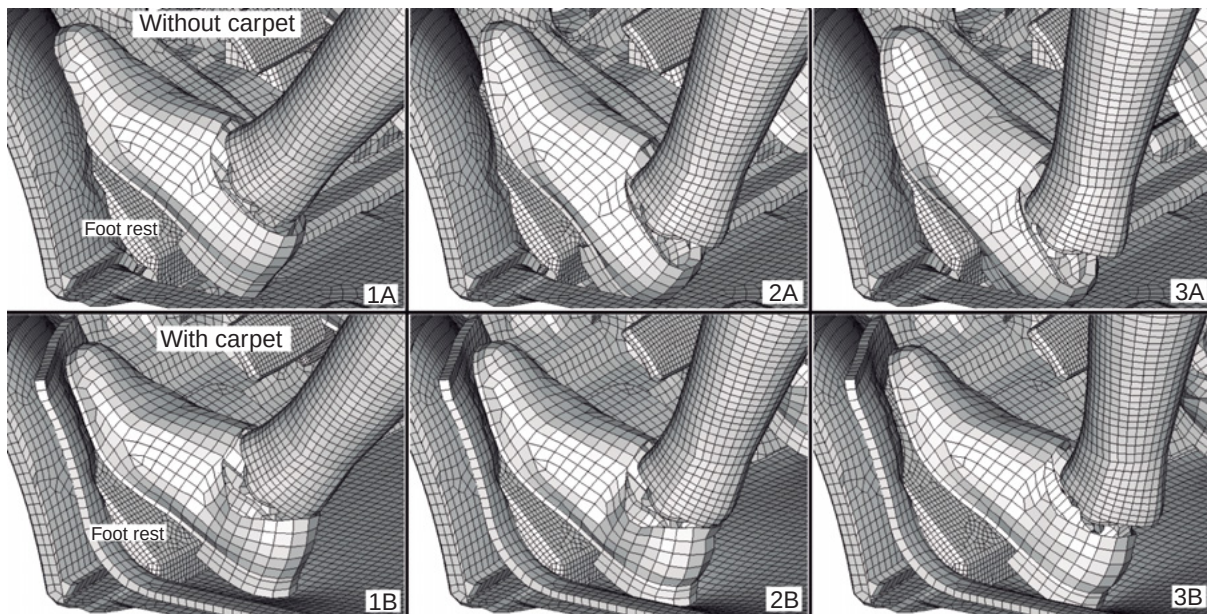


Fig. 14 Comparison of the left foot and tibia kinematics during the occupant simulation with carpet (1A, 2A, 3A) and without the carpet model (1B, 2B, 3B)

with the heels of the occupant from the beginning of the simulation, which prevents high impulsive loads in the tibia when the foot rest and the floor are contacted.

6. Conclusions

A method of modelling the carpet during a frontal crash simulation has been developed. This method presents the development of two material models, one for the outer surfaces of the carpet, and one for the compressible portion. The outer surfaces are to be meshed as 2 mm thick shell elements and modelled with a piecewise linear plasticity material model. The inner portion is to be meshed as brick elements and modelled with a compressible foam model. When this new method is followed, the simulation is able to reproduce the behaviour of the carpet during tension and compression, both loading and unloading. Furthermore, enhanced predictions of lower leg injury have been obtained as a result of the improved lower leg kinematics when this carpet model has been used within occupant injury models.

References

- (1) Hallquist, J. O.: LS-DYNA Theoretical Manual, Livermore Software Technology Corporation (1998).
- (2) Hallquist, J. O.: LS-DYNA. Keyword User's Manual, Vol. 2, pp. 110-114. Livermore Software Technology Corporation (2007)
- (3) Chang, F.S.: Constitutive Equation Development of Foam Materials, Wayne State University (1995).

- (4) Hallquist, J. O.: LS-PRE/Post v1.0 Manual, Livermore Software Technology Corporation (2002).
- (5) Du Bois, P.A.: Crashworthiness Engineering Course Notes, Livermore Software Technology Corporation (2004).
- (6) United States Code of Federal Regulations, Title 49 - Transportation, Chapter V - National Highway Traffic Safety Administration, Department of Transportation, Subpart B - Federal Motor Vehicle Safety Standards, Section 571.208 - Standard Number 208; Occupant Crash Protection. [49CFR571.208]

■ Author ■



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Editorial Afterword

About twenty years ago, one of my colleagues in the department in which I worked at the time was part of the team of volunteers involved in producing the first volume of the Technical Review. I don't recall the details clearly, but I was asked to write a paper, and I did so, without having any idea of what such a paper should be like. Today, having participated in the editing of the 20th anniversary edition of the Technical Review, I remain surprised at the changes that have taken place, but I must say that it has been a true pleasure to me to be involved with engineers who are writing their first papers.

With the passage of twenty years, my view of technical papers today is that while the writing demands objectivity, a writer's statement of their thoughts in the paper will create its own logical order. It has been said that a paper stands in for the business card of the writer. The essential characteristic of a paper, however, is the difference in time between writing and reading; thoughts expressed at the time of writing will be discussed by readers in the future.

Considering another difference in time, I believe that there has been an unbroken sequence of progress between the past and the present of the Technical Review, and that this will continue into the future. The spirit of the first issue lives on in this issue, and looking towards the future, I believe that the sincere interest of the editorial staff in technology and their respect for the logic of the writers will see the Technical Review become a living image of the technologies emerging from Honda R&D.

As I write, the cherry trees outside are bare, but with a small difference in time, when you are reading this afterword, the warm days will be upon us when they will be a riot of blossom.

(Yuta URUSHIYAMA)

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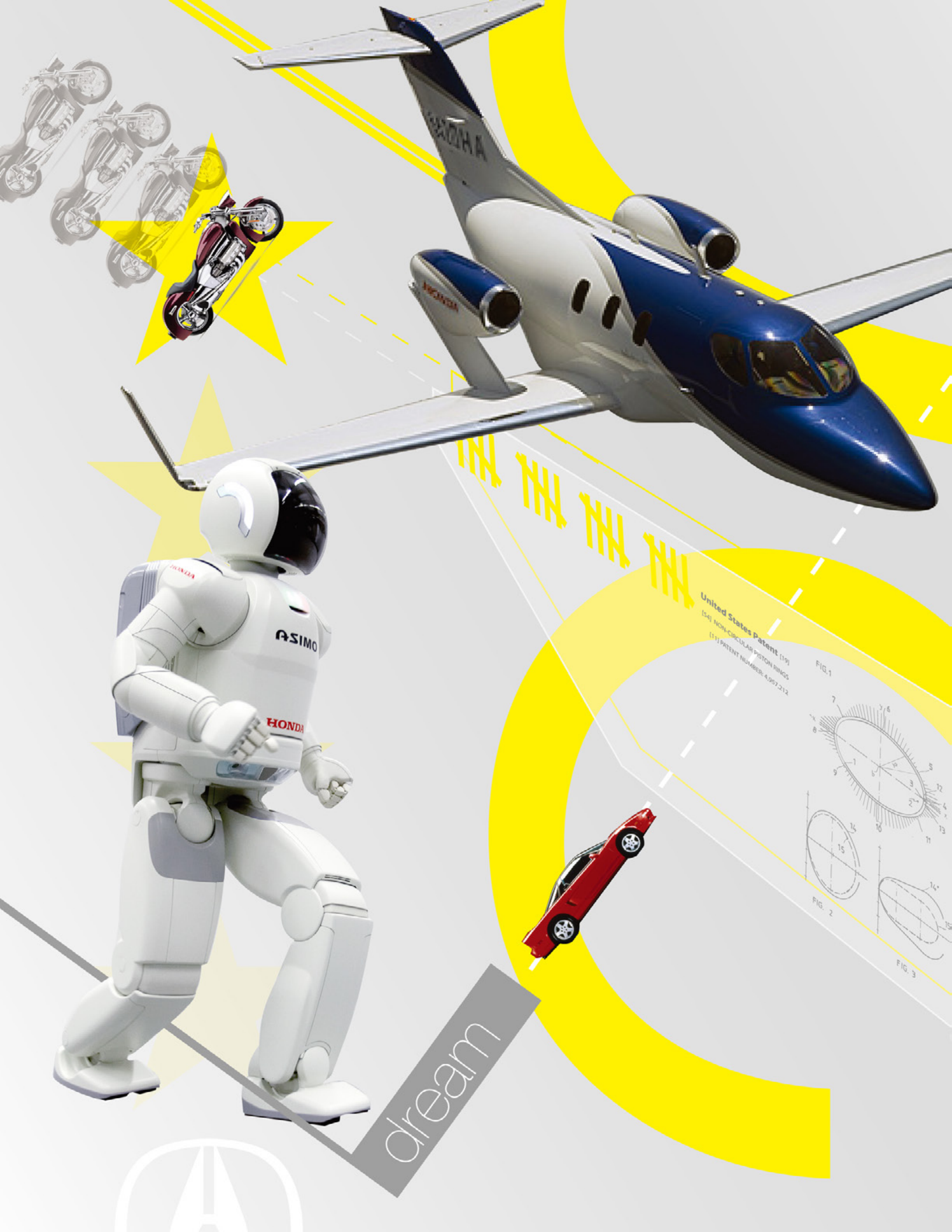
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1-724-776-4970 phone
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