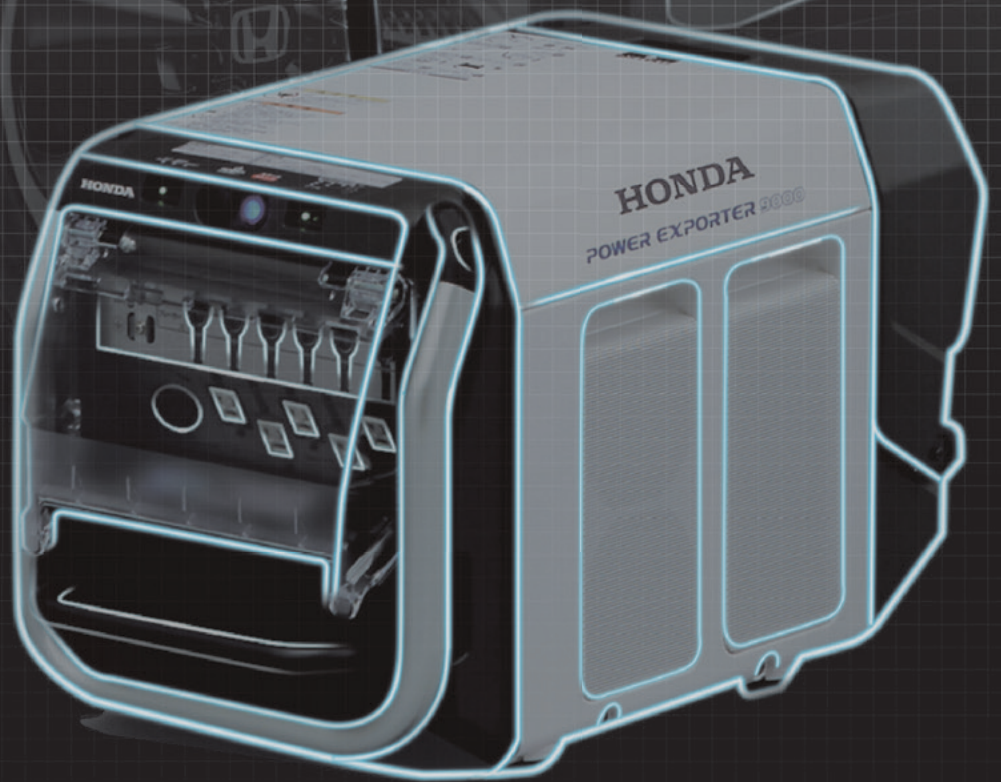


Honda R&D

Technical Review



October 2016

Vol.28 No.2



Comment on the Cover

Besides giving you mobility, the automobile has all sorts of other potential.

The POWER EXPORTER 9000 is one new device designed to elicit the value of the automobile.

Energy stored in the automobile can be used to provide a stable source of quality electricity to devices, from home appliances to medical equipment during an emergency.

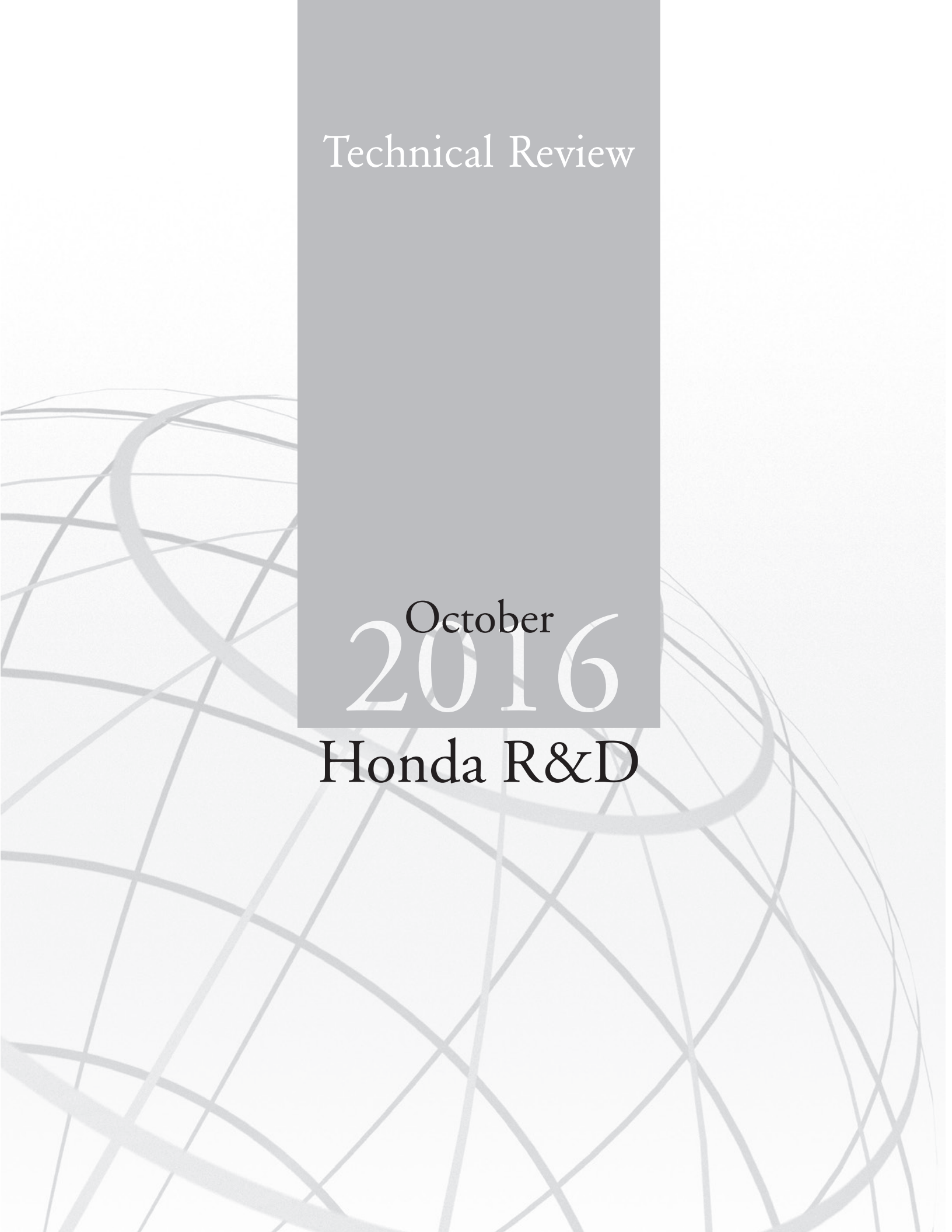
What kind of future will the automobile's new "connection" value embrace? The POWER EXPORTER 9000, with all its hope and promise for a better tomorrow, is the motif for the cover of this edition of Honda R&D Technical Review.



Motorcycle R&D Center
Ryo ITO



Motorcycle R&D Center
Shota NAKAHIRA

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 text.

Technical Review

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Styling Design of the CRF1000L Africa Twin

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ABSTRACT

The CRF1000L Africa Twin was developed as a new large dual sport motorcycle. After a 12-year absence, this model was developed as a successor to the Africa Twin series originating from the XRV650 Africa Twin, which made its debut in 1988 and became famous. The concept in designing this model was to make it immediately identifiable as an Africa Twin and to convey the trends in latest racing machine technologies. Based on this concept, the styling design embodies functional beauty throughout the vehicle, not only in the overall appearance, but also the details including the fairing, fuel tank, headlights and meters, to highlight the distinct personality of the Africa Twin. Additionally, the revival of the Africa Twin brand is placed at the core of the concept for colors, and each of the color variations provided—Tricolor, CRF450 Rally color and Standard colors—have distinct personalities to strike a balance in carrying on its heritage, demonstrating advancement and responding to customer needs. Through this styling design and color scheme, we have achieved the desired design goal of fusing the classic Africa Twin styling with the styling of racing machines backed by the latest technologies.

1. Introduction

The CRF1000L Africa Twin (Fig. 1) is a new model developed by Honda as a large dual sport motorcycle. Among Honda's dual sport motorcycles, the name, Africa Twin, has been given to models that inspire the Paris Dakar Rally, which was held in Africa from 1978 to 2007.

The first-generation XRV650 Africa Twin (Fig. 2) made its debut in 1988. It was based on Honda's factory-backed machine, the NXR750 (Fig. 3), which competed in rallies in the 1980s. Many fans were captivated by the

off-road performance that would allow it to compete in an actual rally and by the unique styling design that included a full fairing. In the aspect of practical use, it met the needs in Europe, which is the original market of sport motorcycles, where they travel long distances at a high speed while asking for comfort. Additionally, other manufacturers also involved to create a category of large dual-sport motorcycles equipped with full-fairings.



Fig. 1 The CRF1000L Africa Twin



Fig. 2 The XRV650, the first generation Africa Twin launched in 1988

* Motorcycle R&D Center

Subsequently, they increased the engine displacements and the maximum speeds and the product families were expanded in other manufacturers' products. Meanwhile, Honda released the XL1000V Varadero (Fig. 4) and the VFR1200X (Fig. 5). Those were developed focusing on usability in the practical use and on-road performances. In the continued trend of applying a larger engine



Fig. 3 The NXR750, 1987 Paris Dakar Rally model



Fig. 4 The XLV1000 Varadero, launched in 2000



Fig. 5 The VFR1200X, launched in 2010

displacement, the Africa Twin was discontinued in 2003.

In recent years, the market of touring motorcycles with a large engine displacement has become fully matured. On the other hand, models that can offer enjoyable off-road riding are attracting customers' interests again. Those new trends all together have led to the louder voices to request the comeback of the Africa Twin.

After more than a decade of absence from the market, the way how Africa Twin should be revitalized to fit to the current market was investigated. It was started with discussions on the requirements and requests from the market. To construct the basis of the investigations, market researches were conducted in Germany, France, Italy and the United Kingdom, which are the major markets in Europe. Further discussions were followed after that to settle the basic concept of the developing model. The discussion was concluded that the new Africa Twin must be a fully off-road compatible motorcycle, which is capable enough to allow a rider "to go anywhere."

Therefore, the development team set the concept for the new Africa Twin as "Go Anywhere—an adventurer's motorcycle that satisfies daily commuting and can be extended to the journey of their dreams of dynamic rides across a vast continent."

As a consequence, it had recognized that the styling design was an indispensable factor in the development that represents the determined concept and is evoking a spirit of adventure. This paper will explain the styling design concept and how it was implemented.

In this paper, the CRF1000L Africa Twin will be referred to as "this model" or "the new Africa Twin," while the XRV650 Africa Twin will be referred to as "the first generation Africa Twin" and the XRV750 Africa Twin as the "previous Africa Twin."

2. Styling Concept

People who have been the users of consecutive models of the Africa Twin's or the customers who have grown up longing for purchasing these models are strongly attached to the former models of the Africa Twin's. Through the results of market researches, which have been mentioned earlier, the customers want the new Africa Twin to have an exterior appearance that makes them immediately recognize it as an Africa Twin at first glance.

Meanwhile, there is another tendency as a recent trend that the customers expect for sport motorcycles to share technologies and characteristics with leading edge racing machines.

Honda come back to the Dakar Rally in 2013 and keeps participating since then. The styling design of the CRF450Rally (Fig. 6), which is the machine participating in that rally, is exactly representing the latest trend of motorcycles of that category.

The styling for the first-generation Africa Twin (Fig. 2) was based on the NXR750 (Fig. 3), one of the

Honda's factory-backed motorcycles that participated in the rallies in the 1980s. To meet the requirements for the set conditions of the stages in those rallies at that time, the NXR750 was designed so as to have a large and sturdy body with a priority in protecting a rider and functionally important parts. For example, a larger sized fuel tank was installed to allow long distance travel, and the fairing was designed in large size to provide enough wind protection for a rider. They showily displayed the presence the Africa Twin being symbolized as its icons. In addition, the headlight system employed two large-sized round shaped lamps to provide better visibilities for tough ridings in the dark. By implementing these styling design elements, the impression of this particular motorcycle that the vehicle could run through a vast land satisfying a capability of long and high speed cruise with ease of mind was realized.

Meanwhile, the Dakar Rally relocated to South America in 2009, and the conditions of the stages have changed significantly from the previous Paris Dakar Rally. In response to this, Honda's factory-based motorcycle, the CRF450Rally, became slimmer, light-weight and compact. Following the evolution in technology, functional parts, including the headlights, also became smaller and lighter. The large fuel tank was split into four and now fits inside the body, making it less visible. Also, to reduce time required for maintenance, covers for functional parts were taken off. Therefore, the styling design needed to creates an image of a motorcycle with superb dynamics and a serious off-road performance that allows you to travel through rough mountainous terrain.

These two images were thought to be essential in designing the styling for the new Africa Twin. In other words, it was important to fuse the classic Africa Twin styling with the styling backed by functions and technologies in the latest factory-based racing machine.



Fig. 6 The CRF450Rally

This was placed at the core of the styling concept for the Africa Twin of the new era. The sketches and renderings created based on this styling concept are shown in Figs. 7, 8, 9 and 10.



Fig. 7 Concept evolution sketches



Fig. 8 Sketches to realistic proportions



Fig. 9 Design sketches of face part of the vehicle



Fig. 10 Rendered image of the final design of the new Africa Twin

3. Specific Methods for Designing the Styling

There are roughly two parts to designing the styling for motorcycles—one is determining how the overall vehicle should look in terms of balance, proportions and volume, and the other is designing the details and expression of textures in the individual parts. The overall design is established by harmonizing these two.

3.1. Overall Image

First, the overall image will be explained. A full-fledged off-road motorcycle has an image of having excellent dynamics that allows riders to journey through rough roads. Therefore, the method used in Honda's motocross motorcycles including the aforementioned CRF450Rally, was incorporated, which was to concentrate mass and create a V-shaped form. The long stroke suspension, an indispensable component of off-road models, was also incorporated to create a long-legged proportion that emphasizes dynamics. The difference in proportion with the previous Africa Twin is shown in Figs. 11 and 12.

As for the overall volume, development team members brought together their various perspectives to define a size that would reassure the rider while not feeling too heavy and difficult to handle. For example, the seat is sufficiently sized but shaped such that it would not hinder the movements of an active rider, satisfying both comfort and dynamic appearance (Fig. 13). The fairing is also compact enough that riders of various body types could feel they could control it as they wish, but large enough that it provides reassurance in that it could protect you from elements that hinder your ride such as wind, sand and dust.

3.2. Details

Next, the details will be explained. In rendering the details, the theme was to have functional beauty embodied throughout the vehicle, by achieving functional beauty in the design of every single part. Specific examples are provided below.

(1) Fairing

The front overhang on the fairing was shortened as much as possible. Doing so would enhance the dynamics through concentration of mass and create an agile and dynamic appearance when looking at the entire vehicle. In order to shorten the overhang, the angle of the front



Fig. 11 Proportional scheme of the previous model of the Africa Twin



Fig. 12 V-shape proportional scheme applied to the new Africa Twin



Fig. 13 Streamlined seat shape that helps smooth actions of a rider

screen is steepened (Fig. 14). This also causes the negative pressure inside the fairing to go up, which may affect the rider's ability to maintain his posture. In order to mitigate this, an air duct was created towards the bottom of the screen. This design enables a styling that looks agile while providing a comfortable ride (Fig. 15).

(2) Fuel tank

In the past models, a tank that was relatively large in proportion to the body was used to create an image of toughness and suitability for long distances. In other words, the distinctive fuel tank was an important element in the Africa Twin's identity. When developing the new Africa Twin, excellent dynamics became essential in addition to the ability to travel long distances. This meant that the tank needed to be slim enough that it did not hinder the rider's movements. In this model, the engine layout was changed from a V-twin to a parallel twin layout, which allows the tank to be expanded downwards. Therefore, the team was able to create a tank that was slim but looked large when seen from the side. This allowed the fuel tank design to maintain the classic Africa Twin identity while achieving excellent dynamics as well.

(3) Headlights

The headlights are an important element in designing the front of the motorcycle. In the case of the Africa Twin,



Fig. 14 Fairing with wind screen with a steep angle



Fig. 15 Air streams around the fairing and the rider

the symmetric and round twin headlights looked like eyes and left a strong impression on those who saw it. However, due to the structure of the slim LED headlights that are used in this model, the illuminated area looks almost like a half circle and the surface area is smaller as well, resulting in the presence of the “eyes” to be reduced. Therefore, signature accent lights are placed on the bottom perimeter to enhance the presence of the headlights as “eyes”. By doing so, the new LED technology could be adopted while also emphasizing the presence of the distinct eye-like headlights of the new Africa Twin (Fig. 16).

(4) Meters

The styling for the Africa Twin needs to carry the lineage of a rally machine and give riders the sense of thrill that it will quickly responds to the changing conditions of a rally. Therefore, the meter design in the latest rally machine was applied to this model as well. Information is stacked and displayed vertically, resulting in the meter to be vertically long (Fig. 17). This meter configuration creates space to the left and right of the meter (Fig. 17), which secures



Fig. 16 Headlights and signature accent lights that emphasize the impression of round edge lines



Fig. 17 Vertically long-sized display unit with information display stack

visibility in the front and allows the rider to see the constantly changing road conditions to understand the ride environment in off-road travel. In addition to that, this model needs to display more information than what is required in normal motorcycles. This includes information on the status of the Dual Clutch Transmission (DCT), Selectable Torque Control and Anti-lock Brake System. Therefore, a wide array of information needs to be displayed in a way that is easy to see during the ride, depending on the conditions and priorities. In order to satisfy that need, information is displayed from the top based on how frequently it is checked. There are switches right at the rider's hand for changing what is displayed, so that the rider can check various types of information without moving their hand from the grip. This meter design inherits the styling characteristics of the Africa Twin, giving riders elation and the feeling that they are really participating in a rally.

Through the design of these details as discussed above, our goal of having functional beauty embodied throughout the vehicle is achieved, and the distinct personality of the Africa Twin is highlighted.

4. Color Design

4.1. Color Concept

The colors used in the motorcycle are important elements that communicate the concept of the model immediately. In determining the color concept for the Africa Twin, the team first discussed about what needs to be expressed the most. The initial idea was to highlight that it was a new model and appeal to customers using a completely new concept for the colors. However, an important segment of the target users for this model included those customers who had cherished riding the past models for many years. In addition to that, the perspective of inheriting the Africa Twin brand, which was defined to be the styling concept for the entire vehicle, was also indispensable. Therefore, the coloring design also needed demonstrate that this model is a next-generation model that maintains the Africa Twin identity and inherits the brand image established by its predecessors. From these perspectives, the revival of the Africa Twin brand was placed at the core of the color concept.

4.2. Logotype and Accent Lines

The design for the logotype, which is common across all variations, inherited the sense of momentum and energy in the brush stroke-like font that the first-generation Africa Twin had. In addition to that, sharpness and edginess was added to the design to give the logotype a more modern twist. The large logotype on the side of the vehicle conveys a dynamic and strong Africa Twin (Fig. 18).

The accent lines on the body aim to create a visual synergy by emphasizing the new styling that strives for further concentration of mass.

Described below are the methods taken for each color variation.

4.3. Three Color Schemes and Methods

(1) Tricolor

When asking ourselves what colors would feel most like an Africa Twin, our answer as designers was tricolor—red, blue and white. This tricolor scheme were used on the first-generation Africa Twin, the XRV650, which was a replica model of the NXR750, the factory-backed motorcycle that won the Paris Dakar Rally for four consecutive years starting from 1986 (Fig. 2). In Europe, many customers associate the Africa Twin with a tricolor scheme. Therefore, this tricolor option is provided to represent the revival of the Africa Twin brand and to leave a strong impression of this model's concept in the market (Fig. 19).

The tricolor option in the first-generation XRV650 entirely consisted of solid colors. In this model's tricolor scheme, pearl and metallic colors that add depth to the tone were adopted to represent the luxury and high quality of a 1000 cc class motorcycle (Fig. 20). In addition to that, the parts listed below are in Tricolor exclusive colors to



Fig. 18 Logotype designs of the first generation Africa Twin and the new Africa Twin



Fig. 19 The new Africa Twin in Tricolor color scheme

emphasize the concept of the first-generation Africa Twin and convey that this is a special specification.

- Gold rims
- Gold handlebars
- White hand guards
- Red rear suspension spring
- Blue bar end weights

These contribute significantly in communicating the styling image as elements that allow riders to identify the new Africa Twin Tricolor variation.

(2) CRF450 Rally color

After participating in the 1989 rally, Honda withdrew its factory-backed efforts in the Paris Dakar Rally at that time, but returned in 2013 after a 24-year absence. The colors from the current factory-backed machine participating in the Dakar Rally, the CRF450Rally (Fig. 6), are provided as an option to demonstrate its iconic presence as the latest adventure model.

This color scheme was designed primarily to fully express the momentum of the rally machines. Only solid colors are used to provoke a sporty image of a racing machine still in competition (Fig. 21). Also, to express momentum in the colors that run across the body, the white line that begins from the front fairing is extended back to the side of the seat (Fig. 22). However, the technological barriers were high in applying sharp lines to soft seat material, as there was a need to ensure that the lines were placed accurately even on the seams on the seat covers and the area where the seat connects to the body exterior part. Nevertheless, this white line was essential in expressing momentum and continuity, so we overcame these technical issues. As a result, we succeeded in using this line effectively, and the momentum of the rally machine was expressed throughout the entire vehicle.

(3) Standard colors

Currently, especially in Europe, the large dual-sport motorcycle market is growing steadily, so color options that cater to this market were also created. These Standard color variations are not bound to specific images like the other two color schemes previously mentioned, but appeal to a wide range of customers with various lifestyles. They are designed to appeal to businessmen that effortlessly ride their large dual-sport motorcycle to work and couples that enjoy touring together. Chic and bold colors are used to create a metallic feeling that is worthy of being owned by an adult, a strong presence in urban scenery, and a design that blends into nature as well as historical landscapes encountered on a journey (Figs. 23 and 24). These color options propose a new value as a touring motorcycle for grown-ups with serious off-road performance.



Fig. 21 The new Africa Twin in CRF Rally color scheme



Fig. 20 Contrast in brightness by metallic colors applied to the painted areas and the stripes



Fig. 22 The white stripe stretches on to the seat side



Fig. 23 Standard color option: Digital silver metallic



Fig. 24 Standard color option: Matte ballistic black metallic

5. Summary

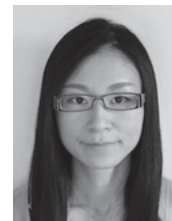
Concurrent multiple approaches were challenged in the styling design process encompassing the whole design aspects of the total balance, details and coloring to accomplish the exterior design goal of the fusion of the inherited styling of the Africa Twin and the styling of racing machines for rallies that is technically backed up by the latest equipment, where it was the consistently held concept footed throughout the development of this particular motorcycle.

As a result of those efforts, the styling design was successfully accomplished and the developed vehicle was recognized by customers as “This is genuinely the youngest descendant of the Africa Twin.” The developed motorcycle has been well accepted by many customers in Europe, the U.S. and Japan since its release in December, 2015. We understand it is the evidence that we have achieved our goal of reviving the Africa Twin. We are truly hoping that this latest model of the Africa Twin will be favored by customers for many years just like it was for the predecessors.

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ABSTRACT

The CRF1000L Africa Twin was developed with technologies for a new era while inheriting the tradition of the XRV750 Africa Twin, which pioneered the adventure sports category. Extensive weight reduction and mass centralization allows the size and weight of the CRF1000L Africa Twin to closely match its predecessor. An engine with parallel twin cylinders and displacement of 998 cm³ was employed. In addition, a dry sump system was applied in which the oil tank is integrated within the crankcase. These features contributed to enabling a powerful and compact power unit. The dynamic performances in off-road riding and the performances sought as an on-road touring motorcycle are fulfilled at the highest levels. Furthermore, a dual clutch transmission was applied for the first time to an off-road motorcycle, and has proven its effectiveness in off-road riding as well.

1. Introduction

While the overall motorcycle markets of advanced countries like those in Europe have recently shown declining trends, the large on-off road models are selling steadily. Until 1985, the market size of large on-off road motorcycle models was small with only a few models seen in that category. Nevertheless, in 1986, Honda launched the XL600V TRANSALP, which is equipped with a full fairing first time in the category. In 1988, the XRV650 Africa Twin was released with transferred technologies from the NXR750, which was the machine that leads winning championships in Paris-Dakar rallies 3 consecutive years from 1986. Following to that, in 1990, the XRV750 Africa Twin with an enlarged engine displacement was put on the market laying the foundation of a new concept of adventure sports models. In the year 2000, the XL1000V Varadero was developed and introduced in the market to cater for the needs of high-speed, long-distance motorcycle travel. In the meantime, taking into account customers' shift of interest more toward touring, the European motorcycle manufacturers reinforced their model lineup by adding off-road-image models while increasing engine displacement to cope with high speed travels, expanding the sales volume and the market share year after year.

Based on this, Honda decided to develop and introduce a large on-off road model, CRF1000L Africa Twin (Fig. 1),

to the global market incorporating modern techniques to meet environmental requirements and to distinguish it as a next-generation model while maintaining the basic concept of XRV750 Africa Twin.

In this paper, the following information will introduce the technologies applied to the CRF1000L Africa Twin including complete vehicle packaging, the newly developed 998 cm³ parallel twin-cylinder engine, and the Dual Clutch Transmission (DCT) control system capable of handling



Fig. 1 The CRF1000L Africa Twin

* Motorcycle R&D Center

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off-road riding conditions.

Hereafter, in this paper, the CRF1000L Africa Twin is called “this model” and the XRV750 Africa Twin is called “preceding model.”

2. Objectives

The development team aimed to develop the new era Africa Twin while maintaining the heritage of challenges in the Paris-Dakar rally that Honda participated in since the 1980s as well as in the creation of a then-new market segment. If referred to as Africa Twin, having a high off-road capability was a must. It was also considered necessary to ensure comfort on pavement on the way to the off-road area, including high-speed travels carrying luggage. Accordingly, the objective was set to achieve a balance of the two contradicting requirements at a high level.

The key word of concept was set as “Go Anywhere - Full-scale adventure model useful for daily commuting as well as for riding across the vast tracts of land you’ve long dreamed about.”

3. Frame and Chassis

3.1. Packaging and Dimension

The newly developed compact parallel twin-cylinder engine was employed in this model. This configuration allows for mass centralization by laying the heavy battery and other electrical parts such as Engine Control Unit (ECU) near motorcycle’s Center of Gravity (CG), where the space would be occupied by the rear cylinder a V engine configuration (Fig. 2). While maintaining the same overall size as the preceding model, the front suspension stroke was increased from 220 mm to 230 mm, and the rear from 214 mm to 220 mm. Using the same 21-inch front wheel as the preceding model, but changing the rear wheel from 17-inch to 18-inch, the ground clearance was increased from 220 mm to 250 mm (Fig. 3).

The steering system employed upside-down type front forks. This type of front fork usually has a large

diameter and the handlebar steering angle becomes smaller. However, by reducing sizes and changing shapes of the body frame adjacent to the head pipe and the air cleaner box, the steering angle was rather increased to 43 deg compared to from 40 deg, which was the angle of the preceding model with conventional type forks. This steering angle made the motorcycle minimum turning radius as small as 2.6 m, which is one of the smallest radiuses in large on-off road motorcycle category. As a result, a motorcycle was created that was easy to handle, not only in an off-road situation requiring a switch back in a limited space such as the woods but also when pushing the motorcycle around the garage.

3.2. Engine Location

The parallel-twin engine exclusively developed for this model was designed to reduce the longitudinal size compared to the V twin engine mounted on the preceding model. This design enabled a shorter the distance between the pivots of the front tire and the swing-arm by 8 mm (Fig. 4), increasing the shared load ratio on the front tire.

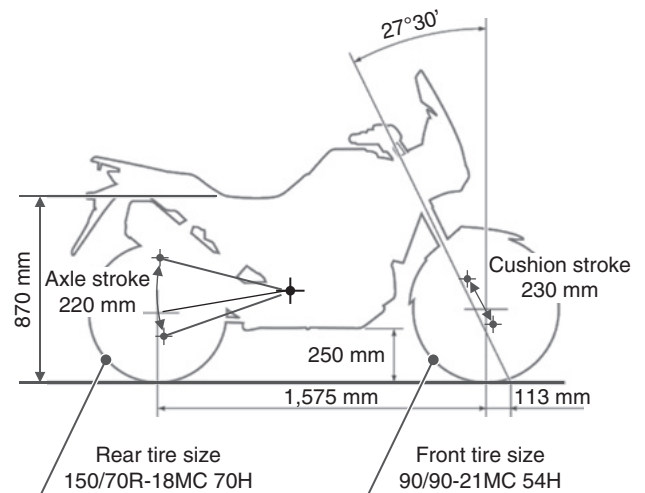


Fig. 3 Dimension and key parameters

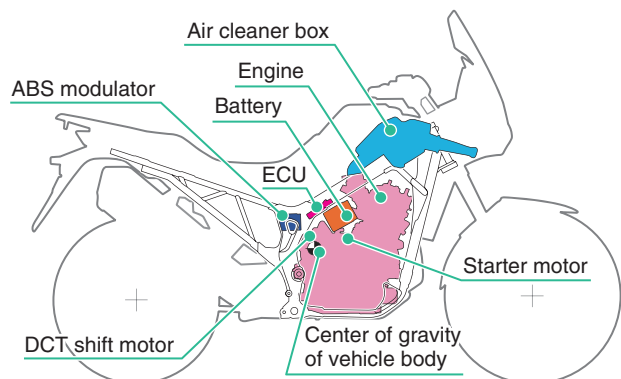


Fig. 2 Layout of key components

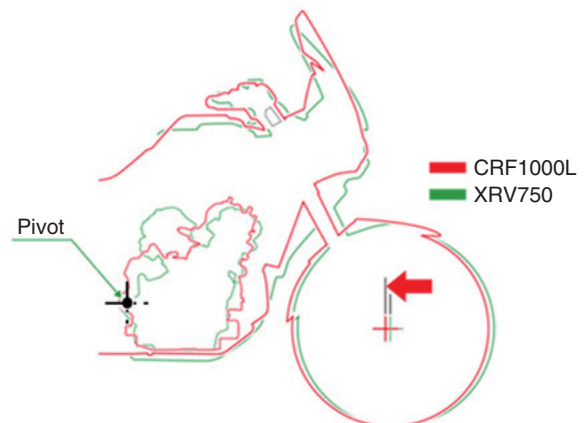


Fig. 4 Comparison of front axle positions

Consequently, the vehicle stability was enhanced and accurate feedback of wheel movements to the rider was achieved. As a result, the road holding property of front tire, which is a typical vehicle characteristic required for off-road type motorcycles, was enhanced.

A V-twin engine has front and rear cylinders but a parallel twin-cylinder engine doesn't have to have a cylinder located in the rear space. Accordingly, the width of the motorcycle was able to be reduced at the area between rider's knees. With this vehicle body shape, the rider can freely take various active riding positions in off-road riding (Fig. 5).

A seat height adjuster that reduces the height by 20 mm from the normal seat height of 870 mm was equipped (Fig. 6). This enhances convenience when riding tandem or situations requiring the rider's foot to frequently reach the ground, such as off-road riding.

3.3. Frame Body

The semi-double-cradle frame configuration was employed (Fig. 7). This configuration has been applied to Honda off-road models for a long time, and also was applied to the CRF450 Rally that took part in Dakar Rally.

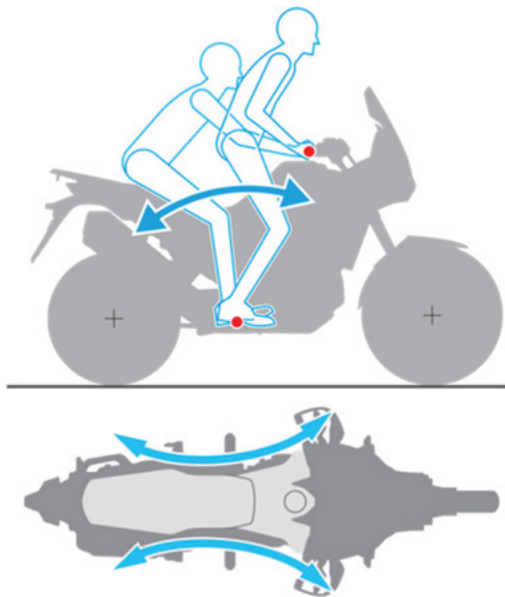


Fig. 5 Rider movements

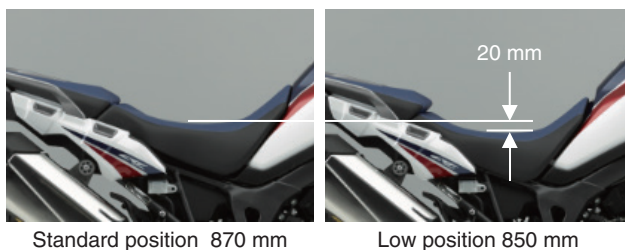


Fig. 6 Seat height adjuster

It was applied to the preceding model as well. Appropriate strength and stiffness were applied to cope with various riding situations, such as a tough riding on off-road, tandem highway cruising in a fully loaded condition or rough road running while heavily loaded. At the same time, the frame is flexible enough to allow the tires to properly trace road surfaces to convey the drive force from the engine to the ground even on rough roads. To achieve the two contradicting requirements, the modified oval cross section as shown by Fig. 8 was employed in the main frame pipe.

In addition the engine is also attached to the frame by the engine hangers at six mounting points surrounding (Fig. 9). As a result of these, the frame body achieved the best stiffness balance. Moreover, the high tensile strength steel was employed for the frame pipes to obtain adequate strength to cope with a wide variety of conditions from high-speed operations to off-road riding, while also reducing weight to enhance the maneuverability of the motorcycle.

3.4. Luggage

A top box and pannier cases were provided for this model as convenient accessories to carry cargo (Fig. 10). To accommodate pannier cases, separate mount brackets



Fig. 7 Frame body (MT model)

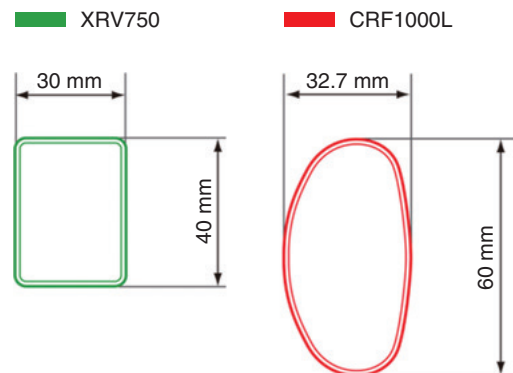


Fig. 8 Comparisons of frame pipe cross section

are generally provided in the motorcycle. Notwithstanding that, the pannier catch system for this model is the same as that used for the VFR1200X, requiring no mount brackets at all. The one-piece construction of the rear carrier, the rear grips, and the pannier catch system permitted a reduction of the number of parts used while contributing to strengthen and stiffness. The use of nylon reinforced by glass also permitted weight reduction (Fig. 11).

3.5. Chassis

3.5.1. Front suspension

A upside-down fork with slide pipe diameter 45 mm was employed in the front suspension reducing unsprung mass, enhancing sliding actions and increasing stiffness. The front axle holder is of a leading axle type to bring the CG of steerable parts close to the steering stem to reduce inertia moment around the steering axis as well as facilitating the opposed 4-pot, radial mount brake calipers.

The suspension had to be widely adjustable because a variety of usage is expected such as daily town use, touring with a passenger and luggage, and off-road riding.

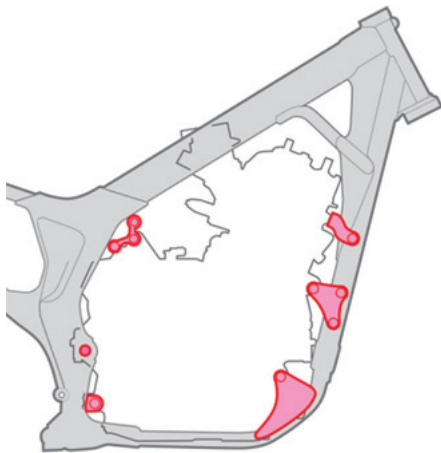


Fig. 9 Six engine hanger locations



Fig. 10 Accessories integrated in motorcycle styling

Accordingly, a fully adjustable suspension system was employed. The system has damping force adjusters both for rebound and compression in addition to a spring preload adjuster [Fig. 12(a)].

3.5.2. Rear shock

In off-road riding, the rider takes positive body actions such as fore-and-aft weight shift, sitting and standing. Accordingly, the motorcycle has to be slim and easy for the rider to reach the ground with his foot. At the same time, to ensure adequate fuel range for touring use, the fuel tank capacity was set at 18 L. To achieve slimness and adequate fuel tank capacity, the upper mount point of the rear shock in this model was lowered by 33 mm from the preceding model. By laying the rear end of fuel tank in the space created by the relocation of the rear shock, the necessary fuel tank capacity was maintained without compromising freedom of riding position. The top-in-the-class ground clearance and rear axle stroke were achieved by modifying



Fig. 11 Pannier system

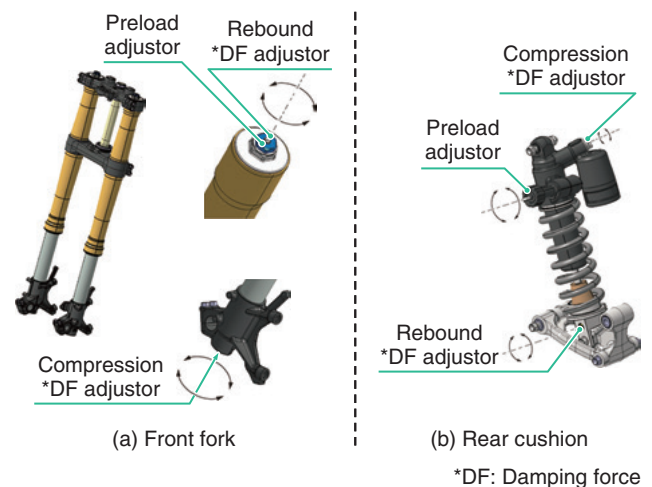


Fig. 12 Front fork and rear cushion

the overall length of rear shock and exclusively designing the Pro-link linkage. Just like in the front fork, the rear shock is fully adjustable having the rebound and compression damper adjusters in addition to the spring preload adjuster to cope with various riding conditions. The frequently-used spring preload adjuster is of a hydraulic type that requires no tool for quick adjustment to cope with changes of load [Fig. 12(b)].

3.5.3. Swing-arm

So as not to disturb an active riding position, the right side of the swing arm in the proximity of muffler had to be shifted towards the inside as far as possible. At the same time, it was also necessary to satisfy the requirements for stiffness and strength appropriately. Therefore, a hollow aluminum gravity die casting method, which is suitable for efficient optimization of the shape and the cast wall thickness, was applied to the swing-arm (Fig. 13).

3.5.4. Brake

To achieve basic braking efficiency adequate when carrying luggage and a passenger, the maximum braking efficiency was increased from the preceding model. At the same time, how the brake works was fine-tuned to allow delicate brake control for off-road. Fig. 14 shows front and rear brake systems. The diameter 310 mm, floating brake disc was exclusively designed for this model, and two of

them are applied to the front brake. The use of aluminum for the disc hub contributes to a weight reduction. The opposed 4-pot radial-mount brake calipers are exclusively designed to achieve stable initial brake feel, high brake controllability and a weight reduction. A 256 mm disc is employed in the rear brake.

3.5.5. Rear ABS function inhibitor and DCT control related to rear brake

Presuming there are off road situations where the front and rear brakes have to be applied individually, a Honda-first rear ABS function inhibitor was employed. This system permits the rider to turn off the rear ABS function by toggling a switch. When the rear ABS function is turned off, the rider can control the rear brake by pedal effort alone. In such a situation, the rear ABS function is deactivated and is shown on the indicator to inform the rider.

The DCT model has an engine stall prevention function. When the rider applies a hard rear braking and the rear wheel is about to lock, the system predicts an imminent rear wheel lock based on changes in engine speed and vehicle speed, and quickly reduces hydraulic pressure to disengage the clutch. This allows the rider to lock the rear wheel without paying special attention to the clutch lever operations, which is inevitable when riding a manual transmission motorcycle.

4. Over View of Engine and Applied Technologies

4.1. Power Output Characteristics and Engine Performance

Figure 15 shows an external view of the engine, and Table 1 shows the main specifications of the new engine and preceding model's engine.

The power output characteristics of this model and the preceding model are compared in Fig. 16. Seeking easy-to-use power output and flat torque characteristics just like those of the preceding model, the shape of the intake and

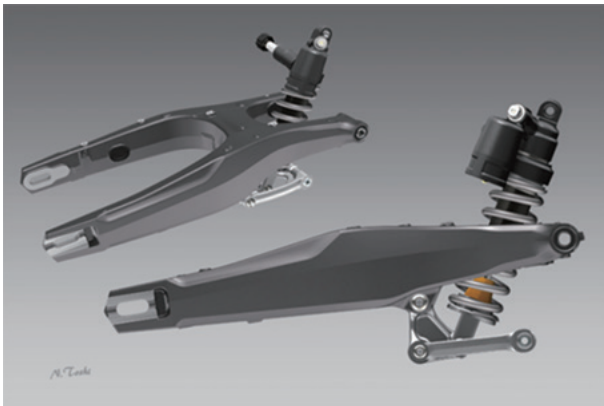
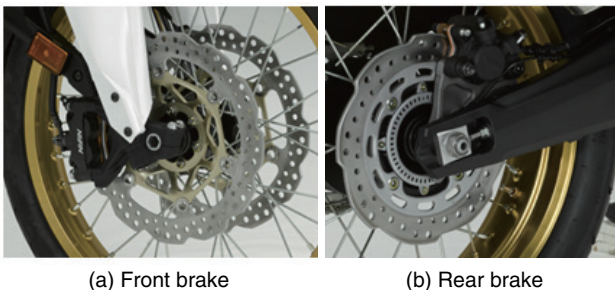


Fig. 13 Swing-arm



(a) Front brake

(b) Rear brake

Fig. 14 Front and rear brake

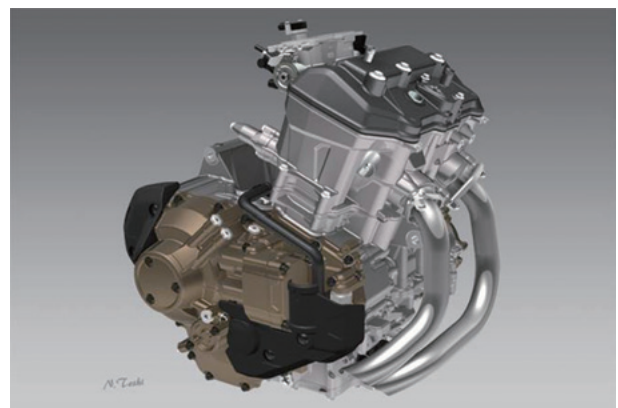


Fig. 15 External view of engine (DCT type)

Table 1 Comparison of specifications of engine

Model name	CRF1000L Africa Twin	XR750 Africa Twin
Displacement (cm ³)	998	742
Bore × stroke (mm)	92.0 × 75.1	81.0 × 72.0
Compression ratio	10.0	9.1
Maximum power (kW/rpm)	70/7,500	45/7,500
Maximum torque (Nm/rpm)	98/6,000	64/6,500

exhaust ports, the valve timing, the intake and exhaust systems, and the two-plug phased ignition timing control were finely tuned. As a result of those measures, the engine's power delivery was easy to control. These features were coupled with increased power output throughout the entire rev range, achieved by increased engine displacement, thus allowing the engine to exert its performances.

4.2. Applied Technologies of Engine for Light Weight and Compactness

4.2.1. Dry-sump lubrication system with oil tank integrated in crankcase

When used off-road, a motorcycle makes large back-and-forth and up-and-down motions, causing extensive changes to the engine oil level. Accordingly in a model having a wet sump lubrication system, the depth of oil pan is increased to pump out engine oil from a lower part to allow steady feeding of oil by the oil pump without being affected by a change of oil level. A deep oil pan, however, means a reduced ground clearance of the motorcycle, limiting off-road capabilities.

Meanwhile in a dry sump system, a separately incorporated oil reservoir permits steady feed of oil by the

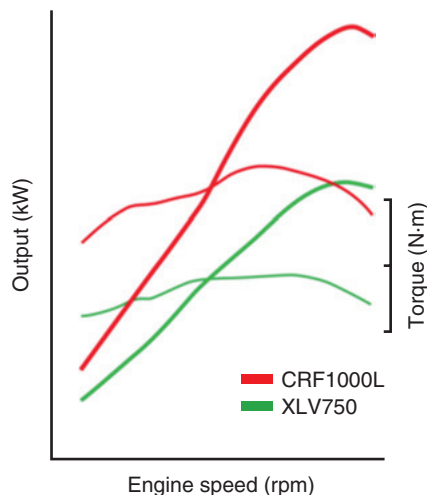


Fig. 16 Engine performance

oil pump. A separate oil tank, however, is a disadvantage from the standpoint of weight reduction and compactness.

Accordingly in this engine, the dry sump system with the oil tank integrated in the crankcase was employed (Fig. 17). The first feature of this construction is that the oil tank is composed as an integral part of the crankcase and oil pan, and contained in the engine.

The second feature is that the oil pump to feed oil to the oil tank is located inside of the tank.

The first-mentioned feature of this model permits efficient layout of the oil tank having a reduced oil pan height as short as 35.7 mm. Thus the top-of-class ground clearance of 250 mm was established. Furthermore, the second feature permits integration of the oil pan and oil tank, allowing the shortest-possible connection of such parts, thus contributing to weight reduction and compactness.

4.2.2. Layout of water pump in clutch housing

A widely-applied conventional layout of a water pump is such that the water pump seating surface is created on

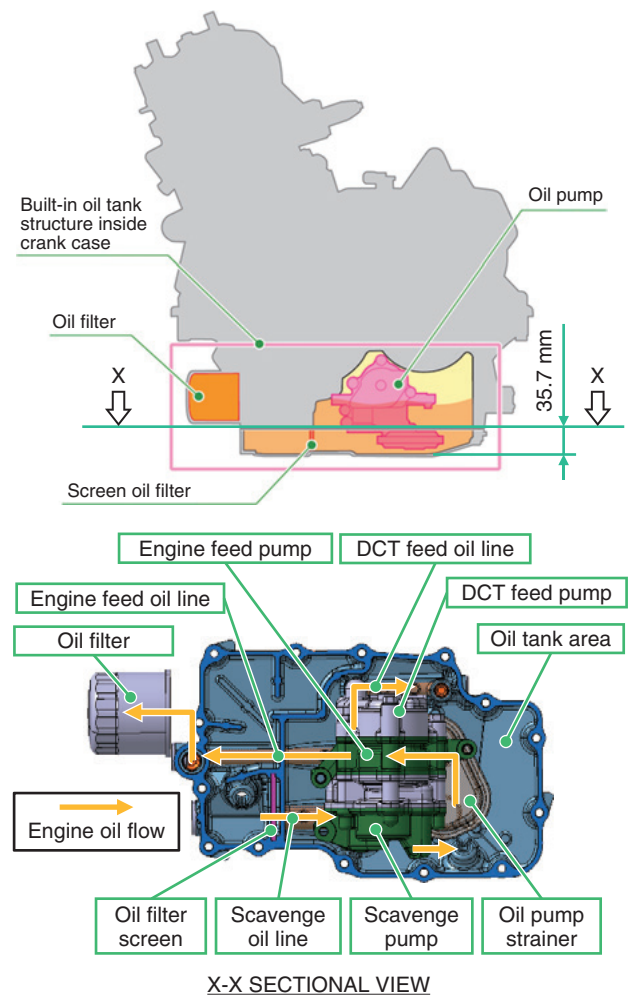


Fig. 17 Construction of dry sump system having oil tank integrated in crankcase

the outside surface of the crankcase or engine cover, and the water pump is bolted on the surface from outside. In such a construction, the presence of a seating surface or bolts on the outer surface of the engine was a cause of limited freedom in the styling design of an engine cover. When incorporating a water pump in the clutch cover, it is necessary to lay the water pump avoiding interference with the hydraulic control devices of the DCT. Accordingly in this engine, the water pump was located inside of the clutch housing (Fig. 18). The feature of this construction is that the water pump seating surface is created in the clutch housing, and the water pump is bolted from inside of the engine. With the said construction employed, the water pump seating surface and the bolts for retention of the water pump are eliminated from outer surface of the engine. This design also eliminates the need to have an external water hose to feed coolant from the water pump to the cylinder water jacket. Moreover, the hydraulic control devices of DCT can be laid in such a manner that overlaps with the water pump when viewed from right side of the engine, contributing to the weight reduction and compactness of the DCT model.

4.2.3. 270 deg phased crank system and biaxial primary balancer

The preceding model was highly praised by customers

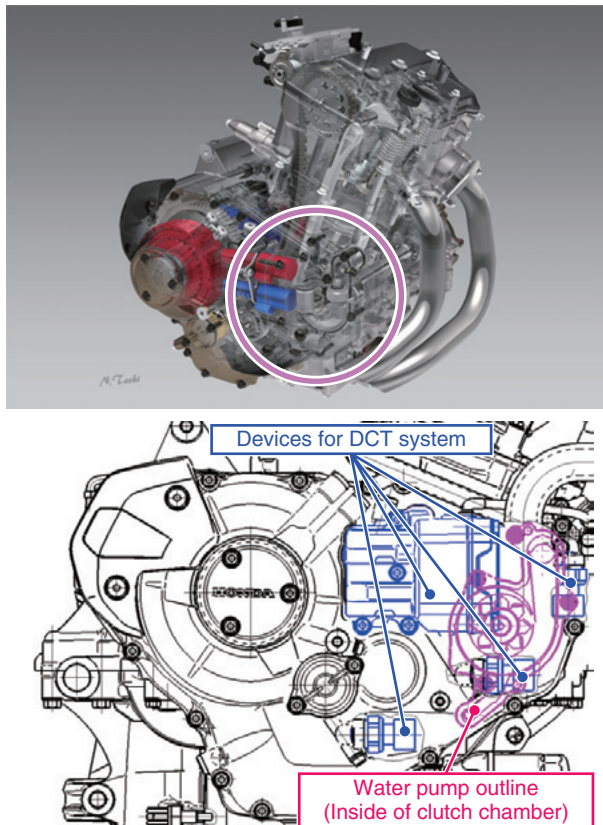
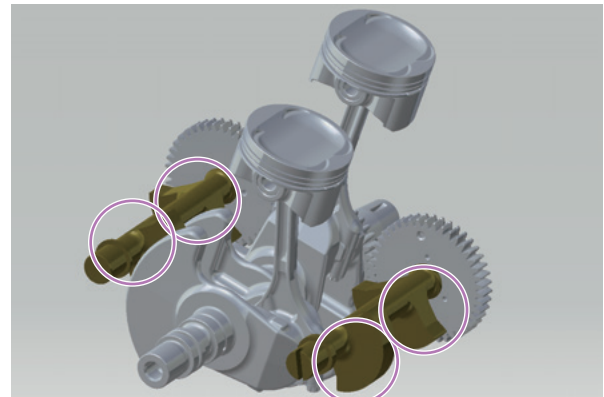


Fig. 18 Construction of water pump stored in clutch housing

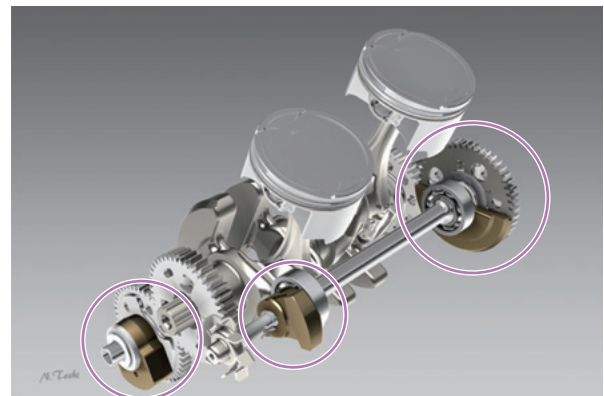
for its unique V-twin characteristics such as the easy control of power, the traction and the pulse feeling at low speeds. The parallel twin-cylinder, 270 deg phased crank system is employed in this engine to achieve further weight reduction, compactness and mass centralization while maintaining the above-mentioned favorable characteristics.

A parallel twin-cylinder engine with 270 deg phased crank system is known to have uneven combustion intervals that produce a “pulse feeling” similar to a V-twin engine⁽¹⁾. On the other hand, in a 270 deg phased crank system, while it is possible to cancel the secondary vibration by the reciprocating motions of two pistons, the primary vibrations cannot be quelled. A conventional way to cancel the primary vibration was to add two balancing weights on each of two balancer shafts. In such a system, however, the engine becomes lengthy in the longitudinal direction to avoid interference of the balancer weight and the connecting rod. To deal with this issue, a unique two-shaft, three weight balancer design⁽²⁾ that permits cancellation of primary vibrations was employed in this engine (Fig. 19).

With this new balancer design, low vibration engine characteristics were achieved while maintaining light weight and compactness.



(a) Biaxial primary balancer (Conventional type)



(b) Biaxial primary balancer (CRF1000L Africa Twin)

Fig. 19 Parallel twin cylinder using 270 deg phased crank shaft and biaxial primary balancer

5. Over View and Control Technologies of DCT for On-off Road Models

5.1. DCT System

The cross-sectional view of DCT system is shown in Fig. 20. In this model, it is assumed that when riding off-road the rider will move his/her upper body in back-and-forth direction with his feet on the pegs or stick out a leg to maintain balance in a corner. Therefore, parts located around the rider's legs should be designed not to disturb those motions. Consequently the right-side crankcase cover and the gear shift mechanism on the left-side were required to be compact. With the hydraulic system redesigned in the DCT of this model, the right-side cover protrusion was reduced by more than 10 mm compared to the NC700/750 series.

The DCT gear shift system is based on that of a manual transmission (MT). Rider's shifting effort from the shift pedal to the shift spindle is substituted by the force from the control motor via the reduction gears.

In this model, the DCT shift motor is laid at the position enclosed by the starter motor, battery box and shift spindle to achieve mass centralization and a ground clearance of 250 mm (Fig. 21).

5.2. DCT Control System

The DCT enables direct transmission of engine torque, just like the drive train of a manual transmission. The automatic gear shifting system, which requires no clutch work or shift pedal operation by the rider, allows smooth shifting of gear without interruption of traction. Such features are big advantages for an on-off road model when riding off-road because the rider can concentrate on throttle and brake operations while maintaining such traction that the rider feels the powertrain is directly connected to the

rear wheel. To take the maximum advantage of this system, the new control technologies described as follows was developed.

5.2.1. Function of G-switch

The G-switch (G means "Gravel") to alter shift mode is added to enhance off-road riding performance of the DCT model. When the G-switch is toggled, a G indicator appears in the LCD on a gauge panel to inform the rider that the G-switch is turned on. Operations when the G-switch is turned on are as follows.

The hydraulic pressure on the engaging clutch is increased more quickly than usual when the throttle is opened from a fully closed condition. This allows a faster transition from partial clutch engagement to full engagement, allowing a quick rise of traction to enhance response (Fig. 22). As a result, traction characteristics that better match rider's demands off-road, such as control of motorcycle the pitching direction and/or intentional tail slides with throttle, are provided.

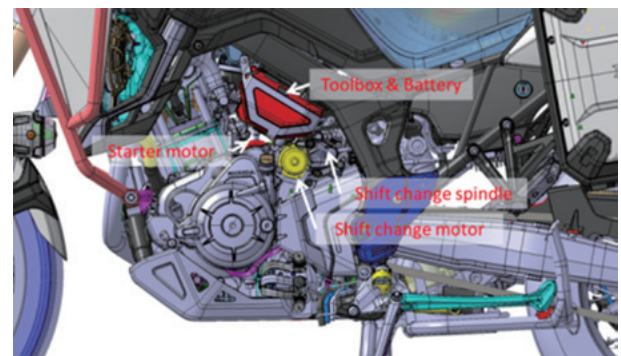


Fig. 21 Location of DCT shift motor

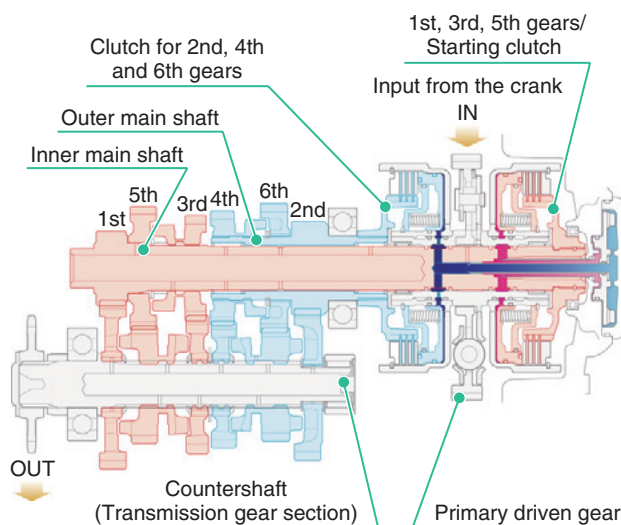


Fig. 20 DCT system

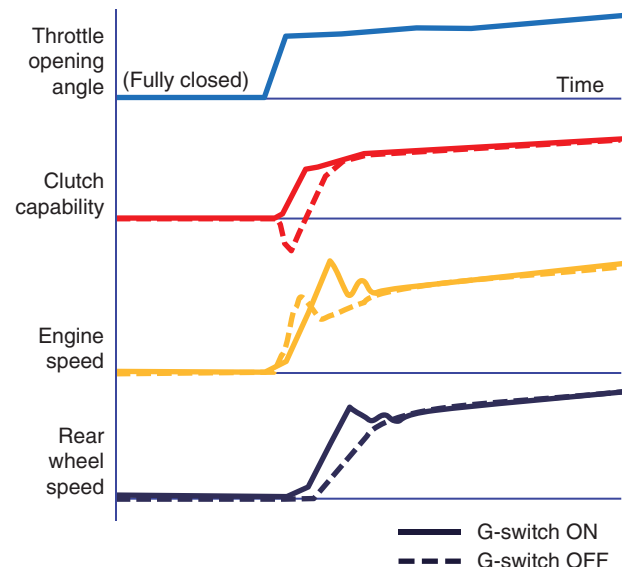


Fig. 22 Clutch capability control with G-switch

To better match off-road use, the shift schedule in Automatic Transmission (AT) mode is modified in such a manner that the vehicle speed for upshift is increased and the vehicle speed for down shift is lowered mainly in low speeds (Fig. 23).

Furthermore, presuming riders' selection of various DCT modes during riding, the G-switch function is maintained even in the MT mode to alter clutch engagement/disengagement characteristics in the same manner as in the AT mode.

5.2.2. Three-level S mode

AT modes of the DCT are roughly classified into two modes. One is D mode for fuel efficiency mainly for city use. Another is S mode for overtaking at a high speed or sporty riding. This model allows further selection of S mode in three different levels so that the rider can choose a shift schedule to his/her preference. In addition to the level 2, which corresponds to the conventional S mode, the rider can now choose the level 1, which is moderately sporty yet fuel efficient, or the level 3, which is the sportiest of all automatic modes (Fig. 24). The selected level of S mode is memorized in the ECU even after the ignition switch is turned off.

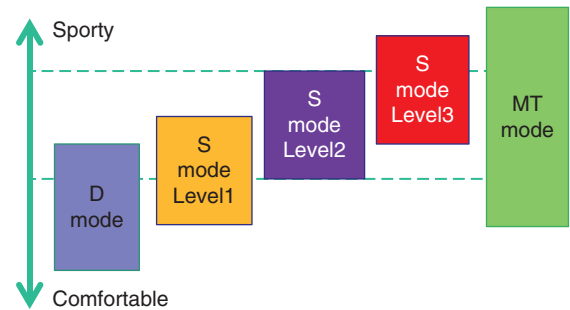
5.2.3. Gradient estimation

The gradient of a road surface is estimated by the inputs from various sensors in the motorcycle (engine speed, throttle opening, vehicle speed, gear position, brake switch, etc.). In the AT mode, the shift schedule is altered in

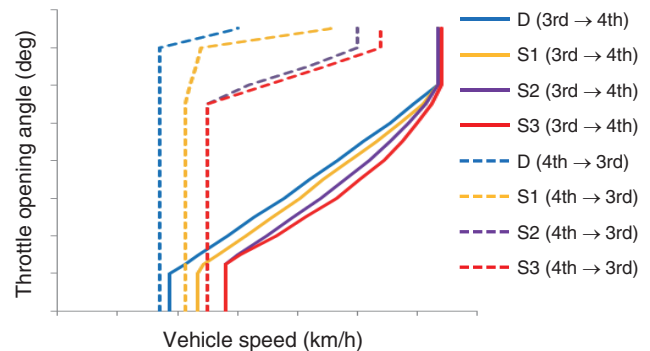
accordance with the gradient. When estimated as a downhill and the brake is used frequently for deceleration, the gear is shifted down earlier than usual to secure appropriate engine brake control. When estimated as an uphill, the shift schedule is promptly altered to allow selection of a lower gear than usual to secure sufficient traction to go up the hill (Fig. 25).

5.2.4. Honda selectable torque control

Honda selectable torque control (hereafter referred to as "torque control"), which was applied to the VFR1200X



(a) Concept of AT mode setting



(b) Example of shift schedule difference

Fig. 24 AT modes with three levels in S mode

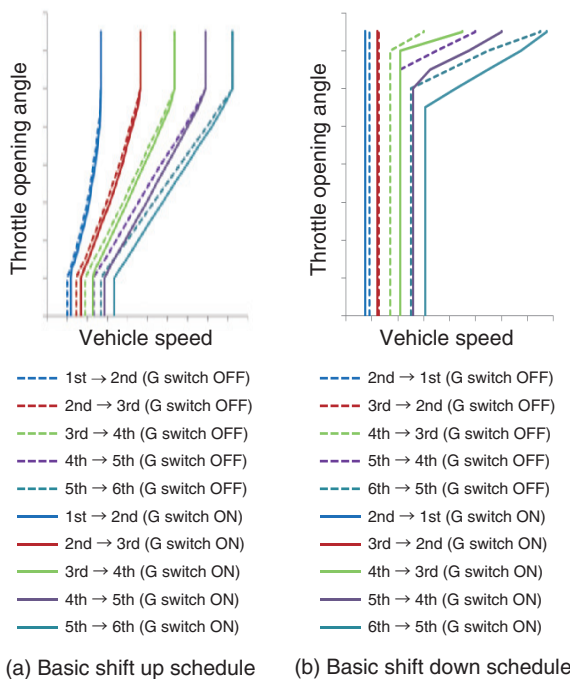


Fig. 23 Shift schedule in AT mode with G-switch on or off

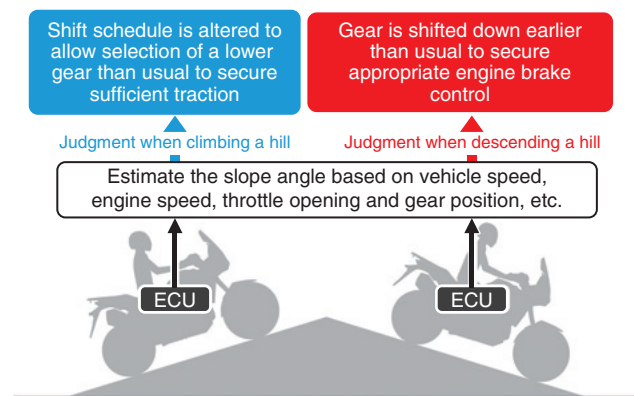


Fig. 25 Image diagram of gear-shifting control at uphill and downhill

and the VFR800X, was employed in this model (Fig. 26). The rider can select a degree of engine torque control intervention from three different levels to their preference by the torque control switch. The torque is controlled by cutting out fuel injection to each cylinder when necessary. When the order of fuel cut is inappropriate in an engine having a small number of cylinders and uneven combustion intervals, the engine torque fluctuates more. Under such conditions, not only a steady torque reduction effect become unattainable, but also the pulse feeling is reduced. Accordingly, the fuel is injected and cut as alternately as possible when the torque control is working to reduce torque while maintaining adequate pulse feeling.

This function is available when the vehicle is starting from the complete stop. This helps prevent rear wheel spin when the throttle is opened abruptly. This feature is highly important for a motorcycle with DCT that has no intervention of rider's clutch operation (Fig. 27).

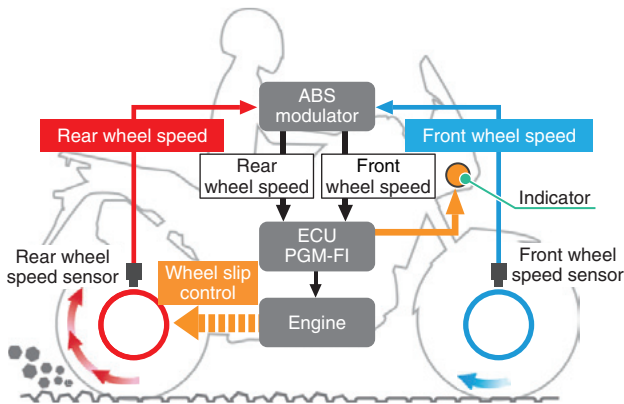


Fig. 26 Honda selectable torque control

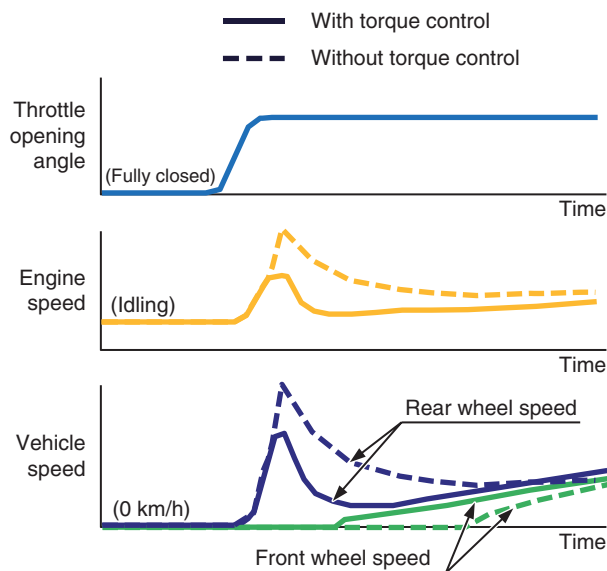


Fig. 27 Honda selectable torque control operation at start

6. Intake and Exhaust Systems

6.1. Intake System

Figure 28 shows the configuration of air intake system. To achieve the maximum trapping efficiency while giving prioritizing complete motorcycle packaging, the air cleaner is composed of right and left ducts and two air filters. The air cleaner box is a three-chamber construction positioned across the main frame behind the steering head pipe. The length of connecting tube from the air cleaner box to the throttle body was set differently for each cylinder (#1: 110 mm/#2: 160 mm) to cope with the uneven intake intervals of the 270 deg phase crank.

To cope with dusty air in off-road use and to ensure a long service life of the air filter, the intake ducts were located in the headlight side cowl, and two viscous air filters having a filtering area of 1,200 cm² were provided in the right and left sides of air cleaner box.

To keep intake noise at a low level while avoiding a weight increase from use of devices such as a flap in the intake duct, an intake duct having a diameter of 25.2 mm, which is as small as those of small displacement engines, was applied. A tapered duct, in which the diameter increases from 25.2 mm to 50.6 mm toward the downstream of air flow, was also applied to reduce suction resistance and achieve the target power output while ensuring drivability. Further, the overall length of duct was set at 286 mm to increase power output by the inertia effect from resonance in the intake system.

6.2. Exhaust System

To represent the concept of this particular model, the aim was to realize an exhaust sound with boldness brought by a 1,000 cc class engine and a distinctly accented beat that is typical character of a twin-cylinder engine offering a light impression. For the sound quality evaluation, criteria such as “deepness” and “pulse feeling” were used. These indexes

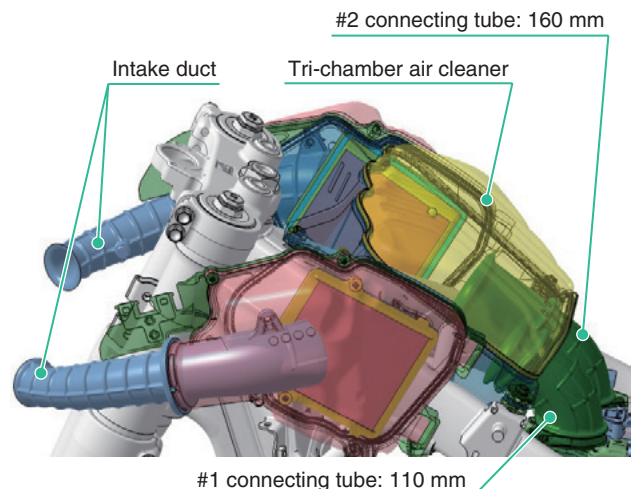


Fig. 28 Configuration of air intake system

are an average of the subjective evaluation scores given by a number of evaluators. Deepness is closely correlated to the sound pressure in the low frequency zone, while the pulse feeling is strongly correlated to the combustion intervals of engine and the sound pressure in the high frequency zone⁽³⁾.

The construction of the muffler employed in this model is such in that an outlet pipe open to the atmosphere from the second expansion chamber is added to the conventional three-chamber-return construction. It is such a construction that has two tail pipes; one that connects the secondary expansion chamber to the atmosphere and another one that connects the third expansion chamber to the atmosphere (Fig. 29).

If the conventional three-chamber-return construction is applied when the sound level has to be lowered to a certain level, the high frequency components lower more, which tends to lower the assessment score in the pulse feeling. In this model, however, with the above-mentioned construction employed, the sound pressure in the high frequency zone is maintained, allowing the addition of effects from the frequency characteristics to the effects from the combustion intervals of engine when evaluating pulse feeling.

Sound pressures measured at each tail pipe outlet of the second chamber and the third chamber are shown in Fig. 30.

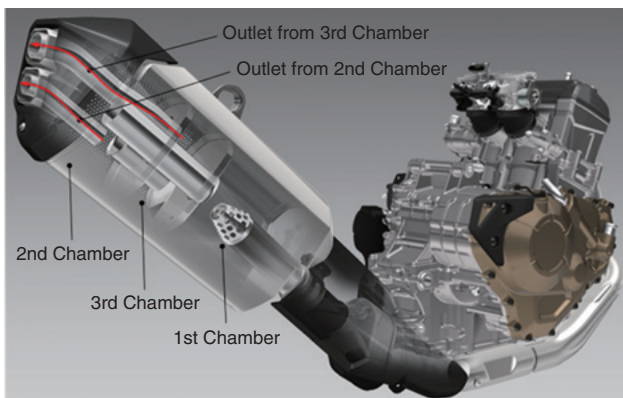


Fig. 29 Structure of muffler

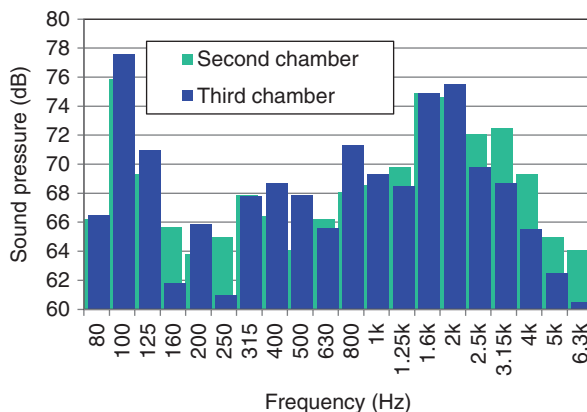


Fig. 30 Measurement results of exhaust sound pressure

It can be understood from the data that the sound pressure in the high frequency zone above 2.5 kHz is higher in the pipe from the secondary chamber construction than in the pipe from the third chamber. As the frequency characteristics of the tail pipe from the third chamber are considered as those of the conventional three-chamber-return construction, the enhanced pulse feeling can be considered as an effect of the tail pipe from the second chamber.

In the meantime, the sound pressure of the tail pipe from the third chamber is high in the low frequency zone around 100 Hz, which contributes to the deepness. The target exhaust sound quality was attained by tuning the diameter of each pipe while maintaining balance with the frequency characteristics and taking into account the total sound level and the power output characteristics.

The evaluation results of exhaust sound quality compared to the conventional models are shown in Fig. 31.

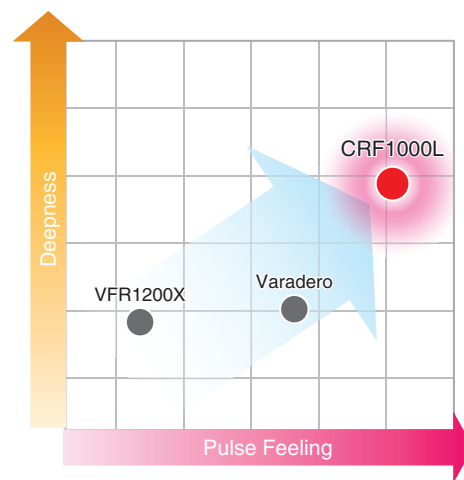


Fig. 31 Evaluation results of exhaust sound

7. Gauge Panel and Switches

7.1. Gauge Panel

Maintaining the image of a gauge panel for rally completion motorcycles, which is easy to read without changing the line of sight right and left, two negative LCD panels are placed vertically, and the display functions are clearly separated by the split line of the upper cover (Fig. 32). The meter select/set switch, which used to be located on the gauge panel, was relocated to the handlebar as mentioned earlier. Thus the stylish gauge panel design was realized. The split lines were also provided around the indicators, which were placed symmetrically beside the meter in a functional manner, thus producing an image of a cockpit.

The speedometer and the tachometer, which should be easiest to read when riding, were located in the upper center of the gauge panel where the rider requires the

least change of sight line. The multi information display was located below the upper LCD to shown abundance of information in the limited space in an easy-to-read manner (Fig. 33).

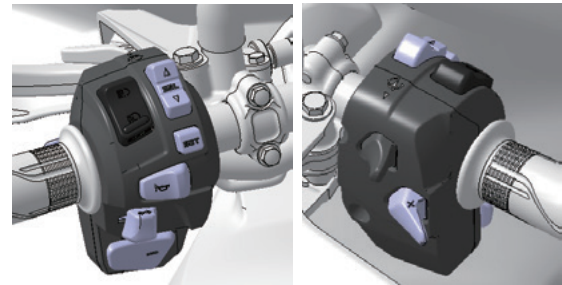
The indicators for DCT mode, gear position, G-switch selection, and torque control level, etc. were also gathered into the right and left indicator units to provide information in an easy-to-read manner.

7.2. Handlebar Switches

The torque control switch and the meter select/set switch were added as a left handlebar switch to allow operation with a minimal finger travel while holding the hand grip [Fig. 34(a)]. The shape and location of switches were elaborated through the operate-ability tests, actual test riding, etc. to best match finger movements and to obtain best “click” feeling and “fit” feeling. The frequently used turn signal switch was located on the lower side of the handlebar for easy operation. Regarding the shift switch for DCT, the shift up switch was located on the back side of the left handlebar switch to allow operation with the left forefinger [Fig. 34(b)], and the shift down was located

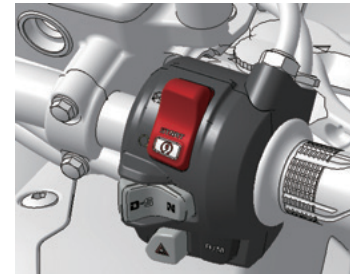
in the front side for operation with the thumb. All those considerations made switch operations easier and surer than ever.

The engine stop/starter combination switch, the AT/MT selector for DCT, and the hazard switch were located on the right hand side of handlebar [Fig. 34(c)]. All switches on the right hand side were laid out to allow operation only with the thumb.



(a) Left handle switch

(b) Shift up switch for DCT on the back side of the left handle



(c) Right handle switch

Fig. 34 Handle switch

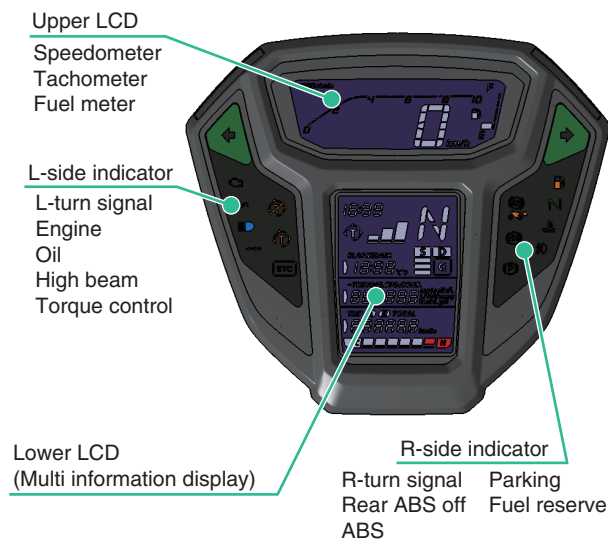


Fig. 32 Gage panel

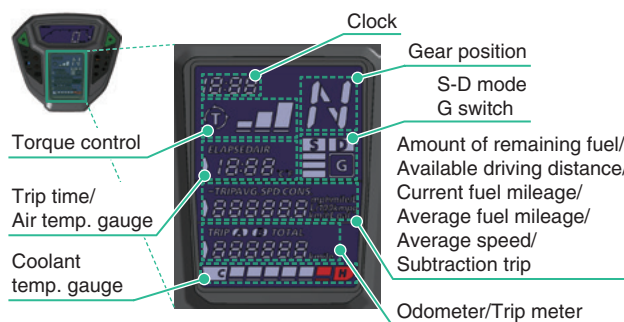


Fig. 33 Multi information display

8. Conclusion

The following were achieved through the development of CRF1000L that adopted technologies suitable for the next generation model while maintaining the heritage of the preceding models.

- (1) Both off-road capabilities and comfort on street including high speed conditions.
- (2) Honda's first DCT tuned for an off-road model is effective on gravel as well as on pavement.

As a result, many customers commended the motorcycle, saying “this is the Africa Twin.”

We hope customers use CRF1000L regularly for a long time as a partner on long trips, as well as for various day to day activities.

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ABSTRACT

The PIONEER 1000 was developed to serve as a flagship model for the PIONEER series in the North American market for Side by Side vehicles, also known as recreational off-highway vehicles. Three-passenger and five-passenger types are made available, both applying a new 999 cm³ parallel-twin engine, the largest in the Side by Side market, and for the first time in the Side by Side market a dual clutch transmission. These are built with a common platform and have excellent versatility, function and durability deriving from the numerous technologies applied. It is a model that presents an enhanced appeal within Honda's multi-category PIONEER series that is popularly used for various purposes such as recreational activities and practical work.

1. Introduction

The history of Honda's off-road buggies began with All-Terrain Cycle (ATC) US90 of the 1970s, the world's first three-wheeled vehicle that a rider would straddle, later evolving into the four-wheeled all-terrain vehicles (ATV) that continue to grow in the North American market to this day. Honda also developed four-wheeled buggies (FL), in which a driver would sit on a seat with back support, beginning with the FL250 (ODSSEY 250), followed by the FL350R (ODSSEY 350R) and the FL400R (PILOT 400R), which were sold on the market until 1990. These ATCs, ATVs, and FLs were all single-rider models. Side by Sides, on the other hand, maintain the mobility and trail capability of ATVs while accommodating multiple passengers to enjoy activities such as hunting and trail driving; their increased cargo and towing capacities allow them also to be used for practical work on farms (Fig. 1). Due to these reasons, the Side by Side market has markedly grown since 2003, and it is still growing as of 2016. There is a wide range of models made available from various manufacturers, with passenger capacities of 2 to 6 and engines having displacements of 150-1000 cm³. Honda's inaugural Side by Side was the BIG RED 700, followed by the PIONEER series that consisted of the PIONEER 700 and the PIONEER 500, and the PIONEER 1000 that we are introducing in this article.

Generally large-capacity Side by Side vehicles are larger and prone to a loss of mobility and maneuverability. The PIONEER 1000 applied a technology that allows the rear seat to be folded and stowed for a more compact body. Coupling a high-power engine with the dual clutch transmission (DCT) and applying long-travel suspension

and large tires, we were able to create points of appeal that would enable the product to be the best in class. Hereafter we introduce the PIONEER 1000 (Fig. 2, Fig. 3, Table 1).



Fig. 1 Usage example of a Side by Side

* Motorcycle R&D Center

Table 1 Model variation and features

Features	3P STD	3P EPS	5P EPS	5P DLX
27 inch bias tire	○	○	○	
27 inch radial tire				○
Aluminum wheel				○
Electric power steering		○	○	○
Tilt steering		○	○	○
Color panel		○		○
Camouflage color		○		○
Manual shift mode		○	○	○
Self-leveling suspension			○	○
LED head light				○



Fig. 2 The PIONEER 1000-3



Fig. 3 The PIONEER 1000-5 DLX

2. Development Aim

PIONEER 1000 was developed under the concept of “King of Works Hard, Play Hard.” The Side by Side market offers models having multiple rows of seats (front and rear) for 4 to 6 passengers, allowing a group of people to enjoy recreational activities together such as trail riding. However, securing cargo space makes the wheelbase longer, enlarging the turning radius and thus impacting the handling that is useful in work such as patrolling on farms and transporting cargo. We utilized Honda’s own packaging technology to provide the model with the maneuverability of a two-passenger vehicle while accommodating a higher number of passengers. Another aim was the achievement of excellent

performance in driving power, trail drivability, ride comfort, quietness, low vibration levels, and workability such as towing and cargo capacities. Further, we aimed to make the model available at a reasonable price for customers by lowering product costs, achieved by using common base frame parts of the frame body, excluding the three-passenger rear bed components and five-passenger rear roll bar.

3. Engine and Powertrain

Based on the concept of the model being a flagship, the following were determined as its targets:

- A lightweight, compact engine with a low center of gravity that would provide both sufficient passenger space and ground clearance.
- High driving power that would allow the vehicle to easily climb a steep angled slope (estimated as having the steepest angle for use of a multi-category Side by Side), while fully loaded, at maximum towing capacity and the sub-transmission in the high range (Fig. 4).
- The acceleration and maximum speed of the vehicle was to become the highest level for the class.
- Transmission that achieves both the convenience of an automatic and a more direct drive feel.

In order to achieve these targets, the engine displacement was set to be 999 cm³, the largest for a Side by Side, the engine to be a liquid-cooled with overhead camshaft (OHC), 4 valves, and inline 2-cylinder system, and the transmission to be a DCT with a sub-transmission.

The key specifications are provided in Table 2.

3.1. Engine Packaging

3.1.1. Engine installation direction/position, axial positioning

From the perspective of mass concentration and weight reduction, the engine and transmission were integrated. The engine was to be located in the center of the vehicle from the perspective of the vehicle’s front-rear weight distribution and placed in the longitudinal direction,

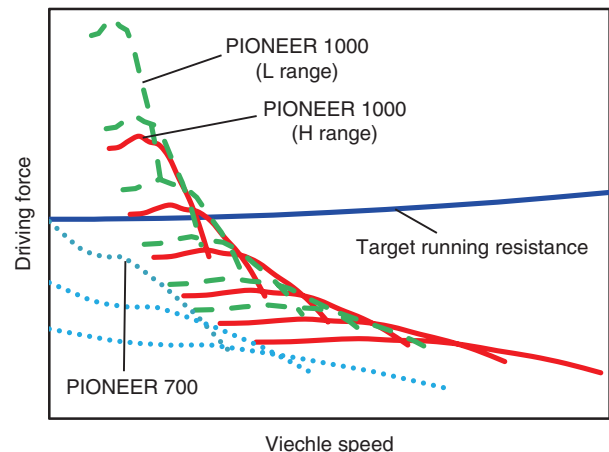


Fig. 4 Driving force diagram

Table 2 Engine specifications

Engine type	Liquid-cooled 4-stroke
Cylinder arrangement	Parallel
Number of cylinder	2
Crank angle	270 degree
Bore/Stroke	92 mm/75.2 mm
Displacement	999 cm ³
Compression ratio	10.0:1
Maximum power (Counter shaft)	50 kW/6000 r/min
Valve train	Unicam/4 valve
Lubrication	Dry-sump
Balancer	Single-shaft Primary-balancer
Transmission	6-speed DCT transmission + subtransmission

eliminating the need for a bevel gear (Fig. 5).

We achieved the targeted weight balance by placing the engine so it is partially under the front seat, with the cylinder head and the intake system towards the back of the front seat (Fig. 6).

3.1.2. Dry sump structure with a built-in oil tank in the engine

Many Side by Sides apply a dry sump to secure engine pressure stability in conditions such as steep uphill, downhill driving and traverse driving while keeping the engine height low. With this model, we applied a dry sump structure in which the oil tank is integrated in the engine to

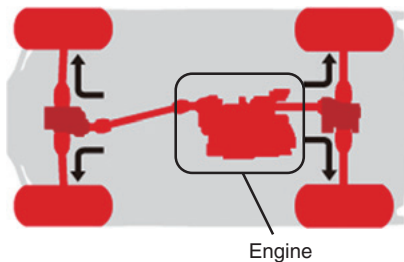


Fig. 5 Engine placement (plain view)

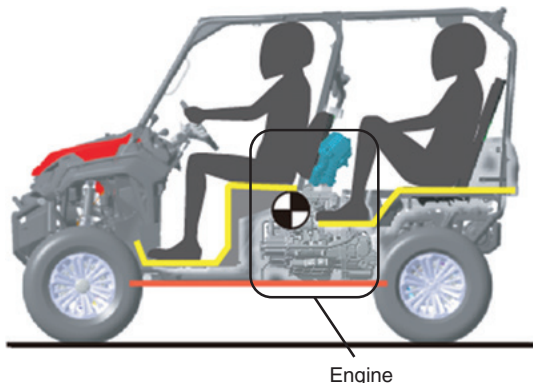


Fig. 6 Engine placement (cross-section)

take it further and reduce the number of parts (Fig. 7).

The oil pan was made flat to keep the overall engine height at 525 mm and the distance between the output shaft and engine bottom at 116 mm. This allows the vehicle to achieve the targeted ground clearance and passenger space, as well as lowering the center of gravity (Fig. 8). An oil tank was formed on the cover in the rear of the engine and integrated into the engine. No longer needing a separate oil tank and piping, this allowed for a reduction in the number of parts as well as a more concentrated mass.

3.1.3. Unicam valve train

The Unicam valve train system (Fig. 9) was applied to achieve reductions of the weight and size of the engine while enabling high power performance. With this, it was possible to reduce the weight by 800 grams and the size of the cylinder head compared to a general dual over-head camshaft (DOHC) mechanism, both of which contributed to securing adequate passenger space and a lower center of gravity.

3.1.4. Transmission

A DCT system was applied for the model to have the convenience, efficiency, and usability at low speeds of an

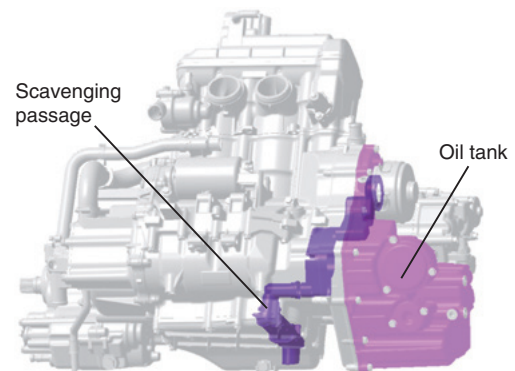


Fig. 7 Dry sump system

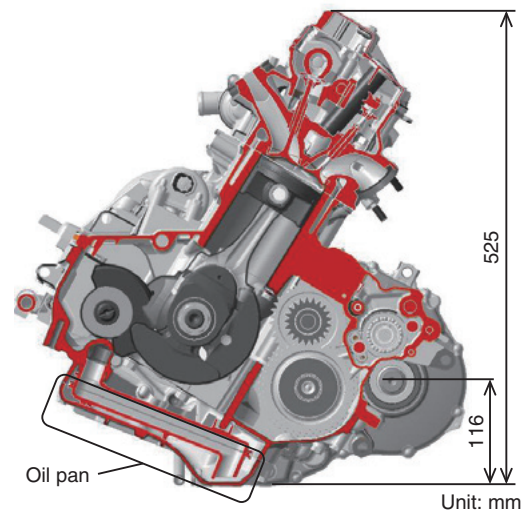


Fig. 8 Cross-section of the engine

automatic transmission (AT) system. As shown in Fig. 10, this DCT system is a carry-over from what is applied to basic structure of the NC 700 series⁽¹⁾ in the motorcycle category. Increasing the number of the discs and plates of each clutch from 3 to 4 provides enough clutch capacity required for recreational uses and utility work. The sub-transmission is positioned towards the lower stream of DCT's power transmission path, and has built-in gears for normal driving (high range), utility work (low range), and driving in reverse (reverse range). The sub-transmission also has a parking dog built in. The structure is a carry-over from Honda automobiles. Figure 11 shows that the parking dog is placed along the outer circumference of low range transmission dog to reduce the number of parts.

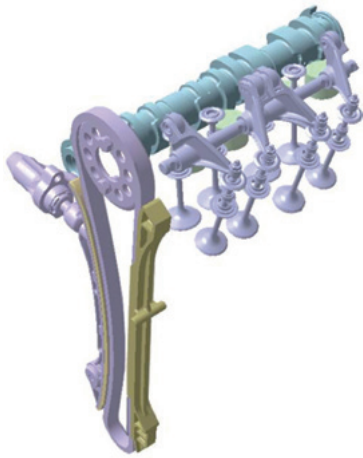


Fig. 9 Unicam valve train system

3.2. DCT Control

Hereafter, the control that was newly developed for use on Side by Sides is explained.

3.2.1. Vehicle start control of the clutch

The ECU receives various types of information from the vehicle, including information about clutch rotation, clutch oil pressure, vehicle speed, and throttle open angle. Based on the information received, the ECU calculates the necessary driving power for the road conditions and applied load in real time. By controlling the clutch oil pressure with such a mechanism, the vehicle take-off has been made smoother. With this particular model, because of the considerations needed for uphill/downhill driving and ease of heavy

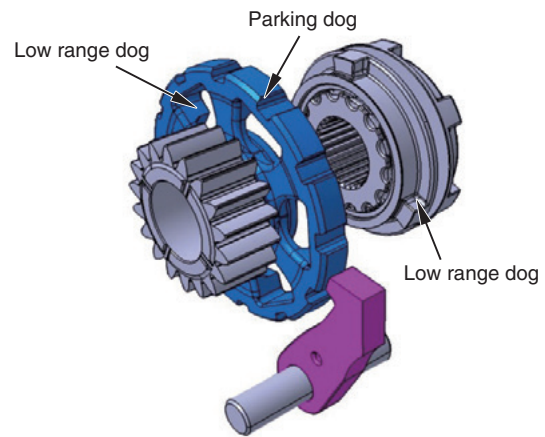


Fig. 11 Parking dog

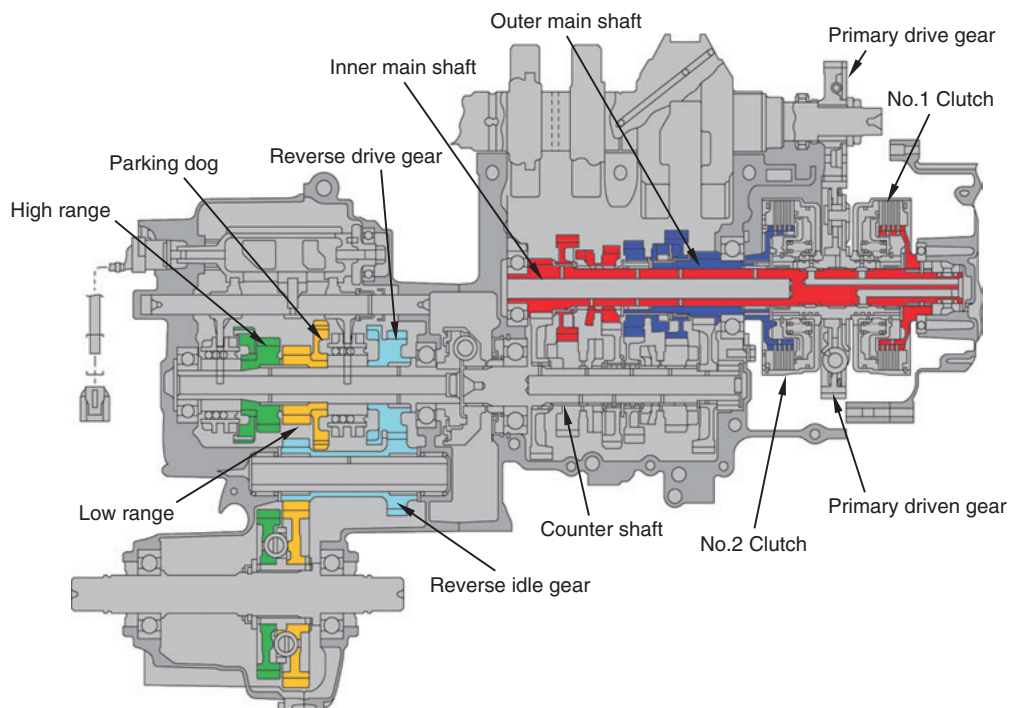


Fig. 10 Transmission layout

towing, smooth control is required at a very low speed range (3 km/h or below). To meet this need, we added a DCT-exclusive speed sensor on the engine, improving the sensing resolution by nearly 300%, to provide an improved and very smooth clutch control at very slow speeds (Fig. 12).

3.2.2. Clutch control when driving

When opening and closing the throttle, a typical transmission hesitates momentarily, causing a change in the driving power and affecting the vehicle behavior. To mitigate this effect, we added a control to lower the clutch oil pressure for a short moment (approximately 300 ms).

With Side by Sides, engine braking when driving down steep slopes is also important. Therefore, the clutch needs to be engaged during deceleration up until immediately before stopping. However, setting up a system in this manner would cause the engine to stall due to a delay in clutch disengagement in situations such as locked tires when braking immediately before stopping. The engine would also be prone to stalling due to engine locking when doing “hard braking” on slippery surfaces such as snow.

In order to prevent such engine stalls, we applied an algorithm that predicts tire locking by monitoring various rates of changes, in addition to clutch control using vehicle speed and engine speed information. This allows for the quicker sensing of a sudden deceleration, making it possible to swiftly disengage the clutch in situations where tires may lock up.

Another cause of clutch disengagement delay is the decrease of clutch oil pressure response in extreme low temperatures, a condition to which Side by Sides are often exposed. As a countermeasure for clutch disengagement delay, corrections by oil temperature were newly added on the control logic.

3.2.3. Shift timing control

In the AT mode, the shift timing setting was made with considerations for ease of use in recreational and practical

work scenarios. For those customers who wish to enjoy a sportier driving style, Sport mode is also available.

When the sub-transmission is in low range, the low-speed gears will be used more frequently. This allows for the model to have a characteristic of ease of use in lower speeds, such as towing heavy items. For the shift timing control logic, the latest motorcycle DCT know-how was applied for use in Side by Sides.

- Predictive cornering shift: Prevents unexpected upshifts when cornering.
- Deceleration adaptive shift-down control: The greater the deceleration amount, the greater the vehicle's shift-down speed is transferred, enhancing the effect of engine braking.
- Automatic map-switching control: The system learns the frequency of the driving load to optimize shift timing.

With regard to the driving style characteristics of off-road vehicles, such as carrying cargo and/or towing, uphill/downhill driving, and tail-sliding, we applied the DCT control technologies built for the TRX420 series ATV to provide drivers with optimal shift timing that respond to individual driving styles and the environment in which the vehicle is driven.

3.3. Powertrain Control System

3.3.1. DCT control system

The paddle shifter that we applied, which enables the driver to shift gears while holding the steering wheel, allowing for quick maneuvering in various driving conditions (Fig. 13). Excluding the three-passenger standard model.

For this particular model, much effort was put in to make it suitable for a flagship model. A detent mechanism was added to the paddle shift structure previously applied to PIONEER 500 to create a high-quality operational feel. Because of the nature of the product's use and the likely exposure to water and dust, the paddle shifter was robustly constructed to make it more durable and more stable in terms of operability.

Figure 14 shows a switch that was applied to switch between the AT and MT modes, which also allows the rider

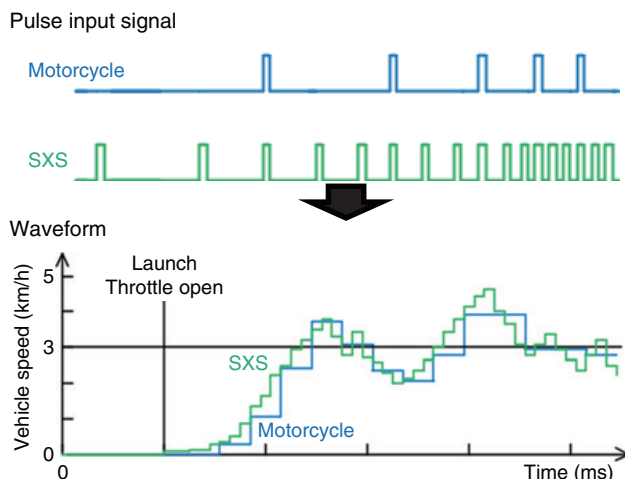


Fig. 12 DCT speed sensor

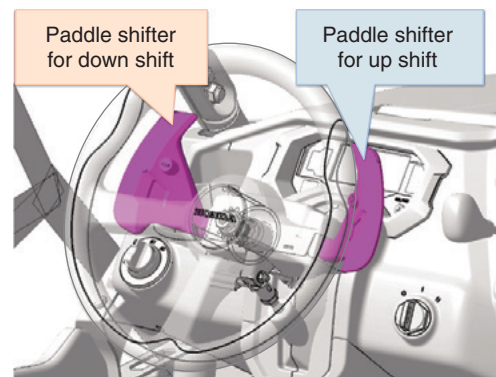


Fig. 13 Shift paddles

to switch to Sport mode within the AT mode.

When in the AT mode, the driver can select to choose the MT override mode by operating the paddle shifter. Using information such as throttle opening angle and vehicle driving speed, it smoothly returns from MT override mode to AT mode with the automatic return function at an appropriate timing. This makes it possible to drive comfortably even when in MT override mode.

3.3.2. Sub-transmission control system

The single lever sub-transmission shift capability that was explained earlier (Fig. 15).

Operating the lever drives the spindle shaft joined to the sub-transmission, so it can switch among parking, reverse, neutral, high range and low range positions.

With this model, Figure 16 shows the lost motion is structured with springs on the sides of the shift fork to improve the feel of shift lever operation.

3.3.3. Drive mode switching mechanism

The driver can select the desired drive mode to meet usability and road conditions from four drive modes using a mechanical mode select lever (Fig. 17).

The four drive modes are: 2WD, 4WD, 4WD Diff Lock, and Turf, which is designed to avoid damage to lawns and pasture grass when turning the vehicle with the rotation difference between inside wheel and outside actuating of front/rear differential gear. The actuation condition of the

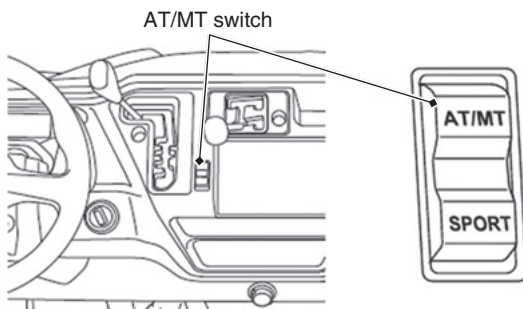


Fig. 14 AT/MT switch



Fig. 15 Shift lever

front/rear differential is shown in Fig. 18. For switching between 2-wheel drive, 4-wheel drive and differential lock, a simple, light and compact mechanical structure (Figs. 19 and 20) was applied.

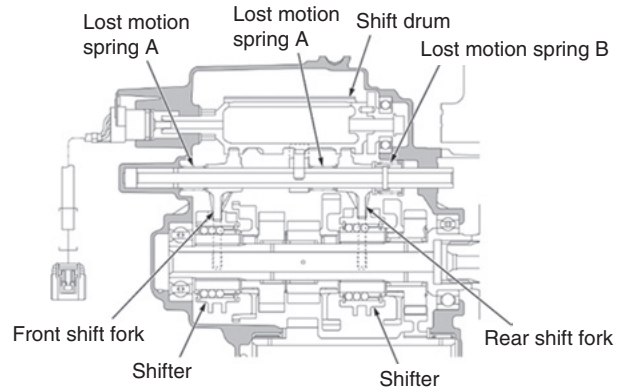


Fig. 16 Lost motion structure



Fig. 17 Drive mode select lever

	Front	Rear	Drive mode indicator
Turf	○	○	
2WD	○	●	
4WD	○	●	
4WD DIFF LOCK	●	●	

○ : Differential ● : Differential lock

Fig. 18 Drive mode

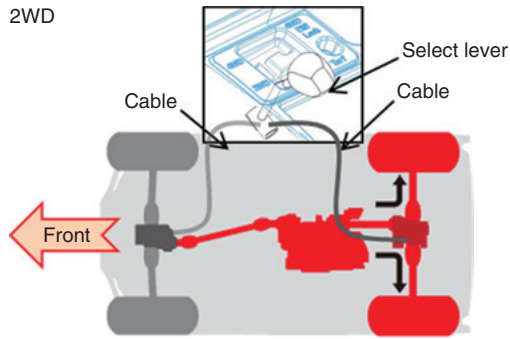


Fig. 19 2WD mode

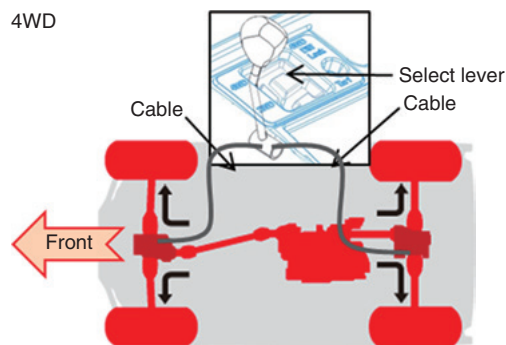


Fig. 20 4WD mode

4. Vehicle Body

4.1. Vehicle Body Packaging

As mentioned in the development aim, securing cargo space necessary for practical work and two rows of seating makes the wheel base long and turning radius greater, making the vehicle unable to have the level of mobility and maneuverability of an ATV. For this model, based on the commonization of the platform between the three- and five-passenger models, we studied how we could make the vehicle body compact, with a shorter wheelbase and narrower width, while still securing an adequate amount of comfortable passenger space necessary for a flagship model.

In order to make the body compact with minimized overall length and a narrower vehicle width, the following three methods were applied.

- Intake parts placed above the engine
- Application of the QuickFlip® seat for the rear row
- Application of a three-passenger seat in front having a new structure

By doing so, we were able to create a complete vehicle with comfortable passenger space with a short wheelbase of 2036 mm and excellent maneuverability, with a minimum turning radius of 4.2 m that is top-in-class level (Fig. 21, 22).

4.1.1. Positions of the engine and air cleaner

For the engine, we minimized the distance between the output shaft and the engine bottom, as well as lowering the overall height, and positioned it under the front seat in the center of the vehicle. The cylinder head was positioned towards the rear end of the front seat and the air cleaner placed above it. This allowed for the shortening of the

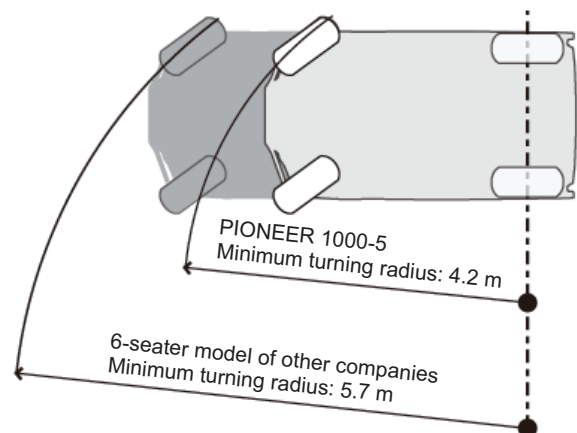


Fig. 21 Turning radius

vehicle's overall length. Also achieved was high ground clearance (327 mm for three-passenger type, 314 mm for five-passenger type) and low center of gravity to improve vehicle stability. Further, the seat height and cargo bed were made low (Fig. 23).

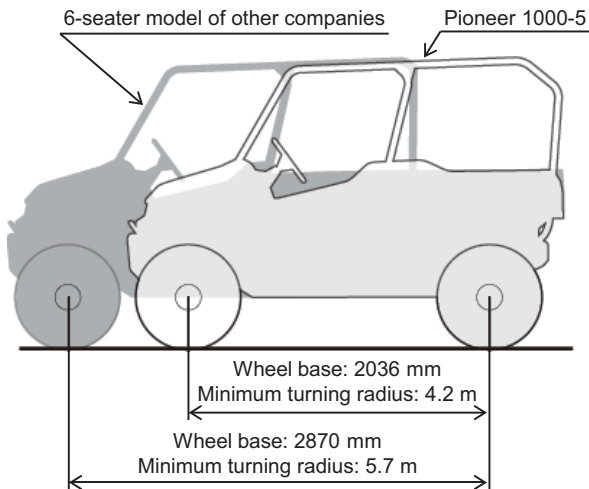


Fig. 22 Comparison of wheel base

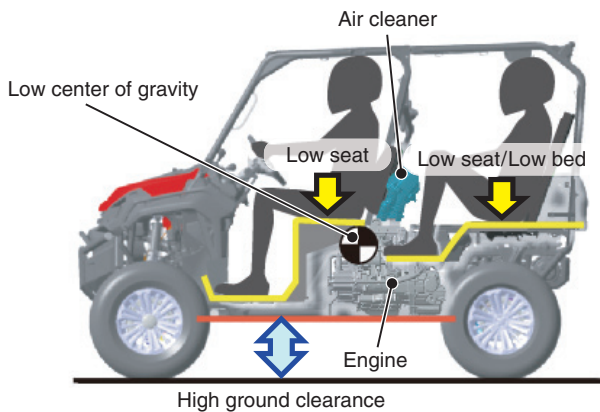


Fig. 23 Location of engine and air cleaner

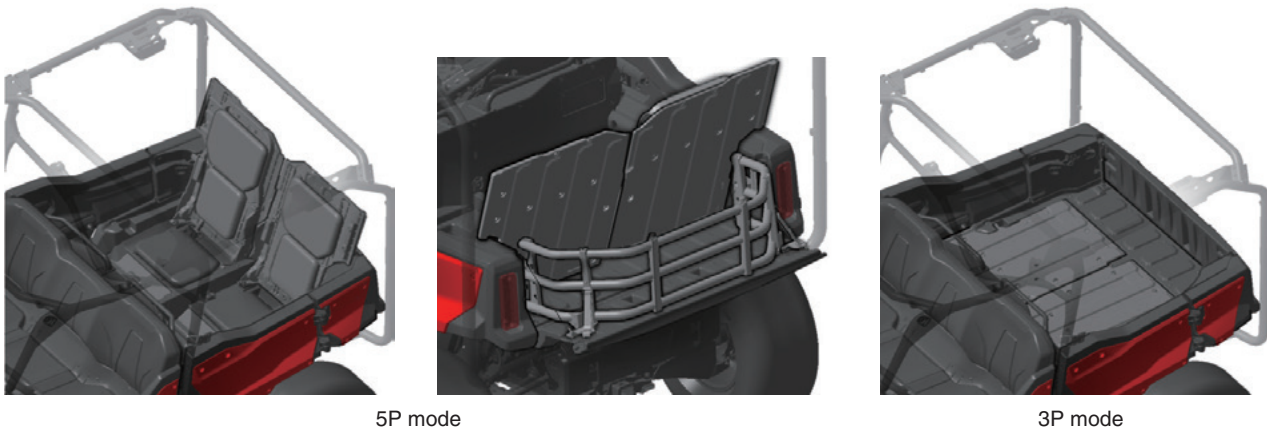
4.1.2. QuickFlip® seat

To solve the issue of a multi-passenger vehicle's tendency to demand a longer vehicle length, for this model we applied QuickFlip® seats to the rear passenger area, a Honda original technology first applied to the PIONEER 700 that allows the rear seatbacks to be folded independently (Fig. 24). The QuickFlip® seat was set to accommodate an AM 95th percentile. Combined with the three seating positions in the front, the model accommodates a total of five passengers. Stowing the seatbacks creates a cargo space having the dimensions of D 1200 mm × W 915 mm (horizontal measurements at the center of loading space). It also retains the ability to tilt the cargo space to dump the load (Fig. 25). The folding and opening of the seats can be done easily and without tools.

With the application of the QuickFlip® seat technology, the cargo space can carry up to 1000 lbs. (454 kg) for practical work. There is also enough capacity in the cargo space behind the seats to accommodate items such as lunch while seating five passengers during recreational use when QuickFlip® seats are expected to be used.



Fig. 25 Dump function



5P mode

3P mode

Fig. 24 QuickFlip® seats

With this, we were able to create a complete vehicle with excellent maneuverability while also securing enough cargo space.

4.1.3. Three-passenger seat in the front row

Vehicle width is often expanded in trying to secure comfortable space for the front-row seat accommodating three passengers at AM 95th percentile. With this model, however, it was required to make the vehicle body compact, with not only a short wheelbase but also a narrower overall width as well. Further, because practical work involves frequent ingress/egress, there was also a need to apply a bench type seat that allows smooth right-left position changes. For these reasons, we developed and applied a three-passenger bench seat. The center seat has the following differences from the adjacent seats: the seat bottom is raised by 18 mm, the hip point is pushed forward by 45 mm, and the seat back is reclined by 4 degrees.

Reclining the center passenger's seat creates a positional offset among the driver and passengers, giving them more shoulder space, making the front row space more practical and comfortable (Fig. 26). Hand-holds were placed on the sides of the center seat for its occupant so as to not block the walk-through path. The bench seat is shaped to better keep occupants in their seats even when in rough driving conditions.

4.2. Quietness Technologies

The targets for quietness were set as follows: allowing occupants to hear each other in conversations up to the speed where wind noise becomes an issue (30 mph); and maximum of 83.5 dB for noise close to the ears at the driver's seat when driving at a cruising speed of 30 mph or below. The intake was placed inside the front hood, further away from the occupants compared to past models, lowering the level of the noise generating in the intake. To mitigate pipe resonance, two resonators were built into the intake duct (Fig. 27). Sound absorbents were also placed to mitigate radiated sounds from the engine and air cleaner box located near the front seat occupants as shown in yellow figure (Fig. 28). Further, when cruising, radiated sound from the engine is suppressed by controlling the DCT shifting timing to keep engine speed low. Through

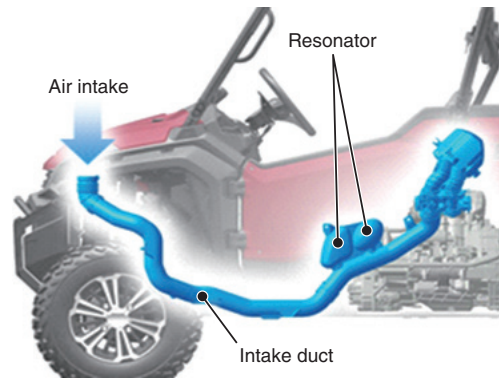
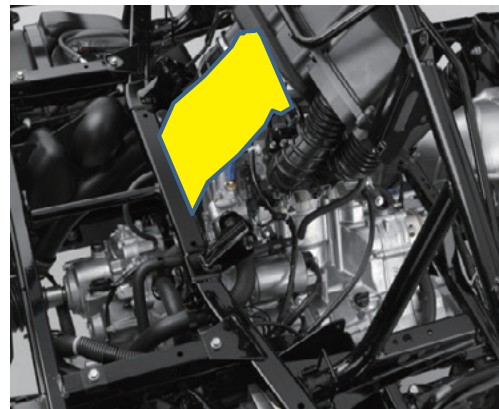
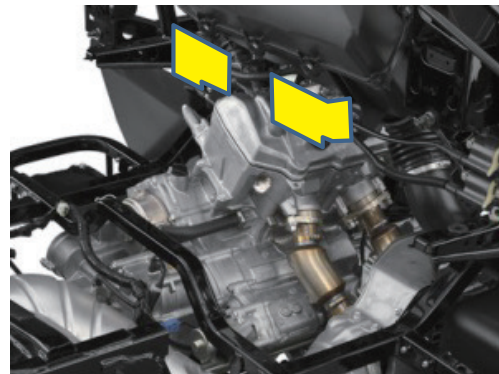


Fig. 27 Intake duct layout



(a) Front side



(b) Rear side

Fig. 28 Noise absorbent location



Fig. 26 Bench type front seat

such technologies the model achieves a level of quietness (Fig. 29) that is advantageous as a flagship model, allowing the occupants to enjoy conversations. Figure 29 shows a comparison of the PIONEER 700.

4.3. Low Vibration Technologies

To mitigate vibration, rubber engine mounts are required due to their effectiveness in damping vibrations at all engine speeds. In particular, when damping vibrations at idle, the spring characteristics need to be greatly reduced compared to those used for previous Honda ATVs and Side by Sides (Fig. 30). As such, we adjusted the spring characteristics on a rubber mount made for a small Honda automobile that has the same engine weight; this resulted in engine vibration mitigation in all ranges, including idling, and realizing a level of vibration that is comfortable for occupants (Fig. 31).

4.4. Intake System

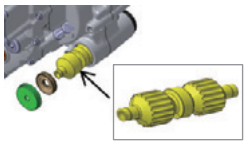
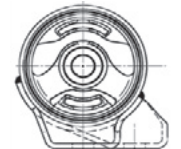
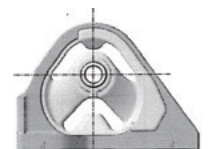
Side by Sides often are used in very dusty off-road conditions. Because plain bearings are used as engine crank shaft bearings in the PIONEER 1000, as compared to the ball bearing equipped engine used in conventional Honda Side by Sides, there was a need to make it more difficult for dust to enter the engine. To accomplish this, for the first time on any Honda Side by Side or ATV, we applied a wet filter paper type air cleaner element that absorbs more dust than the conventional wet urethane type. However, wet filter paper type filters require replacement. The replacement interval was extended by making the air cleaner element's filtering surface area 8 times larger than the washable wet urethane type applied to the PIONEER 700, the previous model. Also, the intake was placed inside the front hood, where dust is less likely to accumulate (Fig. 27). Through these measures, we aimed to reduce the amount of dust that enters into the air cleaner.

4.5. Exhaust System

Gaining high torque from low engine speeds requires

the exhaust pipe to be long. To secure passenger space for the rear passenger seats, the pipe layout was set as shown in Fig. 32. Giving the muffler a capacity suitable for a 1000 cm³ class engine made it heavy, so, with consideration to the right-left weight balance, it was placed in the center of the rear of the vehicle. The exhaust pipe and muffler were joined at a perpendicular angle.

The exhaust system is supported in a way that engine vibrations and vehicle body vibrations, such as jolts coming from road input are mitigated. To enable the system to absorb vibrations from all directions, we applied hanging rubber mounts (Fig. 32) and a spherical joint system

	Mounting rubber shape	Z-direction stiffness comparison with TRX 680
TRX 680		100%
PIONEER 1000		19%
Honda small automobile		19%
PIONEER 700		60%

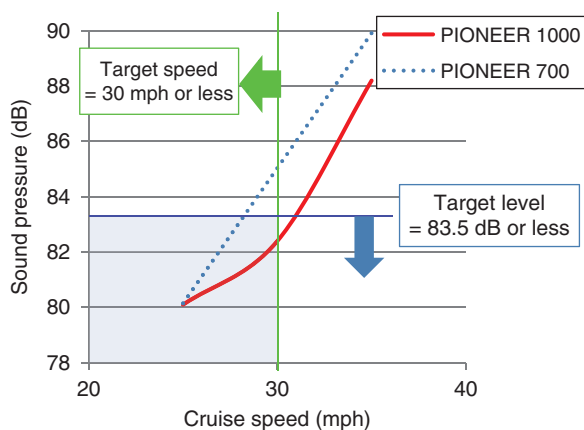


Fig. 29 Cabin noise target and measurement result

Fig. 30 Dynamic spring characteristics and shape

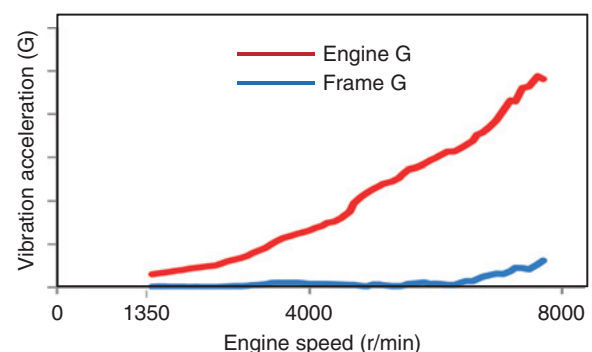


Fig. 31 Vibration mitigation effect

(Fig. 33). Through such measures, the vibrations were mitigated while supporting a heavy muffler with a simple and light-weight method.

4.6. Electrical System

4.6.1. Headlights

The five-passenger deluxe model applies LED headlights, the first for a Honda Side by Side. This gives the model top-in-class brightness while keeping power consumption at only 70% (in low beams) of Honda's conventional light bulbs. To give the feel of brightness to the drivers, the lamps used have the color temperature of 5000 K, which is equivalent to the color temperature of sunlight. Here, 7 direct illumination type LED lights are used to make one lighting body to create an appearance that better embodies the styling concept of "Unstoppable" than using regular light bulbs (Fig. 34, 35).

4.6.2. Multi-function display

The model applies a multi-function display (Fig. 36).

- Tachometer: The layout was designed to allow intuitive manual shifting using the paddle shifter.
- Switching driving powers: By showing the driving condition on the display, it can be immediately understood by the driver.
- DCT shift modes: The two AT modes (AT and Sport)

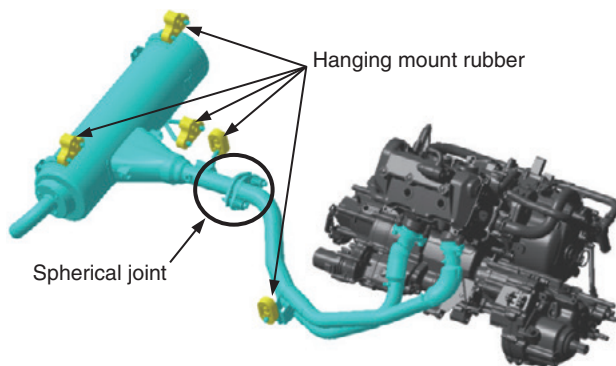


Fig. 32 Exhaust system layout

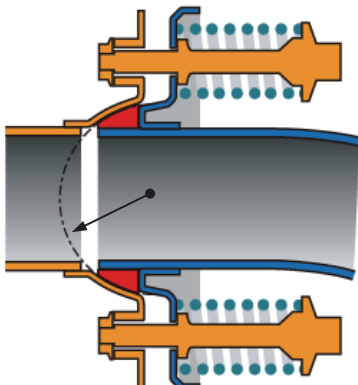


Fig. 33 Spherical joint system

and the MT mode are indicated with individual icons.

In order to make the display easier to see with a Honda Side by Side, a large LCD that is 2.3 times larger than conventional models was applied.

The display was also placed in the center of the cockpit to provide good visibility for a model having improved off-road capabilities. This resulted in the creation of a cockpit with which the driver can further concentrate on driving (Fig. 37).



Fig. 34 LED head lights



Fig. 35 Bulb head lights

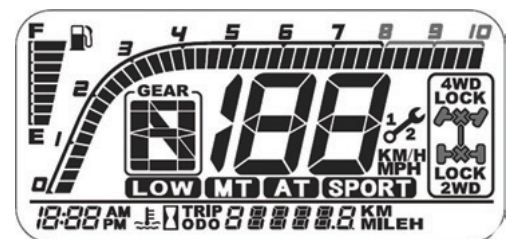


Fig. 36 Multi-function display

4.7. Suspension

A suspension system with excellent drivability on rough roads and ride comfort were applied to this flagship model, with best-in-class wheel travel (front wheel travel of 268 mm or 10.5 in., rear wheel travel of 254 mm or 10 in.). The five-passenger deluxe model applies self-leveling rear cushions made by ZF SACHS. The cushions were applied to overcome the tendency of Side by Sides to sacrifice ride



Fig. 37 Cockpit

comfort due to great changes in vehicle height as cargo weight increases.

In a conventional system, the operator had to manually operate the preload adjusters in the rear cushion springs to change the preload and adjust vehicle height.

For the PIONEER 1000, when the vehicle starts moving after cargo is loaded into the cargo bed, sinking the self-leveling rear suspension, the cushion rods travel vertically and oil is pumped upward from the low-pressure gas chamber to the high-pressure gas chamber. This increases the pressure inside the high-pressure gas chamber and pushes up the piston rods, bringing back the vehicle height to that of a no-load condition (Fig. 38).

By providing a mechanism to automatically adjust the vehicle height regardless of cargo weight or rear-seat passenger loading, all occupants can enjoy a stable drive feel.

4.8. Steering Mechanism

The desire for a more comfortable steering effort in rough trail conditions is increased in Side by Sides. Similarly, and particularly when considering the easy

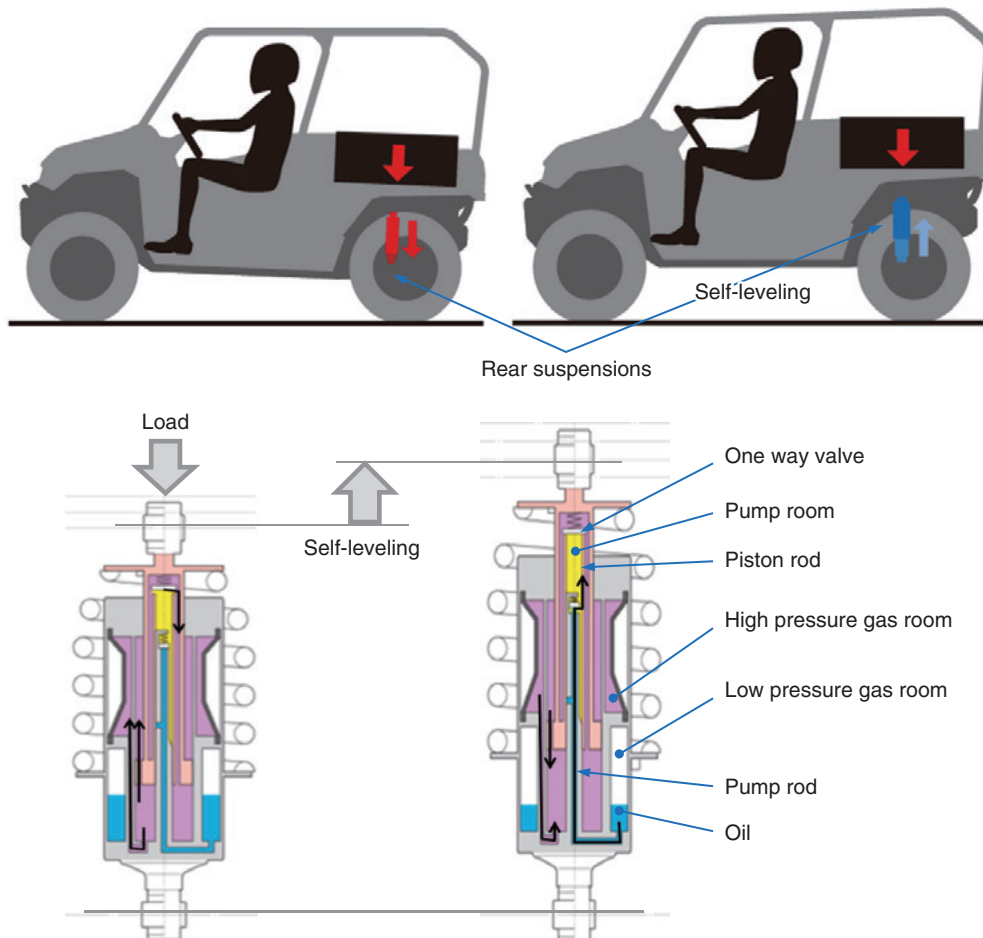


Fig. 38 Self-leveling suspension

maneuverability that is fit for a flagship vehicle, flexibility in driving positions is also desired. For these reasons, this model applies an electric power steering (EPS) and a tilt steering wheel (excluding the three-passenger standard model).

Since Side by Sides are used in conditions that are more severe than those of automobiles, we applied an EPS system for ATVs, which has similar usage conditions, and optimized it by including an assist function and installation method for Side by Side application.

The mechanism was placed in the middle shaft to minimize the likelihood of exposure to water (Fig. 39).

The tilt steering wheel allows for the driver to operate a gas damper lever to easily adjust the angle of the steering wheel to meet their preferences and body type.

Further, to give ease of ingress/egress, the tilt angle of the steering wheel was set at 31 degrees.

It's larger than automobiles.

4.9. Brakes

The model's brake system is based on that of an automobile, with adjustments made in light of the various usage environments. This model in particular required easy and stable braking, while taking into account the likely changes in the number of occupants (from 1 to 5) and the amount of cargo (starting at none). In order to achieve this, 2 piston calipers were applied in the front, a first for a Honda Side by Side (Fig. 40). These front calipers have a small-diameter dust sealing structure originally designed for motorcycle use, to make the body area around the sealing grooves more compact in order to fit inside 12-inch wheels. By making them smaller, the weight of the caliper is reduced by approximately 40% compared to automotive use calipers that previously have been applied to Side by Sides. Applying 2 piston calipers also expanded the discs' effective radius by 10%, improving braking performance

(Fig. 41). The single-piston rear calipers were also made more compact, and the piston size was changed while considering the front/rear braking balance. As a result, we were able to give this model good braking performance in various cargo load conditions, a well-balanced front/rear braking force distribution, and ease of control. For durability, the newly developed calipers have caliper brackets shaped so as to prevent damage to piston surface due to mud and chipping.



Fig. 40 Front brake

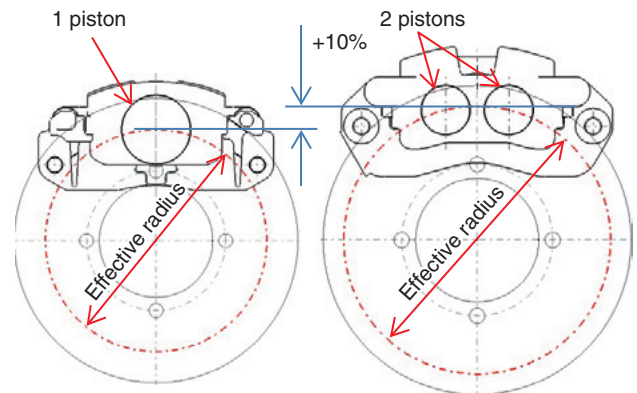


Fig. 41 Front disc effective radius

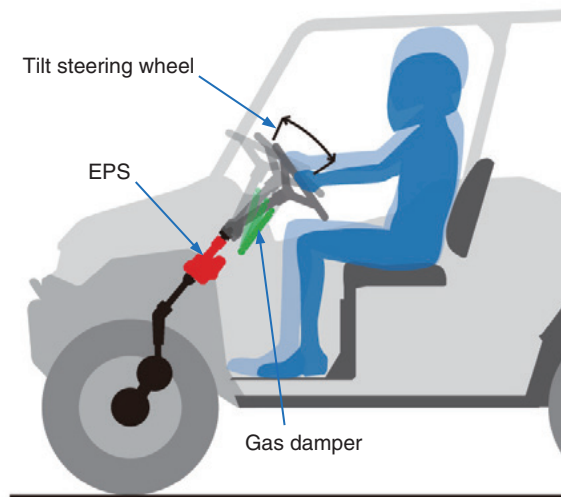


Fig. 39 EPS

5. Styling Design

5.1. Styling Concept

To embody the model's concept of "King of Works Hard, Plays Hard," the following three keywords were set for the styling concept.

Rugged: Durability that withstand tough use

Versatile: Versatility to be used for work and play

Unstoppable: A force that cannot be stopped

We also targeted to give the model an appearance that suggests a sense of continuity by styling the front mask to be immediately recognizable as being a part of the PIONEER family.

5.2. Method of Achieving the Styling

We first focused on clearly conveying the above three keywords.

The feel of force was achieved with the rugged shaping that exudes an air of toughness, proportions with a strong and functional stance of a four-by-four, and a bumper and front grill (Fig. 42) shaped in an aggressive design with vigorousness, resulting in embodying the model concept of “King of Works Hard, Plays Hard.”

To also make the model immediately recognizable from afar, dynamically shaped colored panels were applied in a continuous manner on the body sides (Fig. 43).

As a result, we created a styling design that beautifully balances the functionality that satisfies the pride of the customers for owning a flagship model and its exciting recreational capabilities.

5.3. Digital Modeling

In this development, modeling was done digitally using the 3D-CAD technology (Fig. 44) and without clay models. Simple, life-size models were used to confirm the feel of the size and ergonomics, and large-screen virtual reality displays were used to verify the styling and color appearances.

Using the 3D-CAD technology, it was possible to reflect data obtained through CAE analyses such as aerodynamics, strength and the dimensions of the movable areas such as tire clearances to digital models at high resolutions, thus enabling us to give the model a high level of both styling and functions. As a result, we were able to create a highly precise appearance within a short period of time.

In this development, we utilized these methods to create a styling design that well expresses the “King of Works Hard Plays Hard” concept.



Fig. 44 Styling design using a digital model



Fig. 42 Aggressive front grill



Fig. 43 Colored panels applied to body sides

6. Conclusion

PIONEER 1000 was developed with the aim to “offer both recreational and work capabilities,” “have the power performance, drivability on rough roads, and good ride comfort at a level suitable for a flagship,” and “be a multi-passenger vehicle model that people can enjoy with family and friends with a maneuverable vehicle size.” It applies a new two cylinder 999 cm³ engine and an industry-first 6-speed DCT with an High/Low sub-transmission with excellent transmission efficiency and durability, and the QuickFlip® seat for the five-passenger models, earning itself the title of a flagship. Many new technologies were applied as well, including low-vibration technologies and the self-leveling suspension to further improve comfort. These efforts resulted in the creation of a class-leading flagship model following PIONEER 500 and PIONEER 700 in Honda’s multi-category Side by Side series, with two passenger capacity settings (3 and 5). With PIONEER 1000, anyone can enjoy off-road driving, from first-time off-road drivers to the more experienced and skilled. It enables the drivers to share the joy of recreational uses with a larger group of friends and family as well as offering practical work capabilities that are among the best in the class. It is our hope that PIONEER 1000 will be popular in the market as a model that works hard, plays hard.

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Development of High-output, Portable External Power Output System for Use with Next-generation Environment Vehicles

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ABSTRACT

The external power output device EE90i (the Power Exporter 9000) that provides new value with the capability for obtaining electric power from next-generation vehicles was developed. Through use of the Power Exporter 9000, next-generation vehicles will be able to utilize electrical output at the location where it is needed, allowing the use of those vehicles as mobile power sources that can provide electrical output.

The Power Exporter 9000 has realized a form factor that allows loading the unit into the trunk of a CLARITY FUEL CELL by means of applying downsizing and weight-saving technologies for engine generators. The engine generator's inverter technology and heat-dissipating construction were then used to achieve stable electric output with quality equivalent to grid power as well as high output of 9 kVA. Furthermore, compliance with the Guidelines of Charge/Discharge System for Electric Vehicle V2L DC version has enabled connectivity and compatibility with next-generation vehicles that have external power output function and that are not only from Honda but also from other manufacturers. The general usability of the CLARITY FUEL CELL for connection with external power output devices was also heightened by following the above guidelines in the design. These technologies were found to offer prospects for a method of developing a society that builds national resilience against natural disasters and realizing the hydrogen society that is Honda's aim.

1. Introduction

Since the Great East Japan Earthquake of 2011, there has been heightened concern with preventing and mitigating the effects of natural disasters, and the National Resilience Basic Plan was adopted by Cabinet decision⁽¹⁾. The use of fuel cell vehicles (FCV), electric vehicles (EV), and other such next-generation vehicles that have functionality for generating and storing large amounts of electric power as moving electric power sources is one method that is anticipated for building a resilient society. Realizing a moving electric power source necessitates using the vehicle for electric power at the destination, and the EE90i (Power Exporter 9000, hereafter PE9000) was developed as a portable external electric power source for that purpose. The utilization in a wide variety of scenes such as during disasters or other emergencies, and for outdoor activities and other such purposes is anticipated, and the PE9000 is required to have a high output. The PE9000 was therefore configured to provide output of 9 kVA, making it lower

than the vehicle end's maximum value (10 kW), which is specified as the upper limit in the second clause of Article 199 in an Interpretation of Technical Standards of Electric Installation⁽²⁾. Configuring it for portability and high power output, the PE9000 provides new value to next-generation vehicles as mobile power sources that can provide electrical output.

At the same time, Honda is using the concepts of “generate,” “use” and “get connected” with hydrogen energy for its aim of realizing a hydrogen society with zero CO₂ emissions. The hydrogen used in FCVs can be generated from renewable energy, and they do not emit any CO₂ when they are used. Hydrogen can be stored and transported with high energy density, and is therefore receiving attention as a next-generation energy that has excellent energy security properties. In the Strategic Roadmap for Hydrogen and Fuel Cells⁽³⁾, the Japanese government has further set a dissemination target for increase to about 800,000 FCVs by the year 2030⁽⁴⁾. This indicates that future use of hydrogen energy is expected to expand. This development is targeted

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** Automobile R&D Center

at the realization of a hydrogen society by enabling the FCV and PE9000 to “get connected” for energy production.

This paper will describe the three characteristics introduced in the PE9000 of compact lightweight portability, a high output source of high-quality electric power, and mutual compatibility with vehicles, and it also touches on the power output technology in the CLARITY FUEL CELL.

2. Development Goals

2.1. Development Concept and Performance Requirements

Figure 1 shows a conceptual image of the hydrogen society that is Honda’s goal. The aim is to realize a hydrogen society by the three concepts of (1) “Generate” hydrogen from renewable energy using the Smart Hydrogen Station⁽⁵⁾, (2) “Use” hydrogen by driving an FCV that uses the hydrogen, and (3) “Get connected” with hydrogen by using the PE9000 to connect the vehicle with electrical equipment (Vehicle to Load, hereafter V2L) and using the Power Manager HEH55⁽⁶⁾ to connect with grid power at home and other such locations (Vehicle to Home, hereafter V2H). The purpose in developing the PE9000 was to provide new value in “connecting” based on the concept of “connect with cars, extend into people’s lives.”

Figure 2 shows an external view of the PE9000. With “Inter-Blended” as the keyword, the unit has a clean design that harmonizes with the environment. The look was also harmonized with the design of the CLARITY FUEL CELL, creating a unified appearance for the system.

The hydrogen society that is Honda’s goal.

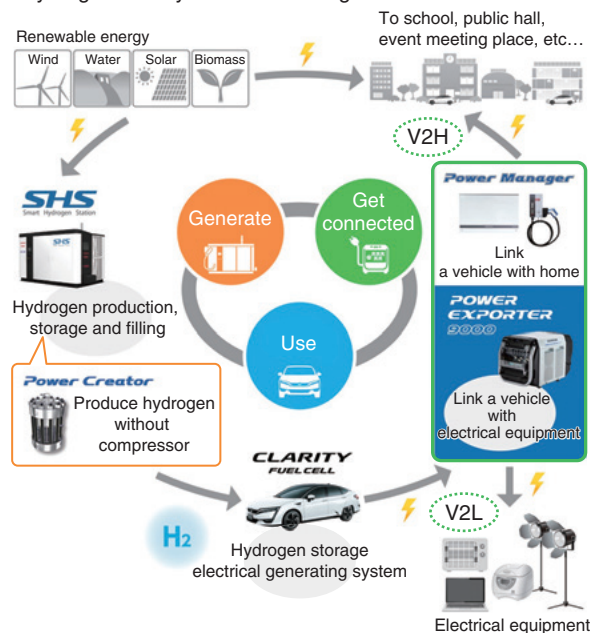


Fig. 1 Conceptual diagram of realization of hydrogen society

The following aspects of performance were defined as goals of development in order to utilize the PE9000 as a method for realizing a hydrogen society and strengthening resilience against natural disasters.

- (1) That it have portability to enable carrying the unit;
- (2) That it have power output at high capacity and high quality equal to those of grid power sources;
- (3) That it have high general usability that makes it possible to connect with a lot of next-generation vehicles.

2.2. System Configuration and Characteristics

Figure 3 shows a configuration diagram of the external power output system. The DC power supplied from the next-generation vehicle is converted into AC power by the PE9000, which supplies the electricity to electrical equipment. The system is set up so that when the next-generation vehicle is a Honda CLARITY FUEL CELL, the internavi system can be interposed to enable one to check the power supply status on a smartphone or other such device, not only at the multi-information display (MID) of the vehicle but also at a remote site.

Table 1 shows the main specifications of the PE9000. The PE9000 incorporates the following characteristics.

- (1) Downsized, lightweight, and portable type

Active use of technology for making an engine generator compact and lightweight achieved high power output of 9 kVA within a size and mass that can be loaded into the



Fig. 2 External view of Power Exporter 9000

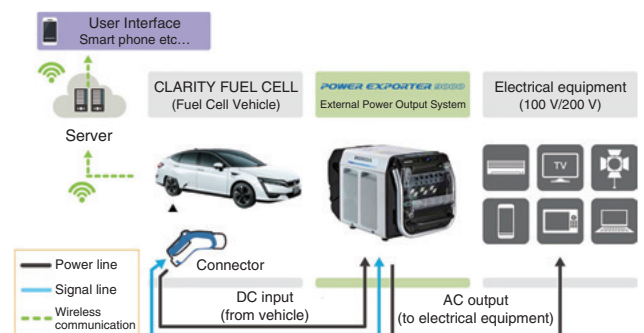


Fig. 3 System configuration of external power output system

Table 1 Specifications of Power Exporter 9000

Item	Specification
Rated output power	9 kVA
Output voltage	100 V/200 V
Dimension (L/W/H)	755 mm × 387 mm × 438 mm
Mass	50.8 kg
Sound power level	L_{WA} 57 dB
Applicable standard	V2L Guidelines for DC system

trunk of a CLARITY FUEL CELL. The handle and wheel construction further assure portability by one person after the unit has been unloaded from a vehicle.

(2) High power output and high quality power source

The layout of electric unit and cooling fan were optimized so as to efficiently cool the heat-generating components of the onboard electric unit. This arrangement permitted a design capable of providing a stable energy supply even during high power output. Inverter design technology⁽⁷⁾ was used in the engine generator to achieve high quality electricity output.

(3) Compatibility with vehicles

Conforming with the charge/discharge system guideline V2L DC for electric vehicle⁽⁸⁾ (V2L Guidelines) ensures compatibility with next-generation vehicles that come with the external power feeding function, including those of other manufacturers. Either EV or FCV can be selected in terms of the zero CO₂ emission, but the advantages of high power output are maximized when connected with an FCV, which has a longer cruising range than an EV as of June 2016. The approximately seven days' worth of general household electricity is available to be provided when connected with a Honda CLARITY FUEL CELL⁽⁹⁾. The adoption of a user interface that is suited to a V2L system provides the design with high usability.

This paper will introduce the developed technology that achieves the above three characteristics.

3. Introduction of Developed Technology

3.1. Technology for Compact, Lightweight, and Portable Type

The unit was designed to have a power/weight ratio yielding a major advantage over other manufacturers (Table 2). This was done by aiming for high power output of 9 kVA and case construction with exterior dimensions that allow the unit to be mounted in a CLARITY FUEL CELL trunk in combination with weight (60 kg or less)⁽¹⁰⁾ that allows it to be loaded and unloaded by two adult males. The unit also incorporates unique measures to reduce the burden on users when moving the unit alone and when loading or unloading it from a vehicle. The following will introduce the technology for making the unit more compact and lighter weight together with ease of handling and the collision energy absorbing structure of the unit when loaded in a vehicle.

Table 2 Compare power/mass ratio with competitors

Name	Power (kVA)	Mass (kg)	Power/Mass ratio (VA/kg)	Portable or not
Honda PE9000	9	60 (Target)	150 (Target)	Portable
Nichicon Vehicle to Socket	3*1	73	41	Not portable
Mitsubishi MiEV power BOX	1.5	11.5	130	Portable
AESC LEAF to 100V	1.5	12	125	Portable

*1: At the time of external power output.

3.1.1. Subdividing and packaging the inverter and converter

The inverter and converter are the main functional components of the PE9000, and they are major components in terms of weight and volume. The PE9000 is composed of five electric units including inverters and converters. The 9-kVA output is not treated as a single unit. Instead, an inverter with 6 kVA of output and an inverter with 3 kVA of output are each treated as single units, and three converter units with 3 kVA of output each are combined to support 9 kVA of power output. This subdivision into units enables the layout to be configured with a large degree of freedom.

Figure 4 shows the inner composition of the PE9000. The basic layout consists of the inverter and converter, and the remaining functional components were configured as described below.

- (1) Electric parts used for control are placed in the upper part of the unit
- (2) Electric parts used for output are placed in the front part of the unit
- (3) Discharging connectors are housed in the back part of the unit
- (4) Cooling fans are placed on the sides.

With the components configured in this way, the external dimensions allowed the unit to fit inside the trunk of the CLARITY FUEL CELL.

3.1.2. Lightweight, high-strength frame

In order to assure the strength to withstand normal handling while reducing the unit's weight, aluminum pipe that is lighter in weight and stronger was chosen as the frame material. Figure 5 shows the frame structure and the distribution of exterior forces applied to it. The structure is designed so that exterior forces are concentrated on the main frame, eliminating the need for brackets and other such parts. Steps were also taken to concentrate functions by attaching functional components directly to the pipe frame so that the number of component parts can be reduced, making the unit lighter in weight. Where the weight of the frame parts as a percentage of the total unit weight for

another Honda generator of similar weight (EU28is) is 54.8%, the figure for the PE9000 is 32.7%.

3.1.3. Converter construction

The input voltage range of the PE9000 is wide as it varies from 150 V to 450 V, and this system requires a converter that can convert constant direct voltage. Figure 6 shows a converter section. Although the converter makes up a large part of the system's weight and volume, the circuit boards were made in a 2 substrates piling composition, thereby reducing the surface area and allowing the converter to be made more compact and the case to be made lighter in weight. The components are also subjected to resin mold processing to assure their water resistance and vibration resistance. Since this system is not equipped with a major source of vibration such as an engine, it is less likely to be exposed to a vibrating environment than a conventional engine generator. Steps were therefore taken to optimize the resin molds for strength, with the result that the space between the top and bottom boards could be left hollow instead of being filled with mold material for strength, and this further reduced weight. Since this is a hollow structure, only the sides of the circuit boards that have parts on them are given the mold treatment. The solder side does not come into contact with mold material, which helps prevent solder-cracking resulting from a difference in rates of thermal expansion between the solder material and mold material. Ventilation holes were opened in the hollow part of the structure in order to limit moisture absorption by the circuit boards. These technologies achieved the unit's greater compactness and lighter weight of converter.

The above packaging, lightweight high-strength frame, and converter technologies yielded a high power output with a maximum of 9 kVA, while containing the PE9000 in a case 755 mm × 387 mm × 438 mm (total length × total width × total height) in size with a total unit weight of

50.8 kg (power/weight ratio: 177 VA/kg). Thus, the unit was made to enable loading in a CLARITY FUEL CELL trunk.

3.1.4. Handling performance

In addition to making the unit more compact and lighter in weight, functions intended for high handling performance were also added. In order to achieve a balance between stability while the unit is stationary and operability while it is being carried, a new wheel structure features a wheel that only touches the ground when the unit handle is lifted up.

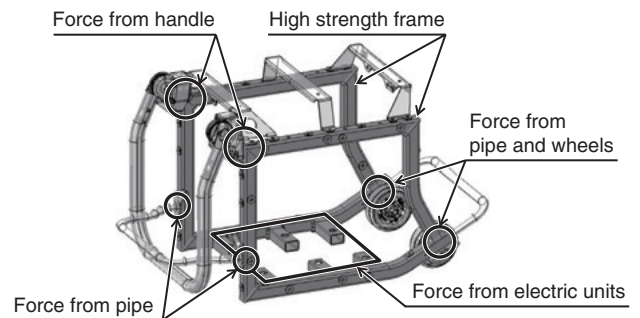


Fig. 5 Force receiving points on high strength frame

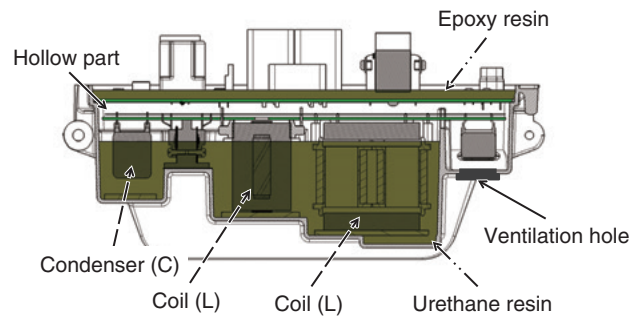


Fig. 6 Section of converter

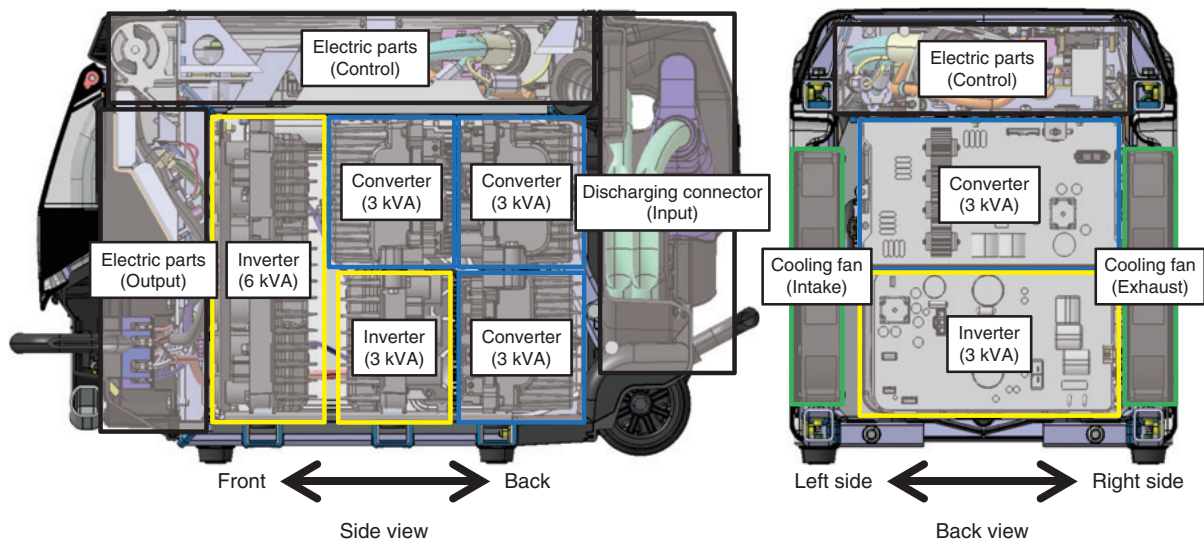


Fig. 4 Inner configuration of Power Exporter 9000

Figure 7 shows the state of wheel grounding when the unit is stationary and when the handle is lifted up. This approach eliminates the need to immobilize the wheels, and enables easy mobility by one person using the wheels of the unit, while helping assure stability when the unit is stationary.

Operability when loading and unloading the unit from a vehicle was also taken into consideration, and grips were placed on the front and rear of the unit and on either side. Figure 8 shows the PE9000 being raised up. Holding the front and rear grips together with the side grips makes it possible to tilt the unit in a stable manner and allows greater ease loading the unit in a car trunk than with front and rear grips alone.

Such considerations made the unit easier to carry and reduced user load while loading into and unloading from the trunk.

3.1.5. Structure to absorb impact force when in a vehicle

The CLARITY FUEL CELL frame structure comprises impact-absorbing sections to help absorb the impact during a collision and a high-strength cabin zone that helps protect occupants and fuel system components.

When the PE9000 is being transported on-board the CLARITY FUEL CELL, it is loaded in the trunk, which is an impact-absorbing section. The PE9000 unit itself has an impact-absorbing structure like that of the trunk, in consideration of the CLARITY FUEL CELL's safety in the event of a rear-end collision. The high-strength main frame is divided into right and left parts that are joined by brackets and pipe. External forces that are applied during normal use are received by the high-strength frame shown in Fig. 5. Strong impacts that occur from the side during a collision are mitigated by the structure shown in Fig. 9, with brackets and pipe comprising a force-mitigating section. In this way, this unit helps ensure the strength to withstand ordinary

handling while also allowing the PE9000 to deform under force at or below the high-strength cabin zone.

3.2. Cooling Technology to Achieve High Power Output and High Quality Power Source

The inverter and converter installed in the PE9000 generate heat during operation due to internal loss, and therefore require cooling. The PE9000 was designed to be a power output system with high power output, but consideration was also given to minimizing the cooling fan capacity in order to make the cooling structure efficient and achieve greater compactness and lighter weight.

The converter's two substrate layering composition and hollow structure shown in Fig. 6 also contribute to heat dissipation performance. This arrangement enabled passive electrical elements that are the main heat sources to be concentrated on the bottom circuit board where they could be closer to the cooling fan, providing for efficient heat dissipation. The hollow structure provides a layer of air inside the converter, promoting priority heat dissipation to the diecast case. In addition, urethane with a superior rate of thermal conduction was adopted as the mold material applied to elements on the bottom-layer circuit board, further enhancing the amount of heat dissipated. As a result, sufficient release of heat was made possible even in the compact form factor with high power output.

Air cooling by electric axial-flow fans was adopted as the cooling method. The use of axial-flow fans has two methods: intake attachment, in which the fan is positioned to draw air into the case interior; and exhaust attachment, in which the fan is positioned to blow air out from inside the case. Intake attachment is effective when heat-generating sections are concentrated within the case. Exhaust attachment is effective when heat-generating sections are dispersed within the case⁽¹¹⁾. Figure 10 shows the composition of inverter, converter, and cooling fans. For this development, a structure combining intake and exhaust attachment was adopted in order to optimally position the fans to match the inverter and converter heat values and heat-generating locations.

Figure 11 shows the results from analysis of heat-generating locations and air-circulation zones. This shows how the inverter, where more heat is generated due to internal loss and the heat-generating locations are

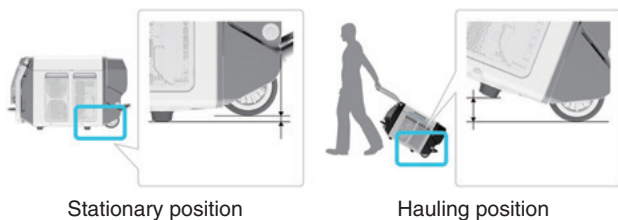


Fig. 7 Configuration of wheels and contact with ground



Fig. 8 Raised up position

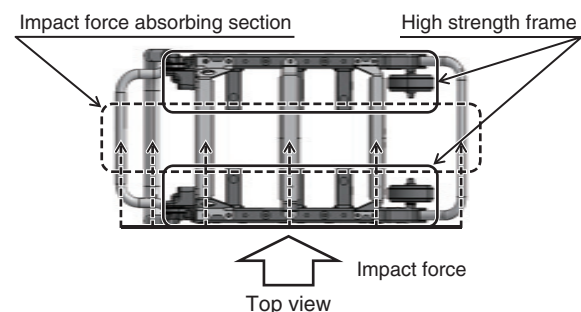


Fig. 9 Frame composition of Power Exporter 9000

concentrated, is cooled using an intake attachment fan. The converter, where less heat is generated and the heat-generating locations are dispersed, is cooled using an exhaust attachment fan. This layout makes it possible to cool the unit with fans that are compact, lightweight, and use less power, than if the fans were concentrated on one side or the other.

By the above technologies, the PE9000 achieved a sound power level of L_{WA} 57 dB while realizing a high power output of 9 kVA.

3.3. Technology for Mutual Compatibility with Vehicles

3.3.1. Conformity with V2L Guidelines

The PE9000 was the first in the world to satisfy the V2L certification standards⁽¹²⁾ for testing and compliance with V2L Guidelines. This makes it possible to connect with next-generation vehicles that have external power feeding function not only of CLARITY FUEL CELL but also of other manufacturers, achieving high general versatility.

On the other hand, avoiding limitations of the connected vehicle means that it is necessary to support a wide range

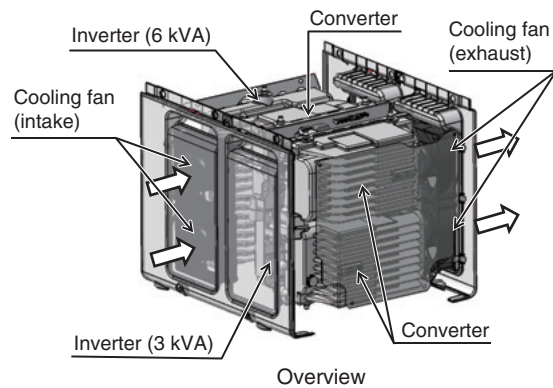


Fig. 10 Composition of inverter, converter and cooling fans

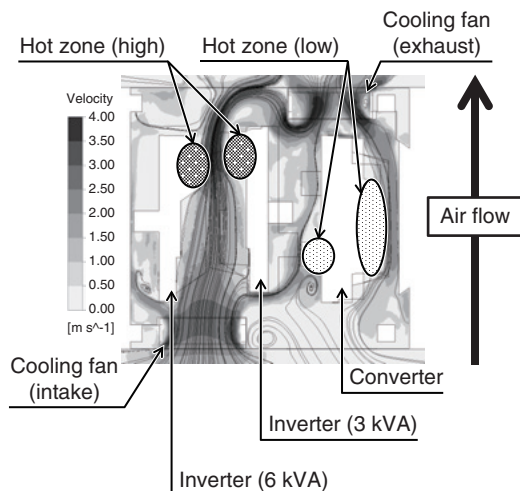


Fig. 11 Air flow analysis results

of input voltages, so the LLC current resonant method was adopted for the converter. The LLC resonance drive method performs soft switching (zero voltage switching) by resonance between the coils (L) and condenser (C) shown in Fig. 6. A wide range of voltage gain can be obtained by changing the switching frequency. By use of this method, the PE9000 can successfully convert a wide range of input voltage from 150 V to 450 V into a constant output voltage with a high degree of efficiency and low level of electrical noise. As a result, the PE9000 achieves a conversion efficiency of 90% or more at rated output when connecting with the CLARITY FUEL CELL.

The CLARITY FUEL CELL was also designed to comply with the V2L Guidelines in order to assure mutual compatibility with external power output systems other than the PE9000. The unit has thus achieved high usability. The power supply technology used in the CLARITY FUEL CELL is described in the following.

3.3.2. CLARITY FUEL CELL power supply components

The CLARITY FUEL CELL generates electricity by means of its fuel cell and provides DC electricity to the PE9000. Figure 12 shows the CLARITY FUEL CELL main components. The hydrogen fuel that is required for the fuel cell to generate electricity is in a high-pressure hydrogen tank. The tank stores approximately 5.0 kg of hydrogen under 70 MPa of filling pressure. This can provide about seven days of electric power for a typical household. Figure 13 shows the components for the section that supplies power. The electric power is generated by the

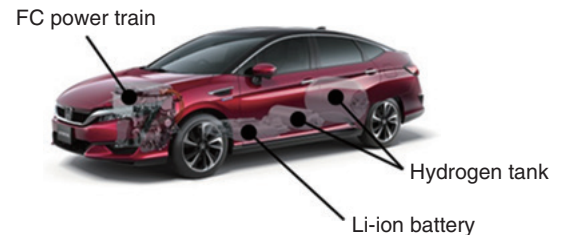


Fig. 12 Main components of CLARITY FUEL CELL

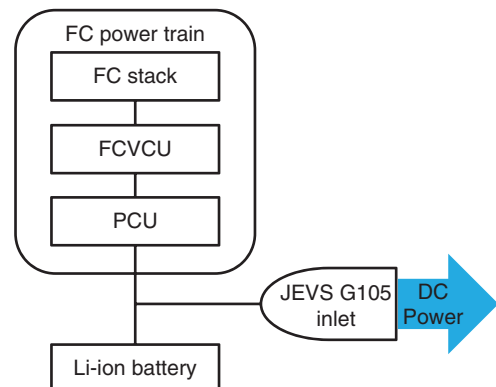


Fig. 13 Components for power export

fuel cell stack and then the output voltage is controlled by the FC voltage control unit (FCVCU) and the power control unit (PCU)⁽¹³⁾. It is connected in parallel with the lithium-ion battery and the power is supplied through a Japan Electric Vehicle Standard (JEVS) G105 inlet. Transient fluctuations in the electric power supply are covered by charging or discharging the lithium-ion battery, thus making it possible to provide a stable supply of electric power.

3.3.3. CLARITY FUEL CELL energy management while supplying electric power

The electric power supplied from the vehicle is generated by the fuel cell stack according to the load capacity of electrical equipment connected to the electric power source. The method of supplying electric power from a high-voltage battery after charging it can cause charge/discharge loss. The aforementioned method was thus adopted to assure high efficiency. Out of consideration for the next time the vehicle is going to be driven, control is implemented to keep the state of charge (SOC) of the high-voltage battery from dropping while power is being supplied.

Envisioning cases when the user is not present in the vehicle cabin while power is being supplied, the system is equipped with a function that automatically halts electricity feeding and uses telematics to notify the user by smartphone or other such means when the remaining hydrogen level becomes low. The system then automatically stops supplying power.

It is envisioned that there will be fewer occasions to supply power than there are to drive. It is necessary, therefore, to make the operation to initiate power supply easy for users to understand. To that end, after the power supply connector has been engaged, power can be supplied by simply following the same operation as for driving (turning the POWER switch ON while pressing down on the brake pedal).

3.3.4. Coordinated display of estimated possible duration of power supply

V2L devices are envisioned as being used across a wide range, from no load to rated output. It is also envisioned that, in the event of emergency, electrical equipment will be used, and a high degree of usability in such cases was aimed for by making it possible to check for a general indication of how long electric power can continue being supplied at the present rate. This system provides a display on the PE9000, the CLARITY FUEL CELL, and a smartphone. Figure 14 shows the indicator LED on the PE9000 and the MID in the CLARITY FUEL CELL. The PE9000 calculates the present supply of electric power from the size of the attached load, and transmits this by telecommunication to the CLARITY FUEL CELL. The CLARITY FUEL CELL calculates the number of hours it can continue supplying power from the remaining hydrogen according to the electric power supply figure it received and its own consumption. That number

is displayed on both screens. As shown in Fig. 3, this information is also transmitted to smartphones by means of the system server. Figure 15 shows the smartphone display. The system specifications provide the means to check the power supply status even from a location that is removed from the vehicle.

These three displays provide a simple, sensory means for judging the status of the PE9000 in a manner resembling the displays on the electrical equipment being used. The time can be checked in detail on the vehicle MID, and it can also be checked remotely by smartphone. The system thus achieves high usability.

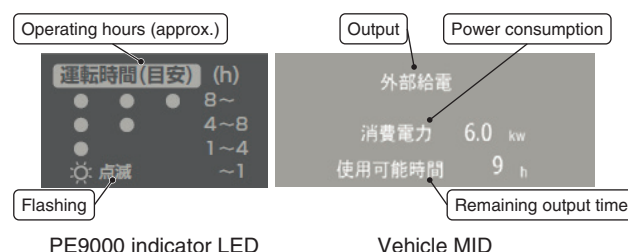


Fig. 14 Design example of indicator LED and vehicle MID on external power output system



Fig. 15 Design example of internavi application on smartphone

4. Conclusion

The PE9000 was developed as an external power output system that provides next-generation vehicles with new value as moving electric power sources. The main technologies achieved yielded the following conclusions.

- (1) Achieving compactness and lighter weight made it possible to load the unit in a CLARITY FUEL CELL trunk. The unit was also constructed to make it easily portable after unloading from the trunk.

- (2) An efficient cooling structure was provided, thereby realizing a cooling function at high power output of 9 kVA. The application of inverter technology of engine generators further achieved high-quality power output.
- (3) The PE9000 is in conformity with V2L certification standards, and ensuring the CLARITY FUEL CELL design's compliance with V2L Guidelines enhanced the widely compatible functionality of the connection.

5. In Closing

In order to verify where to apply the PE9000, the following field tests and demonstrations were performed.

- (1) System matching with medical equipment was confirmed in a joint research project with the Tottori University Faculty of Medicine. The system was also used in participation with a Disaster Medical Assistance Team, which is a medical team trained to provide mobile emergency assistance during disasters (Emergency use).
- (2) The system was used in disaster management training for people unable to readily return to their homes, and was confirmed for usability of next-generation vehicles equipped with external power feeding function and for driving the electrical equipment needed during disasters (Emergency use).
- (3) The system was used to supply power to vehicles involved in the Tokyo Michiterasu illumination and in the event car, verifying use of the external power feeding device in public spaces (use during normal times).

The above results provided confirmation of the PE9000's prospects as a method for building a national resilient society against natural disasters and realizing the hydrogen society that Honda is heading toward.

The PE9000 was developed on the assumption that it would serve a useful purpose at evacuation locations and where medical care is being provided during disasters. Going forward, the system will be expanded with variations for expanded dissemination that can be carried more easily and meet needs for personal use, with the aim of developing this not just for the Japan market, but as a product for the whole world.

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Development of New FC Stack for CLARITY FUEL CELL

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ABSTRACT

In order to make the fuel cell stack lighter weight and more compact, the cell thickness and the number of cell stacks were reduced. This achieved the world's highest level of volume power density at 3.1 kW/L. The reduction in cell thickness was achieved by the uniform distribution of water in the membrane electrode assembly, a reduction in the gas flow channel depth, and reduction in the membrane electrode assembly thickness. The reduction in the number of cell stacks was achieved by narrowing the gas flow channel pitch so as to enhance the power output performance per cell. Structuring the FC stack so that the gas flow channels are oriented laterally allowed the height of the fuel cell stack to be reduced while the connection bar was used as a cell retention structure, increasing the impact resistance. This enabled mounting of the fuel cell stack under the front hood. Making the fuel cell lighter weight and more compact reduced its heat mass so that the time taken to reach 50% of rated capacity when the fuel cell is at a low temperature could be shortened to one-half of the time required by a previous fuel cell. The membrane electrode assemblies that make up the cell were given a resin frame around their periphery, and squaring off their shape reduced the amount of material needed in the electrolyte membranes and diffusion layers while also increasing their continuous manufacturing productivity.

1. Introduction

Fuel cells are anticipated to provide a renewable, clean power train that does not discharge any CO₂ or environmentally harmful substances.

In 1999, an fuel cell stack developed by Honda was installed in an FC test vehicle, and in 2003, a Honda FC stack that allowed for higher power density and starting in cold climates was announced⁽¹⁾. In 2006, Honda announced the V Flow FC stack with 50% greater volume power density and 67% greater weight output density⁽²⁾. An FC stack development initiative was undertaken with the CLARITY FUEL CELL, and the objectives were expanded to further reduction in weight, greater compactness, and installation⁽³⁾ under the front hood. The cell thickness was reduced, the number of cell stacks was reduced, and the impact resistance was increased. This effort raised the volume power density by 60% and the weight output density by 35% compared to the V Flow FC stack. The new FC stack, which also yielded enhanced low-temperature

starting performance and increased MEA⁽⁴⁾ manufacturing productivity, was announced in 2016. Figure 1(a) shows the external appearance of the V Flow FC stack and Fig. 1(b) that of the new FC Stack. This paper will introduce the new FC Stack, which has achieved lighter weight and greater compactness, enabling installation of an FC power train under the front hood.



Fig. 1 Appearance of fuel cell stack

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2. About Fuel Cells

As shown by the proton exchange membrane fuel cell in Fig. 2⁽⁵⁾, an FC directly converts chemical energy into electrical energy by using a polymer electrolyte membrane (PEM) to cause electrochemical reactions between hydrogen and the oxygen in the air.

Hydrogen electrode (-): $\text{H}_2 \rightarrow 2\text{H}^+ + 2\text{e}^-$

Oxygen electrode (+): $1/2\text{O}_2 + 2\text{H}^+ + 2\text{e}^- \rightarrow \text{H}_2\text{O}$

A PEM that conducts hydrogen ions is sandwiched between two electrode layers that are composed of a hydrogen electrode and an oxygen electrode (an air electrode) and diffusion layers to form an MEA. This MEA is then sandwiched on both sides by two separators to form one cell. One cell cannot obtain a theoretical voltage of more than 1.23 V even when the circuit is open. Therefore, as shown in Fig. 3, cells are stacked so that they can produce a high voltage. In order to bring out the performance of the MEA, it is also important to humidify and hydrate the PEM and electrode layer to lower the conduction resistance of the hydrogen ions⁽⁵⁾⁻⁽⁷⁾.

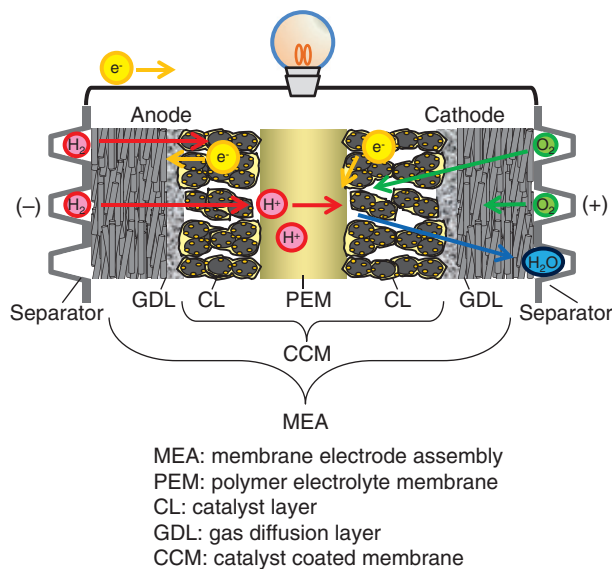


Fig. 2 Mechanism of electricity generation in FC stack

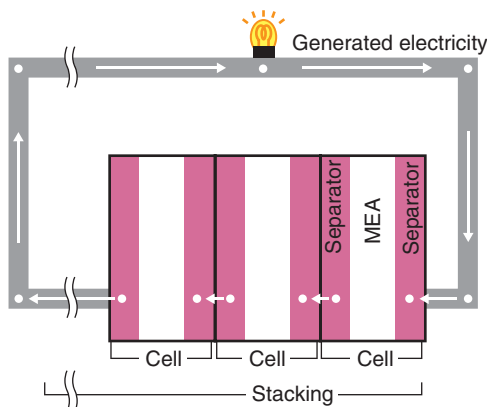


Fig. 3 FC stack configuration

3. Development Goals

The goals of CLARITY FUEL CELL development were to make an FC power train compact in size and install it under the front hood. This would realize the world's first fuel cell vehicle (FCV) to be available on the market in a five-passenger sedan package⁽³⁾.

In developing the new FC Stack, the following goals were adopted in light of the CLARITY FUEL CELL development goals and with a view to mass popularization in the future.

- (1) Make lighter weight and more compact
- (2) Heighten impact resistance
- (3) Enhance low-temperature starting performance
- (4) Enhance MEA manufacturing productivity

4. Achieving Lighter Weight and Greater Compactness

In order to make the FC stack lighter weight and more compact, it is necessary to reduce the cell thickness and reduce the number of cell stacks.

4.1. Reducing Cell Thickness

In order to reduce cell thickness, it is necessary to reduce the depth of the hydrogen and air flow channels and to reduce the MEA thickness. However, the following relationship is involved:

Gas flow channel depth = Adhesion force of generated water / Drainage force of generated water

When the hydrogen and air flow channels are made shallower, the proportion of force with which generated water adheres to the gas flow channel increases in size. This causes the generated water to be unable to drain and more likely to accumulate (Fig. 4). The supply of hydrogen and air is therefore hindered so that the cell becomes unable to generate a stable supply of electricity. Previous FC stacks were constructed so that air and hydrogen gases would flow in a downward direction in parallel flows. Gravity was used to heighten the drainage force and drain away the water produced by the generation of electricity. The cell thickness was reduced by reducing the depth of the gas flow channels while maintaining the stability of electricity generation by the FC stack. In the present development, further reduction of cell thickness has been sought by making the humidity in the MEA uniform and reducing the amount of

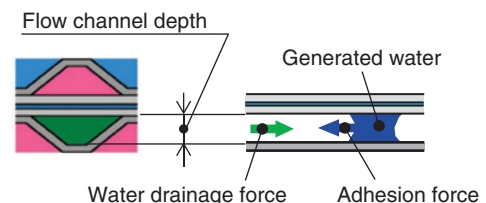


Fig. 4 Relationship between flow channel depth and adhesion force

humidification. This approach enabled the generated water to drain without condensing so that adhesion of generated water to the gas flow channel was eliminated even in the low-load range of operation where the drainage force was diminished. This maintained the stability of electricity generation while making it possible to further reduce cell thickness. First of all, the cells were changed from a structure in which air and hydrogen gases flowed in parallel to one in which the gases flowed in opposing directions (counter gas flow). As shown in Fig. 5, humidified air provides water to the MEA on the entrance side, and the generated water moves toward the exit side and is supplied to the MEA. Then water that has percolated through the MEA is back-diffused to the hydrogen electrode side, and water is supplied to the hydrogen entry side, making it possible to heighten the circulation of water within the electricity-generating surfaces and to make the water distribution uniform within the MEA. It is also important to have a uniform distribution of gas from the gas manifold to the gas flow channels, as shown in Fig. 6. As shown in Fig. 7, the two MEAs adopted from the previous FC stack version are held in place by three separators so that coolant can flow by on both sides. In this cell structure, the separator sandwiched between two MEAs will have hydrogen flowing past on one side and air flowing past on the other side. With stamped metal separators, the shape is indented on one side and protrudes on the other because of the press-forming process, so optimal distribution channels cannot be formed on each side. Consequently, as shown in Fig. 8, it was necessary to design the MEAs so that the

embossed forms would provide for a balance between the hydrogen electrode side and the air electrode side. Therefore a resin frame around the MEA periphery was devised (Fig. 9) and the press-formed surface of the separator was made flat. Grooves were then formed in the resin portions to provide for optimal distribution of the respective gases (Fig. 10) so that the distribution of both gases was enhanced and the water distribution in the MEA was also made uniform. Enhancements were also made to the MEA. The PEM was made thinner in order to enhance the water diffusion performance due to the difference in concentration in the

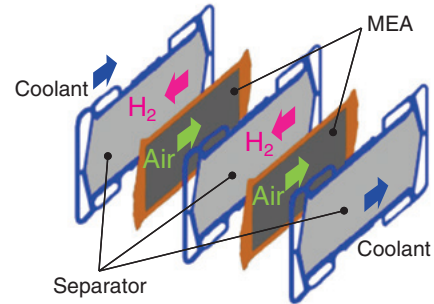


Fig. 7 One cooling layer per two cells

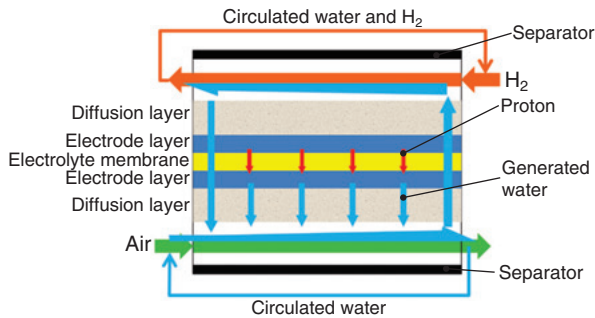


Fig. 5 Diffusion in MEA

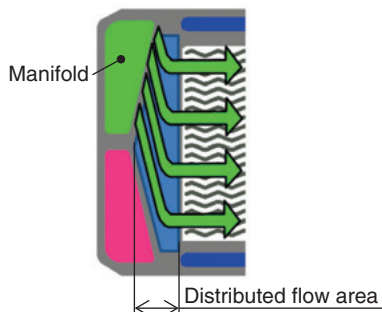


Fig. 6 Distributed flow area

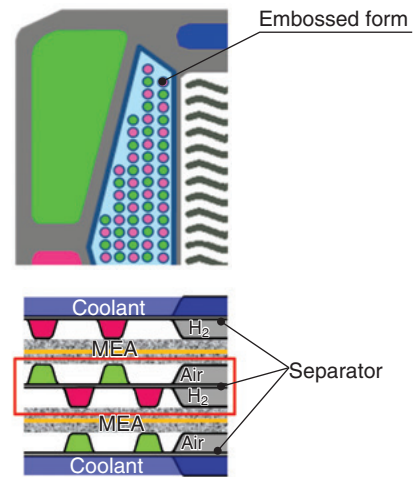


Fig. 8 Previous gas distribution structure

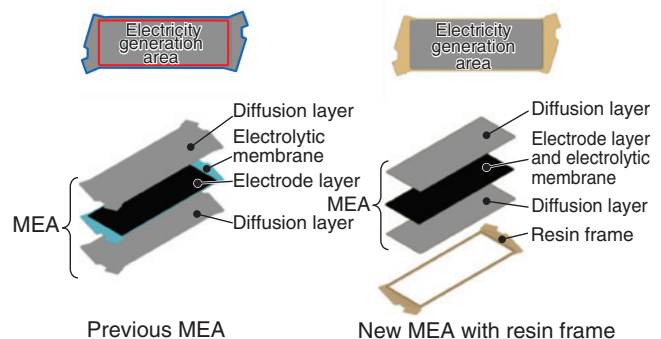


Fig. 9 Comparison of MEA structures

PEM from the air electrode to the hydrogen electrode, thereby enhancing its circulation, as well as to reduce the thickness of the MEA. In the diffusion layers, which are made up of carbon fibers, the density of carbon fibers was

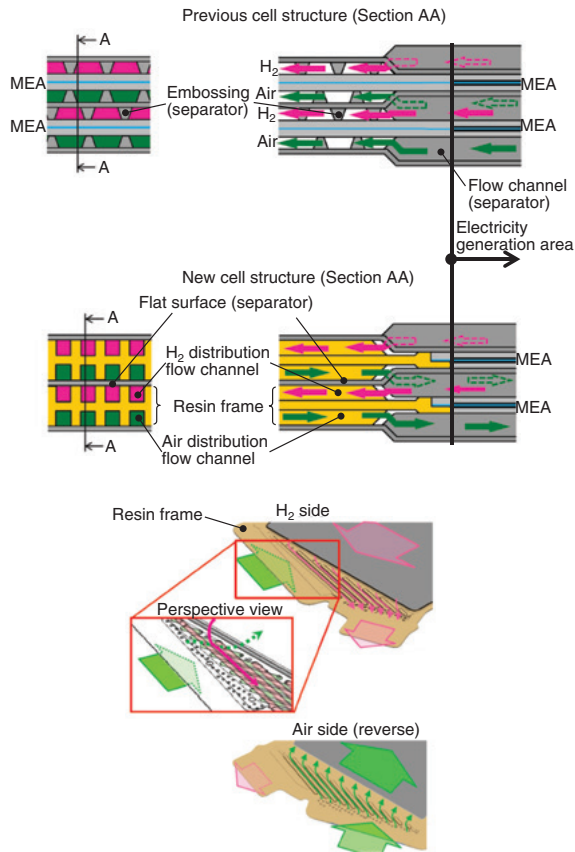


Fig. 10 Resin-framed MEA

made coarser to increase the porosity, thereby enhancing the gas diffusion performance as well as the water drainage performance. On the hydrogen electrode side, the increased hydrogen gas diffusion performance makes it possible to obtain adequate gas diffusion performance even when the diffusion layer thickness has been reduced. These measures enabled a reduction of 40% in the humidification amount compared to the previous version, which means that in the low-load range of operation where the generated water drainage force is diminished, the humidity within the electricity-generating surfaces could be lowered to 100% or less. As a result, it became possible to drain the generated water without condensing it, so that adhesion of the generated water to the flow channels no longer occurred, and the flow channel depth could be reduced by 26% while maintaining the stability of electricity generation. The reduction in overall MEA thickness through reduction of PEM and diffusion layer thickness combined to achieve a single cell thickness of 1 mm, representing a 20% reduction in thickness compared to the previous cell (Fig. 11). It was also no longer necessary to use gravity for draining generated water, so that even if the FC stack was structured to have the gas flow channels flow laterally, the stability of electricity generation could still be maintained, as shown in Fig. 12.

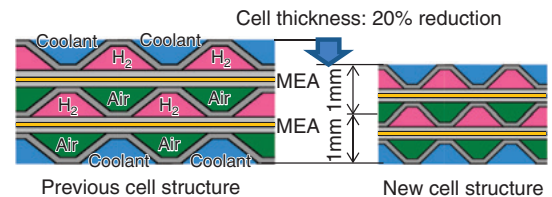
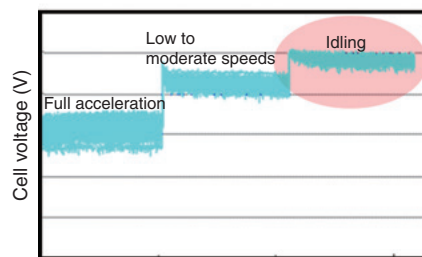
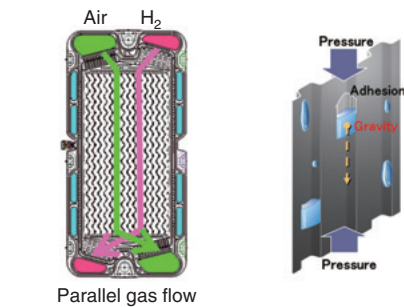
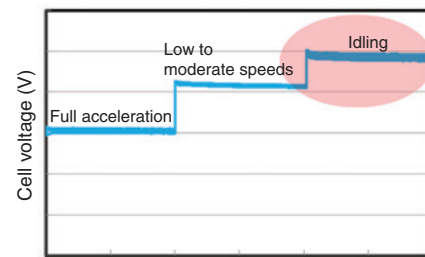
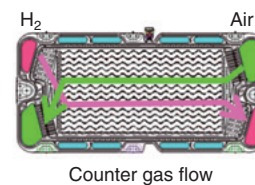


Fig. 11 Cross-section of cell structure



(a) V flow FC stack



(b) New FC stack

Fig. 12 Natural stabilized electricity generation

4.2. Reducing the Number of Cell Stacks

In order to reduce the number of cell stacks without changing the electricity-generating surface area in each cell, it is necessary to further increase the output per unit electricity-generating surface area. One way of doing this is to further increase the electric current density per unit surface area. On the air electrode side, however, there is an increase in the amount of water generated by electricity generation. This hinders the gas diffusion performance of air within the MEA, which raises the issue of possible deterioration in power output performance as a result. It is necessary, therefore, to eliminate the accumulation of generated water within the MEA (Fig. 13).

The separators form gas flow channels that supply hydrogen and air to the MEA, and where those gas flow channels and the MEA come into contact, water generated by electricity generation condenses in the diffusion layers and ends up accumulating there so that hydrogen and air can no longer be supplied to the MEA in a uniform manner. Attention was therefore turned to the fact that the accumulation of generated water can be eliminated by narrowing the ridges where gas flow channel and MEA come into contact, as shown by the neutron visualization test results in Fig. 14, and the gas flow channel pitch was made narrower.

In the case of stamped metal separators, however, narrowing the pitch of the gas flow channels increases the elongation ratio of the sheet during press forming so that cracks may form in the gas flow channel and the sheet may become thinner in places. This can be avoided by dividing up the press forming over a number of times, which, however, tends to reduce productivity. In the present

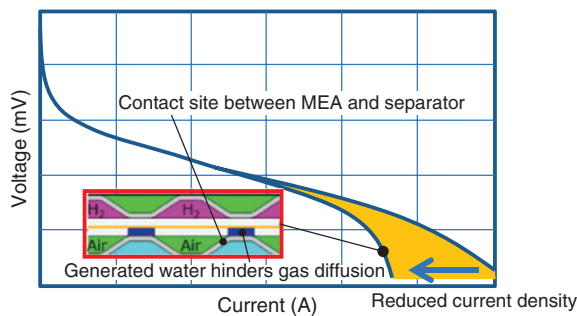


Fig. 13 I-V characteristic

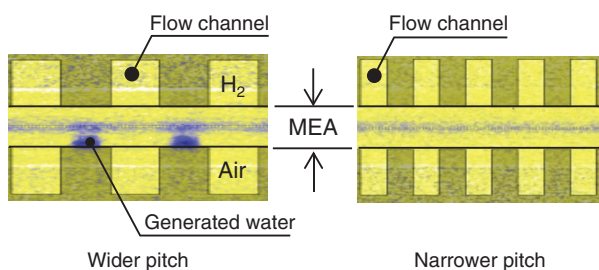


Fig. 14 Comparison of flow channel pitches

development, reduction of the gas flow channel depth yielded a 35% narrower gas flow channel pitch and still managed to achieve a sheet elongation ratio on a par with previous versions (Fig. 15).

As a result, the accumulation of generated water on the channel ridges was eliminated even when the electric current density was increased, and the gas diffusion performance of air was ensured. This made it possible to increase the electric current density by a factor of 1.5 compared to previous FC stacks, which made it possible to increase power output performance per unit surface area by a factor of 1.5 (Fig. 16). These measures realized power

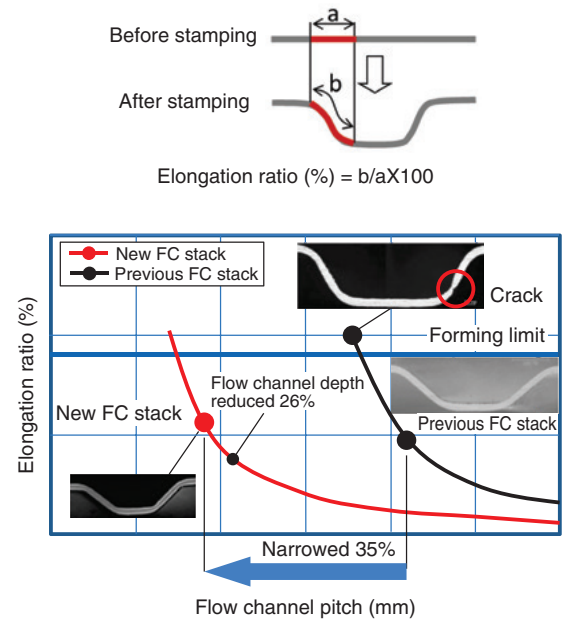


Fig. 15 Narrowed flow channel pitch

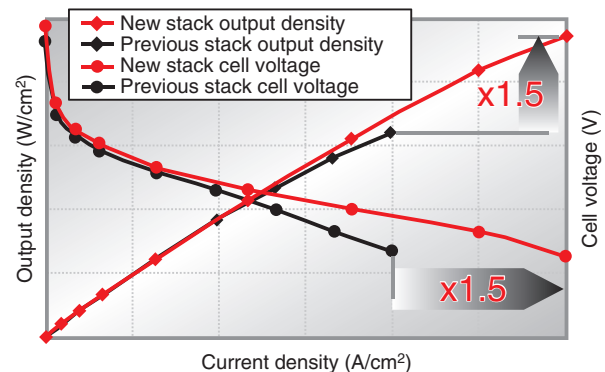


Fig. 16 Comparison of cell output density

output on a par with previous FC stacks while allowing the number of cell stacks to be reduced by 30% (Fig. 17).

The technology for achieving this kind of lighter weight and greater compactness realized increases (by comparison with former versions) of 60% in the volume power density and 35% in the weight output density of the FC stack by reducing the cell thickness and the number of cell stacks. This achieved the world's top level of volume power density at 3.1 kW/L (Fig. 18).

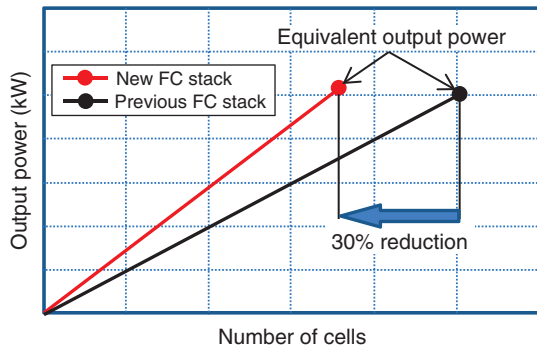


Fig. 17 Reduced number of cells

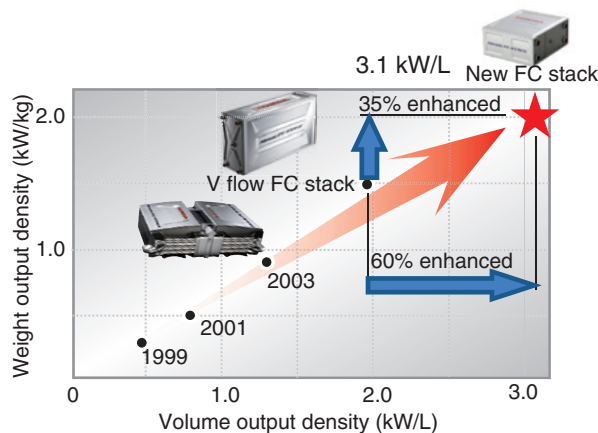


Fig. 18 Comparison of stack output density

5. Enhancing Impact Resistance

Installing the FC stack under the hood at the front of the vehicle involves exposure to greater impact force on the FC stack in a front-end collision than the previous center tunnel installation. This means it is necessary to enhance the impact resistance. As shown in Fig. 19, therefore, a part that protrudes vertically with respect to the cell was added, the end plates at either end of the FC stack were held together by a connection bar that also holds in place the protruding part added to the cell. The bar-connected, single-box stack structure developed in this way is thus able to limit displacement of the cell without fracturing, even under great impact force. As a result, this FC stack achieved

impact resistance four times greater than that of the former panel-connected structure.

Greater compactness and enhanced impact resistance enabled installation of the FC stack on top of the drive motor so that the FC power train achieved a compact size on a par with conventional V6 engines. This made it possible to realize the first FCV to be made commercially available in a five-passenger sedan package.

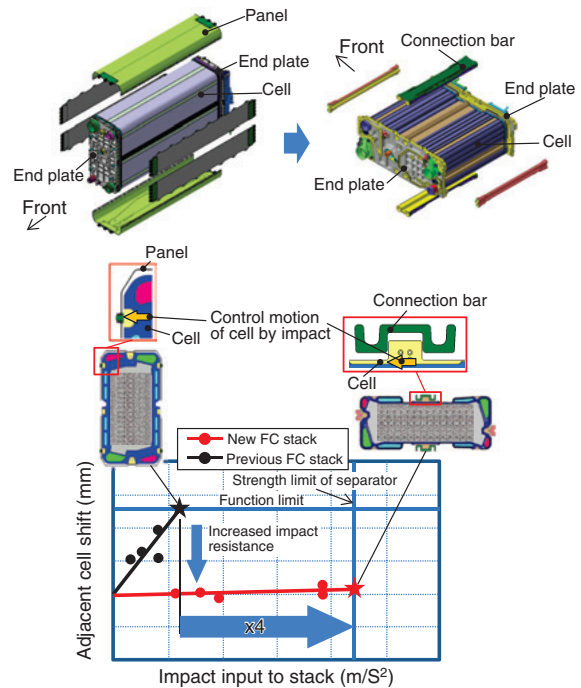


Fig. 19 High impact resistance stack

6. Enhancing Low-Temperature Starting Performance

In the former FC stacks, power output performance at start-up was heightened by enhancing generated water drainage performance by means of the V Flow cell structure and by reducing heat mass by 40%. In the present development, low-temperature starting performance was enhanced by reducing the heat mass and lowering the specific resistance of MEA components.

First, the specific resistance of MEA components was lowered by reducing the thickness of the PEM, optimizing the ion exchange capacity, and making the diffusion layers thinner. The resistance of the PEM in a low-humidity environment was also reduced by achieving uniform humidity in the MEA surface; this was done by establishing a counter gas flow. These measures succeeded in lowering the electrical resistance of the FC stack by one-third in a -20°C environment, which enhanced the power output

performance immediately after start-up. Reducing the depth of the separator flow channels and the number of cell stacks yielded a lighter-weight and more compact FC stack as well as a reduction in the amount of coolant kept in the cell. This achieved a 12% reduction in heat mass which made it possible to raise the rate of power output increase so that the time taken to reach 50% power output when starting at a temperature of -20°C was shortened by one-half relative to the previous FC stack (Fig. 20).

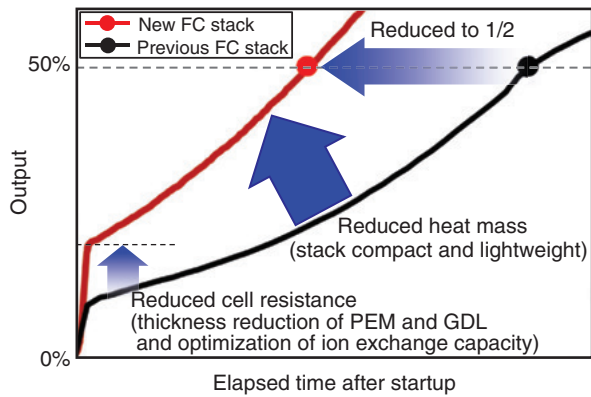


Fig. 20 Comparison of low-temperature performance (operated at -20°C)

7. Enhancing Manufacturing Productivity

As shown in Fig. 21(a), the previous MEA manufacturing technique involved coating a microporous layer on the diffusion layer and coating an electrode layer on the PEM, building up the respective stacks by patterned coating. This production method included portions that did not involve causing gases to flow from the manifold to the flow channels, and so that did not contribute to electricity generation. The MEA was formed as a single entire unit, so the shape became very complex and there were many portions of the diffusion layer and PEM that were wasted. In the present development, a resin frame is placed around the circumference of the MEA, as shown in Fig. 9. Squaring off the shape of the MEA, which is the electricity-generating component, made it possible to form the microporous layers and electrode layers in sheets on a diffusion layer that is in roll form. After that, the MEA shape could be squared off using a multiple-cavity punching. This process therefore became capable of high-volume continuous flow, as shown in Fig. 21(b). In order to coat the microporous layer and electrode layer in sheet form on the diffusion layer, it is necessary to place a flat membrane coating with few undulations in it on the porous diffusion layer surface. An ink with

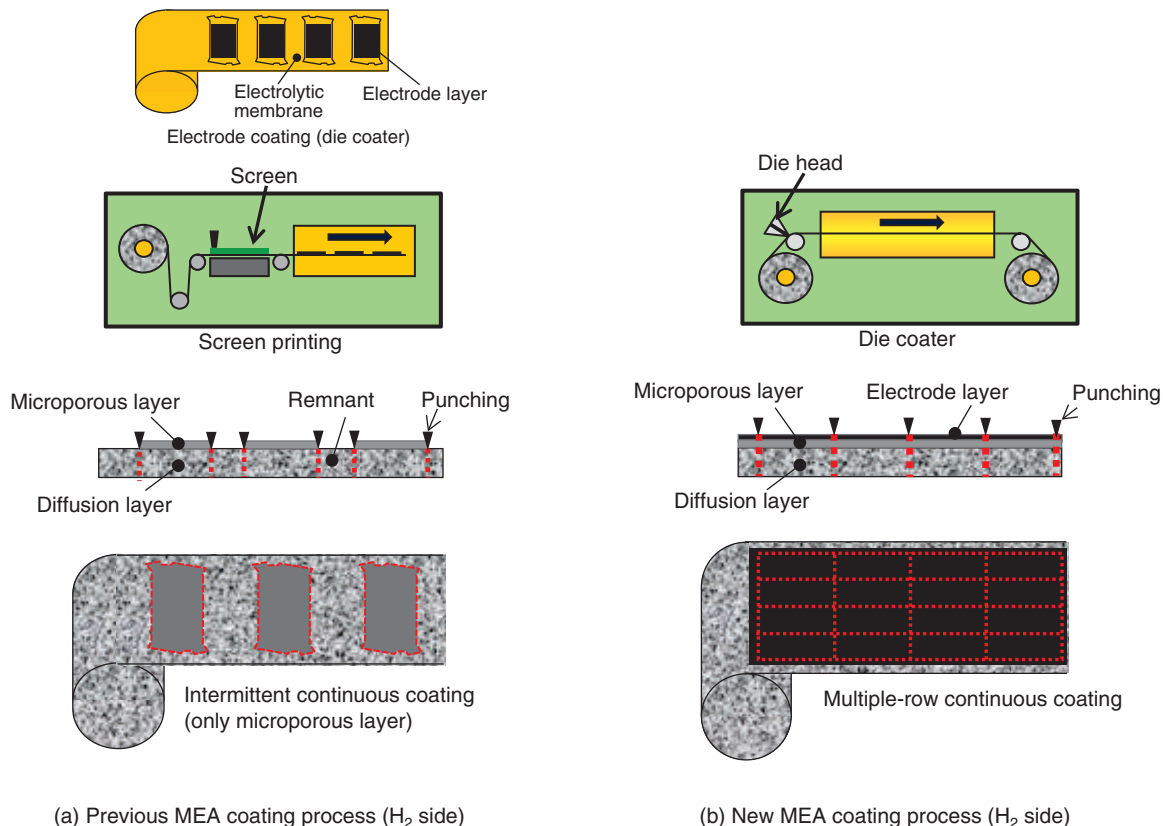


Fig. 21 MEA coating process (H_2 side)

water-repellent properties was therefore developed that would not soak into the diffusion layer, which resulted in a technology for producing a smooth electrode layer in sheet form at high speed. Having the shape of the MEA squared off meant that the electrode layer could be inspected in sheet form for defects, allowing only the areas of good quality to be selectively cut out for use. This technology used for MEA production became possible to apply here, as well.

As a result of these measures, the portions that were wasted in production were reduced, allowing the amounts of diffusion layer and PEM used to be reduced by 40%. A production technology that achieves high-volume continuous flow and cost reduction was created (Fig. 22).

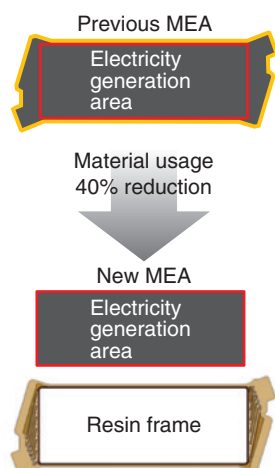


Fig. 22 Reduction of material usage

8. Conclusion

In the present development the FC stack was made lighter weight and more compact, its impact resistance was increased, and its low-temperature starting performance and MEA manufacturing productivity were enhanced.

- (1) In reducing the thickness of cells and the number of cell stacks in the FC stack, the volume power density was increased by 60% and the weight output density by 35% compared to previous FC stacks. This achieved the world's highest level of volume power density at 3.1 kW/L.
- (2) In conjunction with the greater compactness, the gas was caused to flow in a horizontal direction, which reduced FC stack height. This enhancement of both impact resistance and compactness made it possible to install the FC stack under the hood at the front of the vehicle.
- (3) Reducing the MEA resistance and heat capacity made it possible for the time taken to reach 50% power output at a low temperature to be shortened by one-half relative to the previous FC stack.

- (4) Squaring off the shape of the MEA and making the area not used for electricity generation into a resin frame around it both increased MEA manufacturing productivity and achieved a 40% reduction in the amount of high-cost materials used.

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Development of Air Supply System for CLARITY FUEL CELL

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ABSTRACT

A compact air supply system has been developed for the CLARITY FUEL CELL fuel cell system in order to make it possible to fit the system under the front hood of the vehicle. The use of a motorized turbo compressor realizing greater quietness than a conventional Lysholm compressor made it possible to reduce the volume of the noise-reducing auxiliary devices by 50%.

Air bearings that do not require oil were used as the compressor bearings based on the necessity of supplying pure air to the fuel cell system.

To address the issue of restriction of the operating range of the compressor as a result of turbocharging, a mixed-flow compressor was used, and two-stage compression was applied. This realized a wide operating range and made it possible to increase air supply pressure 1.7-fold compared to a conventional compressor.

The development of a new inverter using resolver-less control made it possible to do away with the rotation angle sensor in the motor, contributing to increased motor speed and increased compactness. The use of a full-mold power module and a press-fit connection method reduced the size of the inverter unit.

1. Introduction

In order to generate power using fuel cells, it is necessary to continuously supply hydrogen and air to the generating surfaces within the fuel cell. Because of this, fuel cell systems can be broadly broken down into the four systems shown in Fig. 1.

While hydrogen is supplied to the fuel cells from the onboard hydrogen tanks following depressurization in the hydrogen supply system, air is sent to the fuel cells following intake and compression by an air compressor in the air supply system.

Since the development of the FCX⁽¹⁾ in 2002, Honda has used motorized Lysholm compressors as the air compressors in its fuel cell vehicles. For the CLARITY

FUEL CELL, however, the aim was to reduce the size of the system in order to make it possible to fit the fuel cell system under the front hood⁽²⁾, leading to the development of a next-generation air supply system using a motorized turbo compressor (Fig. 2).

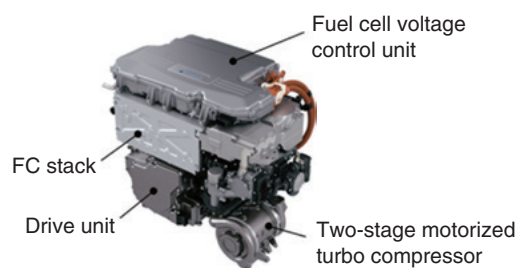


Fig. 2 Downsized fuel cell powertrain

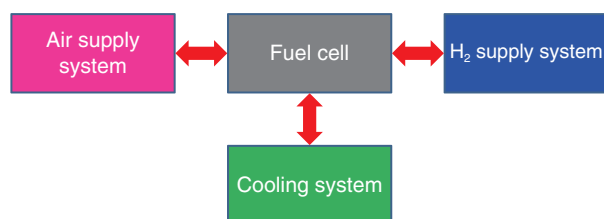


Fig. 1 Overview of fuel cell system

2. Development Aims

Conventional Lysholm compressors release air following its compression by the rotors in the compressor; the noise produced by the discharge of air therefore increases in proportion to the operating pressure. Because

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of this, the capacity and volume of noise-reducing devices used to attenuate this noise also increase in proportion to the operating pressure of the compressor. Turbocharged compressors, by contrast, do away with the internal compression process of conventional Lysholm compressors, and produce a low level of discharge noise. The use of a turbocharged compressor would mean that it would be possible to reduce the number of noise-reducing devices and thus reduce the size of the system even if the operating pressure was increased.

In addition, increasing the pressure of the air supplied to the fuel cells would increase the oxygen partial pressure, reducing the decline in the voltage of the fuel cells when operating at high power. As a result, it would be possible to increase the total power of the fuel cell system as shown in Fig. 3, even when the increase in the power consumption of the air compressor necessary for increasing the air pressure is subtracted. It was thought that this would reduce the necessary number of cells in the stack, and thus contribute to reduced size and cost.

Increasing the operating pressure would also increase the relative humidity inside the stack, as shown in Fig. 4. This would reduce the necessary amount of humidification,

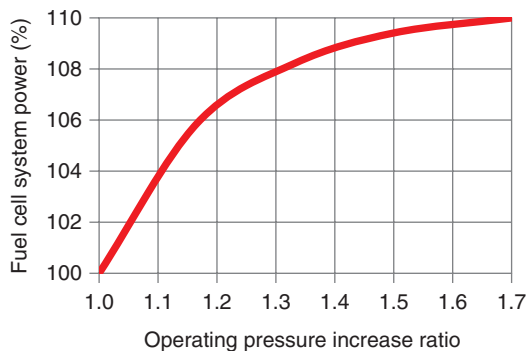


Fig. 3 Correlation between cathode operating pressure and fuel cell system power

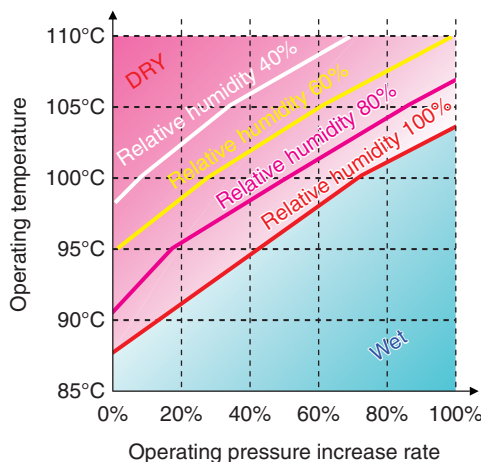


Fig. 4 Correlation between stack humidity and pressure and temperature

making it possible to reduce the size of the humidifier.

An increase in operating pressure would also make it possible to maintain an appropriate level of stack humidity even under conditions in which operating temperature increased. This would mean that the generation performance of the fuel cells could be maintained even in scenarios in which operating temperature increases, such as steep hill climbing, when there is little breeze from driving or when the cooling ability of the radiator is low, making it possible to maintain a high level of dynamic performance.

Based on the considerations above, the aims for the development of the air supply system for the CLARITY FUEL CELL were set as follows.

- (1) Reduction of the necessary number of fuel cells through the realization of increased fuel cell power by increasing air supply pressure, reducing the size and cost of the system.
- (2) Reduction of the size of the humidifier and expansion of the high-temperature operating range of the fuel cells by means of the reduction of the necessary amount of humidification through the realization of increased air supply pressure.
- (3) Scrapping of auxiliary noise-reducing devices as a result of the realization of increased quietness through the application of a motorized turbo compressor, and the consequent reduction in size of the air supply system.
- (4) Development of an inverter capable of sensor-less control, realizing a resolver-less motor able to be reduced in size, helping to enable the system to be fit under the front hood.

3. Characteristics of Two-stage Motorized Turbo Compressor

Figures 5 and 6 respectively show an external view and a sectional view of the two-stage motorized turbo compressor developed jointly with Honeywell.

This compressor configuration has the following characteristics.

- (1) Air bearings are employed as the bearings.
- (2) The unit is a two-stage turbo compressor, provided with a low-pressure-side compressor and a high-pressure-side compressor at the respective ends of the rotor.



Fig. 5 Two-stage motorized turbo compressor

- (3) The turbocharging of the compressor increases quietness.

3.1. Configuration of Bearings

Oil-lubricated bearings are normally used for turbochargers in internal combustion engines. However, there was a concern that when using a turbo compressor in a fuel cell system, oil flowing from the bearings might poison the fuel cells, causing a decline in generation performance. Air bearings, which are used in the turbochargers in aircraft air cycle systems, were used for the first time in an automotive application. Figure 7 shows the structure of the radial air bearings as an example of the bearing configuration.

Figure 8 shows the principle of rotor lift-off. As the rotor rotates, the viscous action of air forces air into a wedge-shaped gap, generating pressure (dynamic pressure), lifting the rotor off the bearings.

Following the lift-off of the rotor, the generated pressure is transmitted to a bump foil via a top foil, as shown in Fig. 9. Fluctuations in pressure are absorbed by the deformation of the bump foil, and the fluctuations are attenuated by the friction force between the foils. This makes it possible

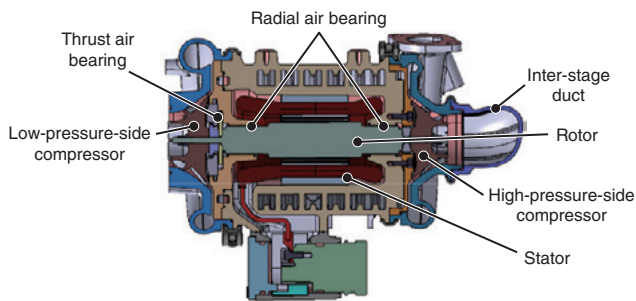


Fig. 6 Sectional view of motorized turbo compressor

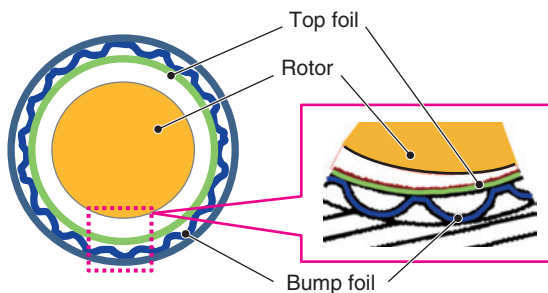


Fig. 7 Structure of radial air bearing

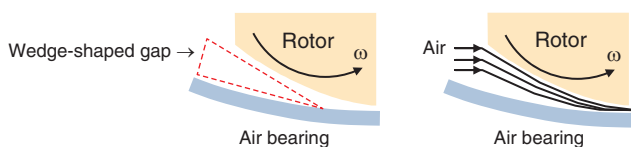


Fig. 8 Rotor lift-off mechanism

to maintain an optimal thin air layer thickness, even with fluctuations in pressure due to fluctuations in rotor speed, thus maintaining the lift-off of the rotor.

3.2. Compressor Configuration

In order to reduce the size of the fuel cell system, it was necessary to increase the pressure of the air supplied to the fuel cells. In addition, because it is necessary to control pressure and flow rate in response to changes in the operating environment (for example load, temperature, or atmospheric pressure), and to control transient states, as exemplified by acceleration and deceleration, it is important to help ensure a wide operating range in an air compressor used in a fuel cell system.

Figure 10 shows standard turbo compressors. Centrifugal compressors of these types are widely used as turbo compressors in engine applications. Because all the fluid flows out from the peripheries of the impeller in a centrifugal compressor, the units are able to realize a considerable pressure increase⁽³⁾. However, when the flow rate is reduced, the system pressure and flow rate begin to fluctuate⁽⁴⁾, and surges occur that restrict the operating range.

In contrast, while the axial compressors used in jet engines are able to realize a high flow rate, these compressors are not able to achieve a high pressure increase using a single-stage impeller. It is necessary to use a multi-

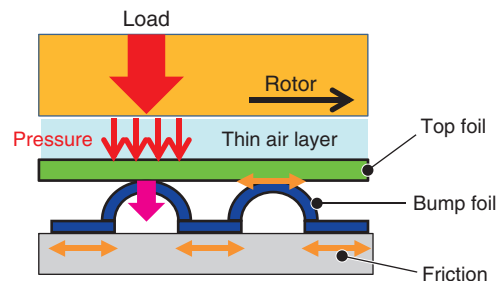


Fig. 9 Operation of air bearing

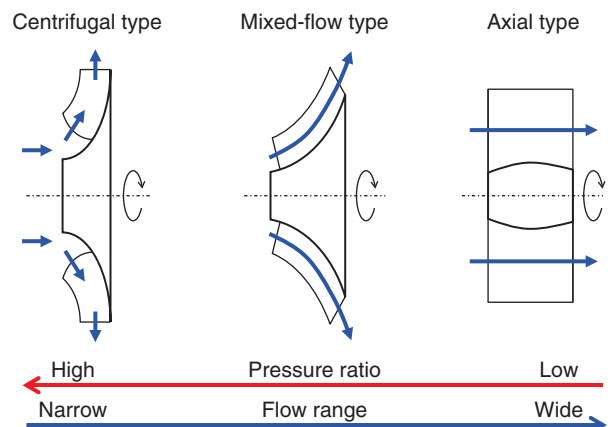


Fig. 10 Compressor wheel type

stage impeller when a high pressure increase is important.

In order to realize a wide operating range, a mixed-flow compressor configuration offering characteristics intermediate between those of the centrifugal and axial compressor types was adopted. A two-stage configuration was applied, making it possible to balance a high ratio between intake pressure and discharge pressure (pressure ratio) with a high flow rate (Fig. 11).

Figure 12 and Table 1 compare this configuration with a one-stage centrifugal compressor. The use of the mixed-flow compressor made it possible to balance a 1.7-fold increase in the compression ratio against the centrifugal compressor with the realization of a wide operating range.

3.3. Realization of increased Quietness via Turbocharging of Compressor

Because they do not use internal combustion engines, fuel cell vehicles are quiet during operation. Given this, it is important to reduce the operating noise of the air compressors used in fuel cell vehicles.

Figure 13 shows the configuration of a conventional Lysholm compressor⁽⁵⁾. Lysholm compressors compress air internally between a pair of rotors. Because intake and discharge are intermittent, pulsation noise is generated at the inlet and outlet sides. In addition, because the rotors

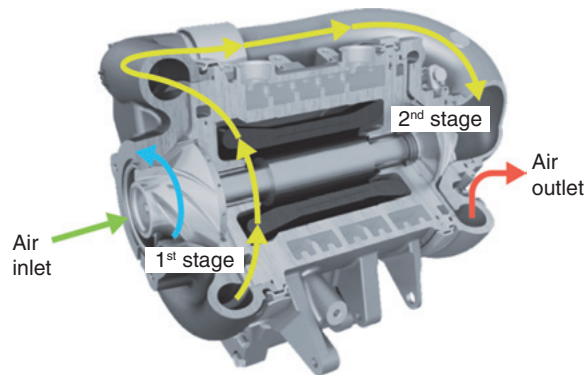


Fig. 11 Internal air flow of two-stage motorized turbo compressor

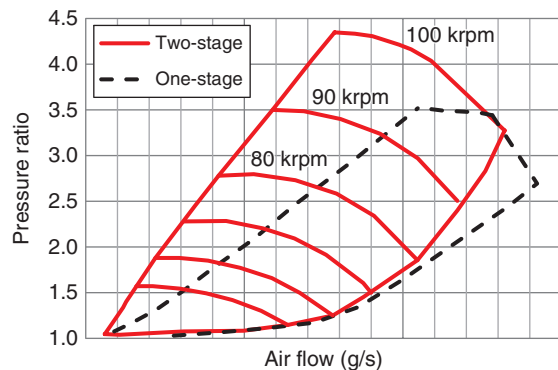


Fig. 12 Performance map

Table 1 Specifications

	One-stage	Two-stage
Wheel type	Centrifugal	Mixed-flow
Maximum rotation speed	100 krpm	100 krpm
Maximum pressure ratio	3.5	4.2

are driven by gears, gear noise also infiltrates the cabin as compressor operating noise. This has necessitated the use of a large number of noise-reducing auxiliary devices in order to maintain the quietness during operation that is a characteristic of fuel cell vehicles.

The application of the new turbo compressor has reduced pulsation, making it possible to reduce noise on the inlet and outlet sides as shown in Figs. 14 and 15 respectively.

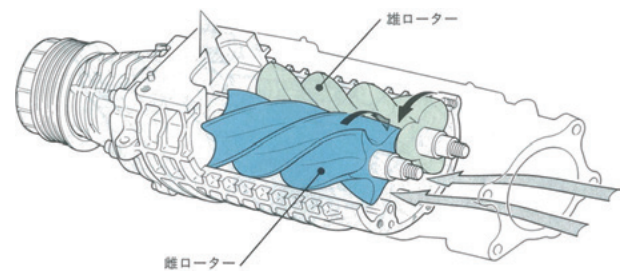


Fig. 13 Cross-section of Lysholm compressor

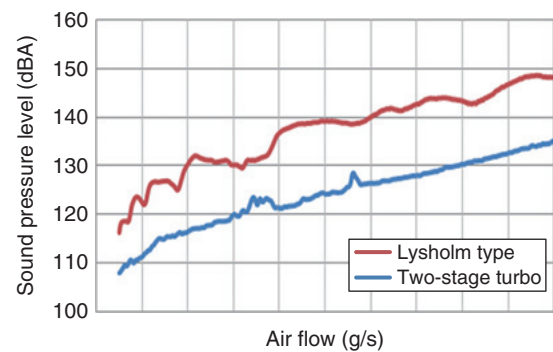


Fig. 14 Inlet noise comparison

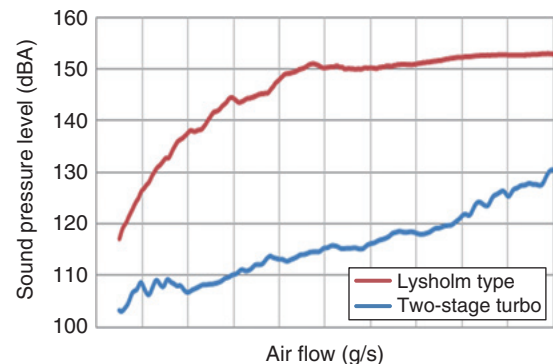


Fig. 15 Outlet noise comparison

In addition, while the twin rotors in conventional Lysholm compressors are driven by gears, using the same shaft for the compressors and the rotors in the new unit has made the gears unnecessary, making it possible to realize the reduction in radiation noise from the unit shown in Fig. 16.

Increasing the quietness of the compressor made it possible to reduce the size of the resonator used to address inlet pulsation noise and do away with the silencer used to address outlet pulsation noise and the cover for reduction of radiation noise, which previously occupied a considerable amount of space under the front hood. As a result, it has been possible to integrate the auxiliary noise-reducing devices with the air cleaner, as shown in Fig. 17, reducing volume by 50% against the previous model, the FCX Clarity⁽⁶⁾.

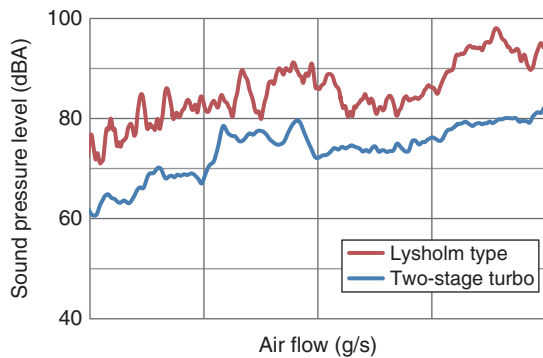


Fig. 16 Comparison of radiation noise near compressor

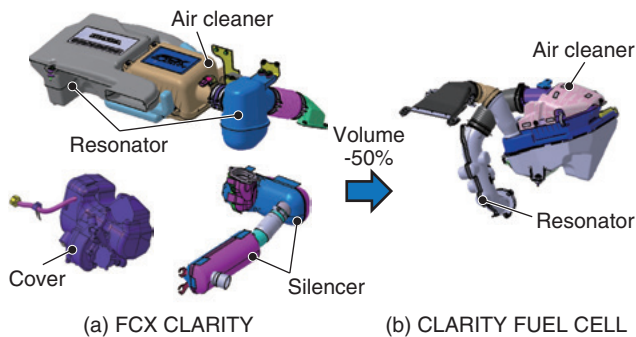


Fig. 17 Downsized noise reduction devices

4. Drive Inverter for Two-stage Motorized Turbo Compressor

Figure 18 shows the inverter unit jointly developed by Honda and BRUSA. The unit has the following characteristics.

The inverter is integrated with the Intelligent Power

Unit (IPU) box to help enable fitting in a limited space, and is provided with devices capable of high-speed switching and cooling structures to help enable sensor-less control at a compressor shaft speed of 100,000 rpm.

4.1. Integration of Inverter and IPU Box

When an inverter unit is fitted in a vehicle, it is necessary for the packaging to satisfy two criteria.

The first of these is that the direct-current high-voltage cable (DC cable) connected to the primary side of the inverter unit is integrally connected with the IPU box outside the cabin. The other is a layout that helps to ensure that the unit's case is not damaged in any of the crash tests that the vehicle undergoes.

It was necessary to fit a package of a size that satisfied these conditions in an area at the front of the IPU box in which there would be no incursion from rigid bodies during crash tests. Following the satisfaction of performance demands, a dedicated inverter that could be installed in this area was developed, and its packaging was integrated with the IPU box (Fig. 19).

To help ensure the safety of technicians conducting maintenance, the configuration used makes it unable to access the area in which the DC cable is connected when the unit is fitted in the vehicle. A layout in which the DC cable is directly extended from the IPU box to the inverter unit was necessary in order to realize this configuration. The waterproof performance of the IPU box was an issue in this. To help ensure waterproof performance, a flexible rubber duct was used to house the connection between the

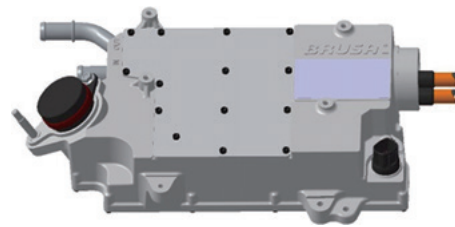


Fig. 18 Air pump inverter unit

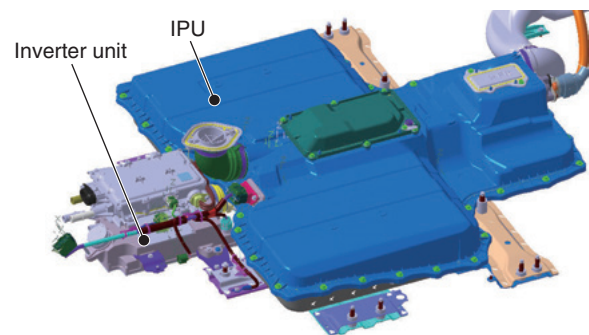


Fig. 19 Potential area for fitting of controller unit

IPU box and the inverter unit (Fig. 20). In addition, the fact that the inverter unit would be positioned under the floor of the vehicle, where it could be submerged in water (Fig. 21), necessitated consideration of waterproofing and corrosion prevention in the design of the unit. An aluminum material possessing a high level of rust resistance was therefore used for the inverter case. Formed-in-place-gaskets (FIPG) were used in the gap between the case and the lid for waterproofing as an anti-corrosion measure.

4.2. High-speed Switching Technology and Technologies for Reduction of Size

The following three element technologies were used to reduce the size and increase the efficiency of the inverter unit.

The use of a full-mold module increased heat radiation, and the use of a press-fit connection made it possible to reduce the size of the unit. The size of the motor was also reduced through the use of sensor-less control.

The use of a power module in which a direct copper-bonded (DCB) substrate was sealed by means of transfer molding (Figs. 22 and 23) reduced thermal resistance from the semiconductor chip to the base plate, realizing highly efficient heat radiation. This made it possible to realize switching at 24 kHz, a frequency exceeding the switching

frequency of conventional insulated gate bipolar transistors (IGBT).

With regard to the press-fit connection used for the power module pin, the high-pressure insertion of the press-fit pin into the base plate through-hole to form an electrical connection with the power base plate helps to eliminate any decline in reliability due to solder cracks originating in heat impact. The size of the unit was also reduced through simplification of the wiring and reduction of the distance between parts. In order to reduce development time, a press-fit terminal for which design and production licenses based on the IEC standards could be obtained was used. The clarification of the relationship between the value of temperature increase and the value of contact resistance in the area of contact with high current-carrying parts (Fig. 24), which is important from the perspective of specifications, and management on this basis, has helped to ensure the durability and reliability of the electrical connection sections.

24 kHz, which is outside the audible range, are used as the switching frequency for sensor-less control, and a single electrode couple has been used in the motor. This has reduced switching noise and helped to ensure stable motor control at the maximum compressor speed of 100,000 rpm.

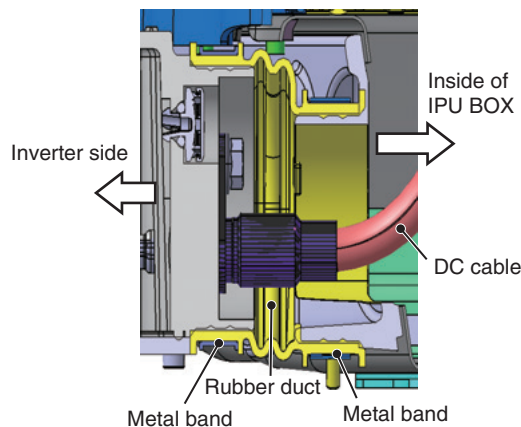


Fig. 20 Sectional view of duct



Fig. 21 Inverter mounting position

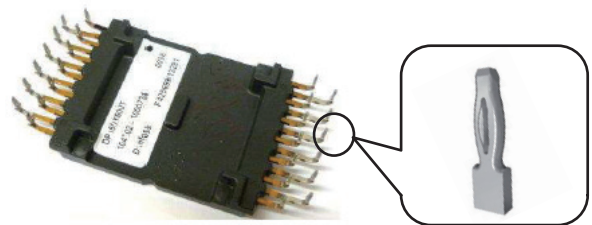


Fig. 22 Full-mold module and press-fit pin

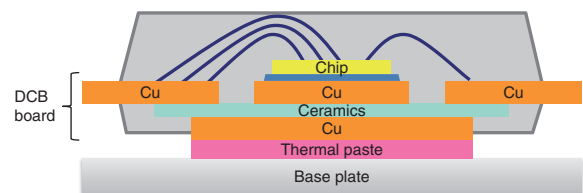


Fig. 23 Sectional image of full-mold module

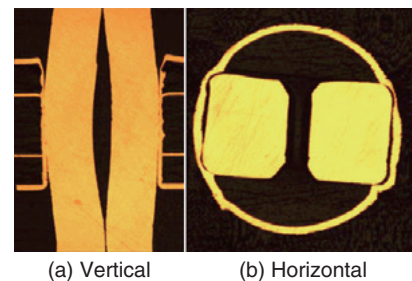


Fig. 24 Cross-section of press-fit connection

Figure 25 shows the control values for sensor-less control and the behavior of the control at different compressor speeds. This control conducts power regeneration during deceleration using PWM control in order to reduce the amount of time that the rotors stop rotating, helping to realize a high level of responsiveness during both acceleration and deceleration.

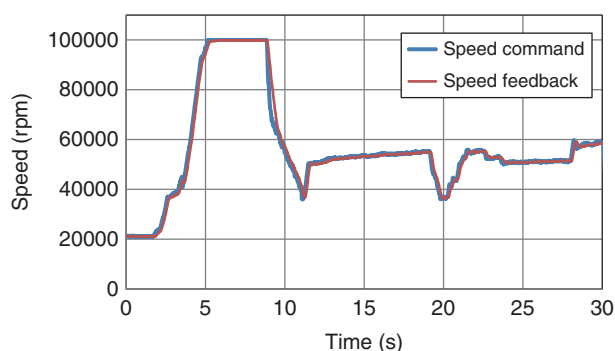


Fig. 25 Rotor speed behavior with sensor-less control

5. Conclusion

A two-stage motorized turbo compressor has been developed with the aim of increasing the pressure of air supplied to a fuel cell system and increasing quietness. The following outcomes were obtained.

- (1) The use of two-stage compression in a mixed-flow compressor has made it possible to realize a 1.7-fold increase in air supply pressure compared to a conventional compressor.
- (2) Air bearings were used to realize high-speed bearings that do not require oil, making it possible to use a turbo compressor in a fuel cell system supplied with pure air.
- (3) The use of the motorized turbo compressor made it possible to reduce the volume of the auxiliary noise-reducing devices by 50%.
- (4) To help ensure collision safety and electrical safety, a full-mold module and press-fit connection technology have been used in the inverter, which is integrated with the IPU box. The application of these technologies made it possible to realize a compact, high-speed inverter using sensor-less control, contributing to the reduction of motor size.

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Technology for Embedding Engine Models in ECU for Model-based Development

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ABSTRACT

Consistency in the control subject model from the top level to the lower level of the V-process used in model-based development is an important factor when designing internal combustion engine control. For this reason, parameter calibration was used to provide relevance between the 1D engine model in the top level and the mean value engine model in the middle level so that the deviation is within a certain level. In addition, an environment was constructed for embedding the mean value engine model used by Hardware-in-the-Loop Simulation as is in an ECU. The model is described using a formula simulator and converted to C code. A tool was developed that automatically converts this code into C code for mounting in an ECU. The converted C code was actually operated using a CPU evaluation board, and was confirmed to operate in 10 ms or less, which is the calculation cycle for engine device control. This made it possible to link the models in the top and middle levels of model-based development and also enabled model mounting to an ECU in the lower level, which increased the reusability of V-process engine models.

1. Introduction

Increasing attention is being given to fuel economy enhancement technology that focuses on increasing thermal efficiency, such as downsizing turbocharged engine technology and research on Low Pressure Loop (LPL)-EGR⁽¹⁾ and lean burn.

High-efficiency engines call for dedicated sensors, devices, and software. However, systems are becoming more complex overall due to factors such as enhancement of catalysts used to process emissions. Calibration has been performed thus far by relatively simple work such as mapping with unit bench tests, but the parameter settings for mass production currently take an enormous amount of time. Attempts are being made to enhance optimization tools and simulations to achieve optimization with the goal of minimizing deviation by means such as the use of efficient data sampling methods and response surfaces⁽²⁾. In addition, it is predicted that exhaust emission regulations will become stricter around the world, and there are concerns that demands on engine control will increase, such as more accurate air-fuel ratio control and EGR control to support fuel economy and exhaust emission regulations.

Meanwhile, due to the push for model-based development, Hardware-in-the-Loop Simulation (HILS)⁽³⁾ is becoming popular as a verification tool. In the field of control system design, attempts are being made to develop control logic using HILS and actual ECU. To increase the effects of model-based development, it is desirable to promote advances in models by increasing model reusability. Therefore, this paper mounted an accuracy-assured mean value engine model⁽⁴⁾ created for HILS and calibrated for control design and verification as is in a control ECU, and investigated the reuse of this model as an actual engine-state predictor in an ECU. CPUs have thus far lacked sufficient calculation performance, so while there are cases of embedding partial engine models⁽⁵⁾, there are few known cases of embedding a full engine model including from the intake system to the combustion and exhaust systems. The mean value engine model used in this paper was a direct fuel injection turbocharged engine model created by a formula simulator, and was optimized beforehand using a mathematical model. This model was executed using a commercially available CPU evaluation board to verify mounting in an ECU, and the calculation times and calculation results were compared.

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2. HILS and ECU-embedded Model Sharing and Issues

2.1. Engine Control HILS for Model-based Development

When performing function design in the middle level of model-based development, control logic that satisfies the function requirements is designed using Model-in-the-Loop Simulation (MILS) or HILS as shown in Fig. 1. An engine model is used as the control subject model, and the model parameters are calibrated so that the actual engine and steady-state behavior match. In addition, the transient-state behavior should also be reproduced in the same manner as the steady state. The use of a common model by MILS during function design and by HILS during verification helps prevent differences between design and verification. However, although the MILS model does not call for real-time execution, HILS uses an actual ECU, so real-time execution is needed.

2.2. Setting Targets for ECU-embedding

Models that can be executed in real time on HILS consist of comparatively simple calculations, so it was

thought that these calculations could also be performed by an ECU. Therefore, it was investigated whether models could be reused to predict temperature, pressure, and other characteristics at points that are a challenge to observe. Unlike an actual engine, the sensors needed for measurement can be freely mounted in a model inside an ECU. This paper performed development with a focus on torque calculations using a combustion model. Driving force control calls for a torque calculation deviation of 10 Nm or less, which is 5% of the full-throttle torque, so the torque calculation deviation of the model was also set to 10 Nm or less to satisfy this requirement. The control cycle for devices such as the throttle is 10 ms, so the control cycle was set to 10 ms or less. The development targets are listed below.

- (1) The HILS mean value engine model used for control system design and when verifying controllability is a full model including all systems from intake to exhaust, and can be mounted in an ECU.
- (2) Development of a tool that automatically modifies the C code generated automatically from a mathematical model into code that can be mounted in an ECU.
- (3) The ECU calculation cycle for the engine model is 10 ms or less, and the torque calculation deviation is 10 Nm or less.

3. Calibration of Mean Value Engine Model with an Actual Engine

3.1. Embedded Engine Model

Figure 2 shows the flow of engine model parameter calibration in sequential system identification⁽⁴⁾. Different tools are used in each of the top, middle, and lower levels of the V-process flow, so the architecture performs calibration to match the setting parameters of each model with the simulation results. A 1D model is calibrated using a current engine in the initial stage of development, and in the next

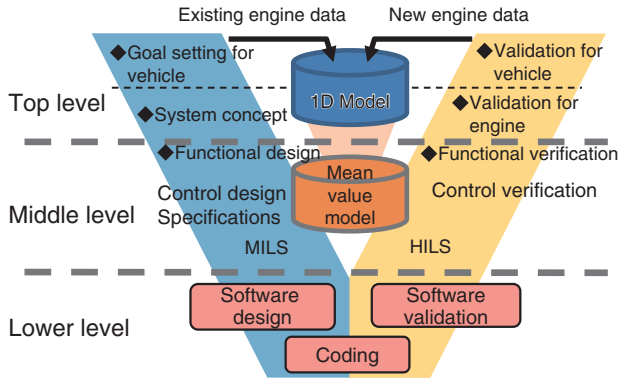


Fig. 1 Standard V-process

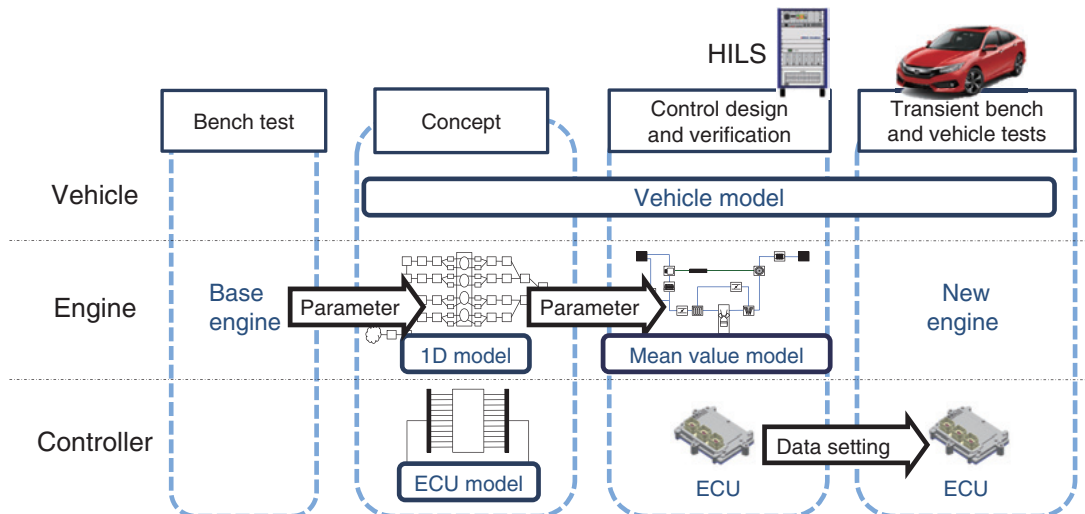


Fig. 2 Model parameter identification flow for engine plant model

step calibration is performed to approach the mean value engine model. The final stage is the development step where the model is mounted in the control ECU. This step is then repeated to enhance the developed engine and also raise the system development level.

Figure 3 shows the developed engine model. A mean value model of a downsizing turbocharged direct fuel injection 1.5 L 4-cylinder gasoline engine was created using MapleSim, which is a modeling simulation tool with formula processing functions. The model parts configuration used the actual engine parts combination. The layout took into consideration modularization in order to minimize the changes to the model when changing the parts configuration or specifications. This enabled to support changes to parts specifications by modifying part unit bench measurement data and changing parameters to achieve the expected parts model simulation results. Standard parts components are provided for MapleSim, but non-standard models such as the combustion model were expressed mathematically and created using custom components. The LPL-EGR and combustion models created using custom components are described below.

3.2. LPL-EGR Model

When the exhaust gas introduction delay is not reflected in LPL-EGR, the issue arises that the control system design using HILS and the transient state behavior of an actual engine do not match. Simulations were therefore performed to confirm whether the actual EGR gas delay behavior could be reproduced by parameter settings. Figure 4 shows the MapleSim simulation results on a PC. These are the results when

step response is performed by LPL-EGR valve-opening control. EGR_rate indicates the ratio of the EGR gas entering the intake pipe. The EGR gas ratio when closing the LPL-EGR valve was compared for rate 1 when the

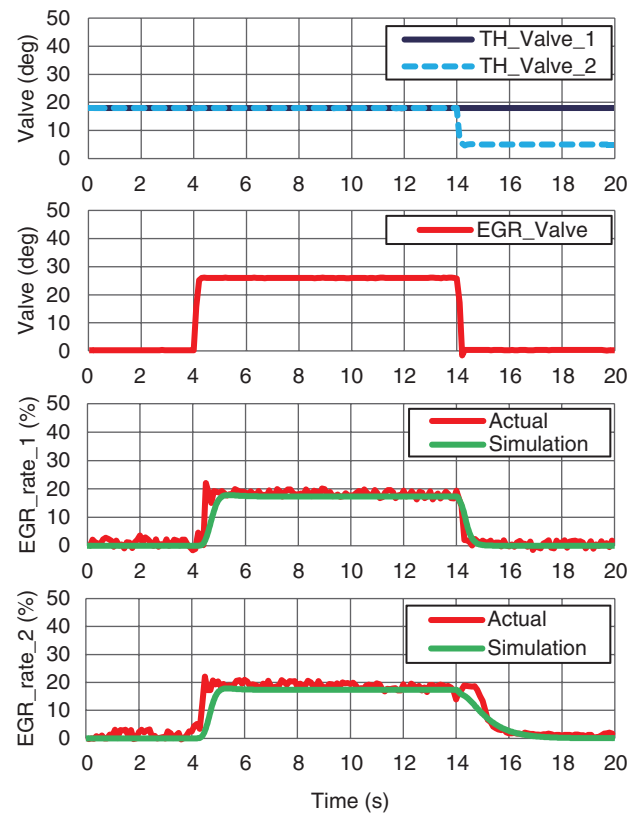


Fig. 4 LPL-EGR simulation results

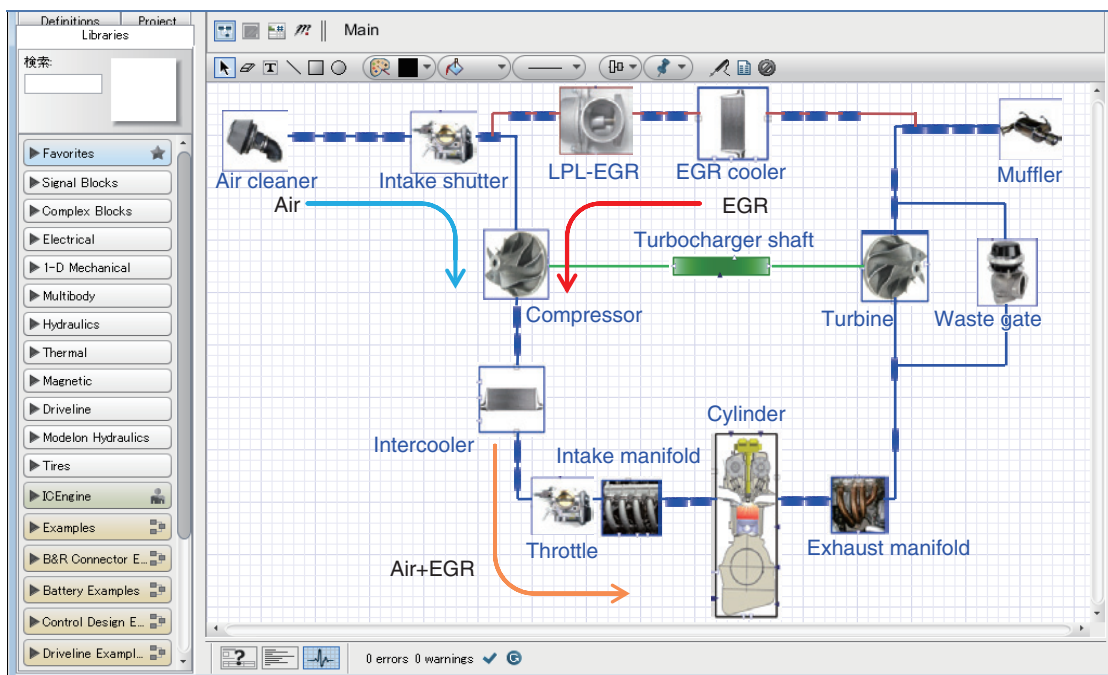


Fig. 3 Mean value engine model with turbocharger and LPL-EGR

throttle at the entrance to the intake pipe is open and rate 2 when the throttle is closed. These results show that the EGR gas responds immediately in the rate 1 (throttle open) condition. However, in the rate 2 (throttle closed) condition, the time to replace the gas inside the chamber such as the intercooler before the intake pipe increases, and an extended time of 2 s is needed to completely reduce the LPL-EGR gas. The actually measured response waste time and response delay was the same 2 s as in the simulation, so it was determined that the LPL-EGR model can accurately express the gas delay.

3.3. Engine Combustion Model

A Wiebe function is often used to perform combustion calculations for applications such as normal combustion analysis systems. However, a number of operations equal to the number of crank angle steps (approximately 0.5 deg to 1.0 deg/step) is needed, which makes real-time execution for use in HILS a challenge. Therefore, the calculation formula was simplified by making it possible to set the heat release pattern using typical points extracted from premeasured data. The model used by HILS employs functions of the engine speed, intake air volume, ignition timing, and other engine control parameters so that these setting values match the actual engine. Engine measurement used a standard Kistler sensor (305B) and an Indicom combustion analysis system made by AVL.

The red points in Fig. 5 represent the typical points set based on the heat release amount. A total of seven points were set, including the three points of the calculation start point, heat release start position, and heat release peak value, the two points of the second-order differential

value peak positions, and the two points indicated by triangles near the mass burnt fraction 5% position and the combustion end position.

Interpolation was performed by straight-line approximation from each point to obtain the heat release pattern relative to the crank angle. The cylinder pressure during the combustion period was calculated from the obtained heat release pattern and the stroke volume.

Equation (1) is used to calculate the heat release from the cylinder pressure, the stroke volume, and the specific heat ratio. Equation (2) is obtained by transforming Eq. (1), and expresses the cylinder pressure.

$$\frac{d}{d\theta} Q(\theta) = \frac{1}{\kappa - 1} \cdot V(\theta) \frac{d}{d\theta} \cdot P(\theta) + \frac{\kappa}{\kappa - 1} \cdot P(\theta) \cdot \frac{d}{d\theta} V(\theta) \quad (1)$$

The parameters used in the above relational expression of cylinder pressure and heat release are as follows.

$V(\theta)$: Volume (cm³)

$P(\theta)$: Pressure (kPa)

$Q(\theta)$: Quantity of heat (J)

κ : Specific heat ratio

$$P(\theta) = \left\{ \int_0^\theta \left[\frac{d}{d\theta'} Q(\theta') \right] \cdot (\kappa - 1) \cdot V(\theta') \cdot d\theta' + \frac{P_{ini}}{V(0)^{-\kappa}} \right\} \cdot V(\theta)^{-\kappa} \quad (2)$$

However,

θ' : Integral value from crank angle 0 to θ

P_{ini} : Initial pressure

IMEP is expressed by Eq. (3), NMEP by Eq. (4), and PMEP by Eq. (5).

$$IMEP = \frac{1}{V_d} \int_{V_{-360}}^{V_{360}} P \cdot dV \quad (3)$$

$$NMEP = \frac{1}{V_d} \int_{V_{-180}}^{V_{180}} P \cdot dV \quad (4)$$

$$PMEP = IMEP - NMEP \quad (5)$$

V : Volume (m³)

dV : Derivative of Volume

V_d : $V_{max} - V_{min}$ (m³)

P : Pressure (kPa)

IMEP: Indicated Mean Effective Pressure

NMEP: Net Indicated Mean Effective Pressure

PMEP: Pumping Indicated Mean Effective Pressure

NMEP during the combustion period is calculated by integrating the cylinder pressure over the stroke volume as shown in Eq. (4). Next, the pumping loss (PMEP) has a relatively small impact on the torque calculation, so it is obtained simply by determining the measured value from a map according to the pressure inside the intake manifold and the engine speed. This made it possible to shorten the IMEP calculation time.

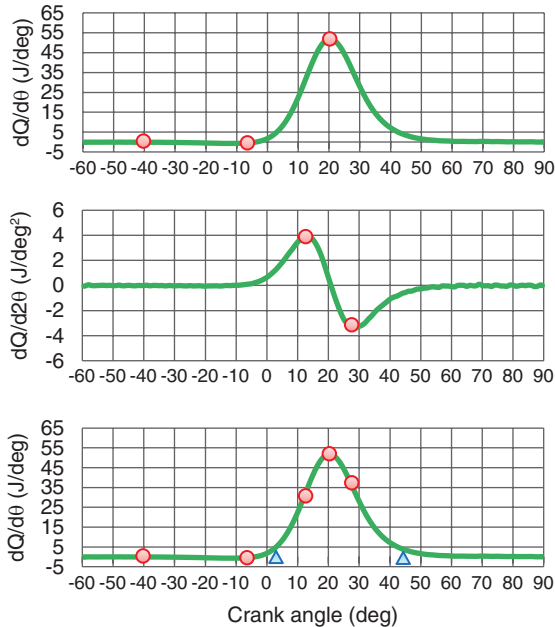


Fig. 5 Heat release rate of combustion and setting points for model calibration

3.4. Comparison with 1D Model

1D models are generally used from steady state to transient state as seen in cases of calibration with actual engines⁽⁶⁾. Calibration was performed so that the 1D model and mean value engine model parameters match the actual engine measurement results.

Calibration for the mean value engine model consisted of calibrating the setting values of the seven points of the combustion model described above to minimize the torque deviation. Figure 6 compares the calibration results of the two simulations with the measured engine torque. These results show that the two simulations exhibit a linear relationship with the measured torque from low to high power output, and the torque calculation value deviation of both the 1D model and the mean value engine model was 10 Nm or less. Based on these results it was determined that there are no issues for use as ECU-embedded models.

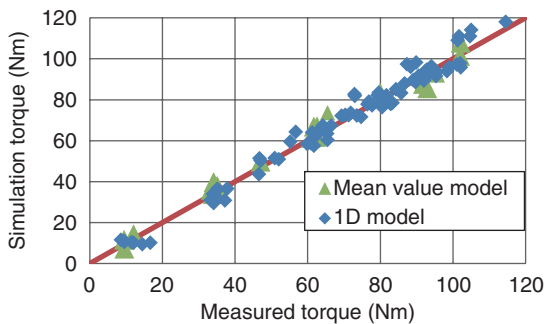


Fig. 6 Comparison of simulation results

4. Development of ECU Embedding Tool

4.1. Engine Model Code Conversion

The model introduced thus far is described using MapleSim, and C code is generated from the model using the auto C code generation function of MapleSim. This C code can be selected from MATLAB Simulink code and generic code, but generic code was used to minimize the impact of future tool version upgrades and other factors. Next, it is necessary to convert this code to the embedding program format in accordance with the program creation rules to enable embedding in the ECU. Embedding is then completed by using the target CPU compiler to create an HEX file and downloading the file.

Work efficiency was increased by developing a tool that automatically converts the code into C code for embedding. This enables provision of timely support for various engine models that are updated as needed in future development.

Figure 7 shows the execution screen of the developed code conversion tool. C code conversion can be executed simply by selecting the subject file on this simple screen. The development tool body was created using MATLAB

in consideration of continual version upgrades. The code conversion tool functions are listed below.

- (1) Application of program creation rules such as definition of variables

Variable name change, type name change, addition of comment text, limit processing, divided by zero prevention, type declaration of cast operators, function prototype declaration, addition of variables

- (2) Reduction of the processing load

Changing double precision to single precision, changing floating point division to private functions

- (3) Application of existing libraries

Header file load process

The C code conversion time using this tool was approximately 11 minutes, and the code size was 500 kbytes.

4.2. Operation Check Using a CPU Board

Figure 8 shows the appearance of the evaluation board used to confirm operation.

The Infineon TC297 evaluation board was selected due to its multicore CPU and the ability to set an arbitrary clock frequency. The program was mounted in this evaluation

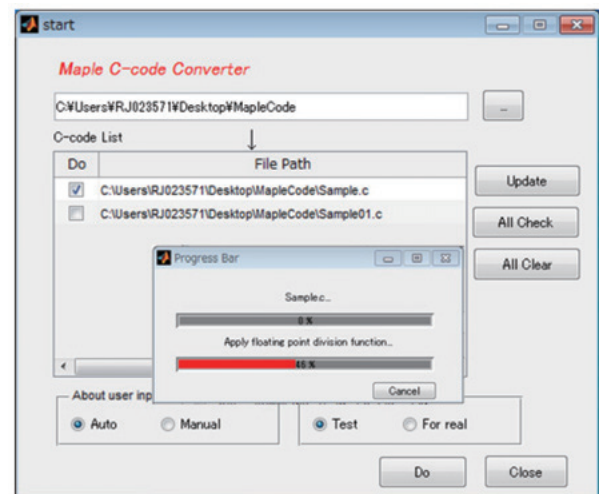


Fig. 7 File setting screen of conversion tool

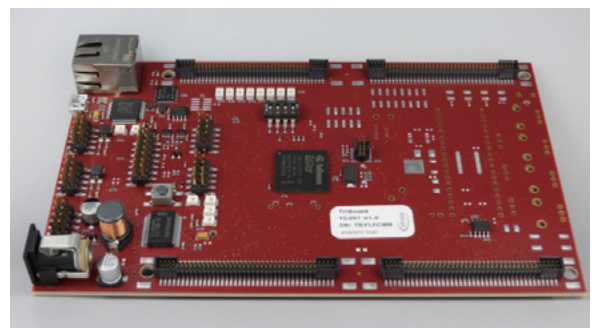


Fig. 8 Appearance of CPU evaluation board

board and the calculation time was measured. The performance of this board is approximately twice that of current mass-production ECU in terms of ROM and RAM capacity and processing capability.

These performance settings provide sufficient margin to support future expansion of the embedded model. Normal engine control and other calculation blocks are not mounted, so the impact of interrupts and other factors are not taken into account in the time measurements in this paper.

Figure 9 shows the calculation time results measured using Euler's method and the Runge-Kutta method. The ECU uses discretized⁽⁷⁾ signals when calculating the plant model, and typical Euler's and Runge-Kutta methods were compared as the discretization method. The CPU clock cycle was assumed to be the standard 200 MHz. The operation cycle of the engine model in the ECU should be as short as possible, but the torque control cycle using the intake air volume is 10 ms, so the operation cycle should be sufficiently shorter than this time. The comparison results show that the Runge-Kutta method, which has a high calculation load, had an execution time of 2.5 ms. The engine operating conditions during measurement were the vehicle operating conditions in the LA4 mode.

Discretization has the characteristic that the signal input and calculation values change in a step shape between the previous calculation and the current calculation. For this reason, when the difference increases, the calculation process easily becomes unstable due to overflow or other factors. In particular, when the calculation cycle becomes longer for a simple discretization process using Euler's method, the difference in the internal calculation results increases and produces a step in the calculations, so a short cycle is demanded. However, the overall calculation times increase, so when the engine speed increases, the number of event interrupts such as ignition timing and fuel injection also increase with the result that it takes time to finish calculations with a 10 ms cycle. The results of this study showed that even when using the Runge-Kutta method, the calculation time approximately doubled but was still within the target time, and stable operation could be obtained. Therefore, the Runge-Kutta method was selected.

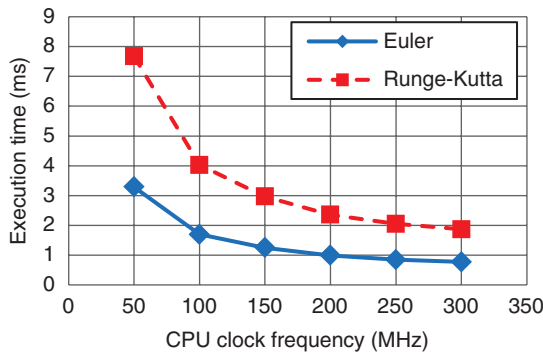


Fig. 9 Comparison of execution time with Euler's and Runge-Kutta methods

Table 1 Performance comparison between CPU and HILS

Execution condition	Evaluation board	HILS
Data length	16 bit	32 bit
Control cycle [ms]	10	0.1

5. Comparison of Calculation Results for HILS and ECU with Embedded Model

The difference between the calculation results when the engine model is mounted in HILS and when mounted in an evaluation board that simulates an ECU was verified. The driving pattern used for verification was the same LA4 mode used thus far. The calculation results were compared by simultaneously monitoring HILS and the evaluation board using CAN and measuring at 100 ms intervals.

Table 1 shows the difference in calculation performance between the HILS and ECU used.

The data lengths (16 bits, 32 bits) and the calculation cycles (10 ms, 0.1 ms) differed, so the monitored calculation results differed in terms of the monitor refresh cycle and the loss of significant digits due to the difference in the number of valid digits. As a result, difference waveform that resembled fine noise was observed when simply comparing the calculation results.

Figure 10 shows the results of comparing the torque calculation values at the 2nd peak of LA4 mode. Deviation such as fine noise also occurs, but this is due to the

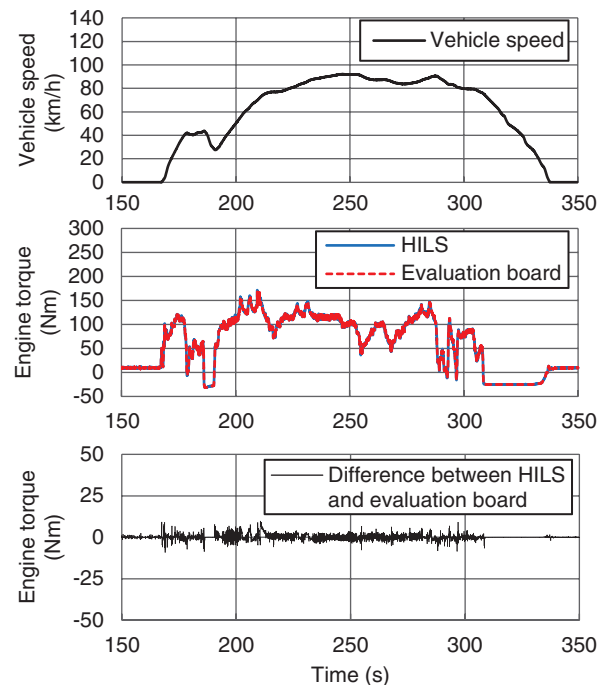


Fig. 10 Comparison of calculation results in LA4 mode

previously described difference in CPU performance.

As described above, embedding the mean value engine model mounted in HILS in the ECU enabled to standardize the engine model used to design the control system and verify operation by HILS with the engine model used for actual engine control. Accurate combustion calculations on the same level as a combustion analysis system can be performed by using a device such as a direct fuel injector integrated with a cylinder pressure sensor⁽⁸⁾. In addition to further enhancement of the engine combustion model, use of the embedded model in combination with this type of sensor can be expected to enable applications such as lean burn control using detailed cylinder information, and engine vibration suppression.

6. Conclusion

An environment was constructed for embedding the same engine model used for control design and verification in an ECU. As a result, when deviation or imperfections in the engine model are corrected anywhere in the V-process from upstream to downstream, the corresponding imperfections in other processes are also corrected. This can be expected to reduce reworking and increase the overall process efficiency.

These contents are summarized below.

- (1) The HILS mean value engine model used for control system design and when verifying controllability was the full model including all systems from intake to exhaust, and could be mounted in an ECU.
- (2) A tool was developed that automatically converts the C code generated automatically from MapleSim into code that can be mounted in an ECU.
- (3) The engine model calculation time using a CPU evaluation board was 2.5 ms, which met the target of 10 ms or less. The torque calculation error compared to HILS was 10 Nm or less, which is within 5% of the maximum output value.

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Establishment of NV Design Technology for Power Transfer Unit Gear Noise

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ABSTRACT

Prediction technology for NV performance of power transfer units installed in four-wheel-drive vehicles was established at the drawing stage.

A finite element analysis model was created for predicting gear noise generated by the mesh of hypoid gears built into power transfer units. A model of hypoid gears that are a source vibration was created by combining hexahedral elements and shell elements in order to compensate for the mass of the gear teeth and the inertia around the rotating axis. The model of the hypoid gear mesh employed a quintuple-node model that takes tooth rigidity into consideration. This approach achieved a peak frequency gap between prediction and measurement within $\pm 5\%$ and peak level gap within ± 2 dB in the 400–1600 Hz frequency range.

The predictive accuracy and time required for calculation are sufficient to make it possible to examine specifications in the early development stages.

1. Introduction

Low fuel consumption, low noise performance, and off-road drivability are being demanded for SUVs and other similar four-wheel drive (4WD) vehicles. A variety of measures are being taken to reduce overall weight as well as cabin noise. In order to simultaneously satisfy these demands, it is important to investigate specifications that could realize target performance at the design stage of a prototype unit through computer-aided engineering (CAE) analysis, and to determine the specifications with consideration of the effects on other functions. In NV marketability development of 4WD vehicles, therefore, it is necessary to perform CAE analysis to achieve the target for housing vibration of the power transfer unit (PTU). The PTU transfers drive power from the transmission to the rear axle, and the hypoid gear mesh in the PTU is taken to be the source of vibration. Figure 1 shows the transmission, PTU, and hypoid gears.

Prediction methods for PTU housing vibration at the design stage include the use of mesh force (MF), which is the excitation force caused by the gear mesh, and the use of gear-to-housing frequency response function ($GtHFRF$) at the vibration evaluation point on the housing. There has been a report, in which MF , derived from a structural analysis model, in combination with a $GtHFRF$ obtained by actual measurement, efficiently reduced gear noise in

an automatic transmission (AT)⁽¹⁾. In another report, design guidelines for gear noise reduction in a rear differential unit in the 400-600 Hz range were decided using CAE analysis⁽²⁾.

In this paper, CAE analysis is used to obtain both the MF and the $GtHFRF$ for analysis of hypoid gear noise in a PTU for a front-wheel-drive-based 4WD vehicle (FF-4WD). Those results were used to predict the PTU housing vibration level and the vibration characteristics. Reflecting the necessity for decoupling the resonance frequency of body-side transmitting parts and the PTU vibration peaks, the target frequency is defined more broadly than before as from 400 to 1600 Hz. On that basis, this paper will introduce an analysis method that has the accuracy to

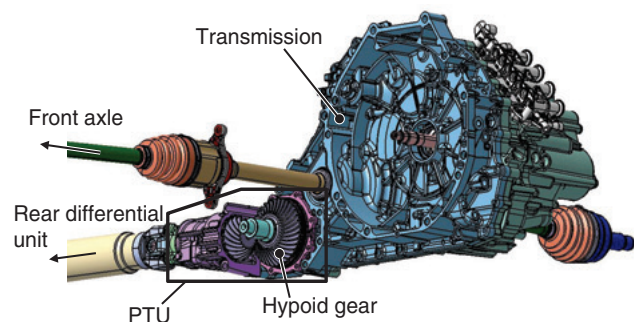


Fig. 1 View of PTU and drive train

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enable determination of the specification from structural analysis alone, by clarifying the relationship between the design variables that influence housing vibration peaks, the eigenmode, and the operational housing vibration.

2. Development Issues for PTU Gear Noise Marketability

Regarding marketability, in terms of hypoid gear noise, in a PTU for FF-4WD vehicles the target for cabin noise level is achieved by adjusting the peak level and the peak frequency of PTU housing vibration, which is the excitation force input to the vehicle body. The housing vibration level is limited to the set target value or lower, and the housing vibration peak frequencies are decoupled with the resonance frequencies of the propeller shaft and other body-side transmitting parts. The operational vibration level (*OVL*) of the PTU housing that is caused by hypoid gear mesh is shown in Eq. (1) in terms of the *GtHFRF* and transmission error (*TE*) caused by hypoid gear mesh⁽¹⁾. In Eq. (1), *TE* and *k* are real numbers that are not dependent on frequency, while the rest are functions of complex variables.

$$\begin{aligned} OVL &= TE \times \frac{1}{2/k + \phi_1 + \phi_2} \times GtHFRF \\ &= TE \times MF \times GtHFRF \end{aligned} \quad (1)$$

k: Spring constant of teeth

ϕ_1 : Drive-side gear meshing point compliance

ϕ_2 : Driven-side gear meshing point compliance

TE is defined as the relative displacement, advance or delay, that occurs between the tooth surfaces while the gears are meshing. The relationship between the gear path of contact and the *TE* is shown in Fig. 2.

The sound pressure level (*SPL*) of gear noise in a cabin, where PTU hypoid gears are the source of vibration, is

expressed in Eq. (2) as the sum of the structure-borne noise and air-borne noise. Here, the structure-borne noise, as expressed by the first term in Eq. (2), is the product of the *OVL* and the acoustic sensitivity between the PTU housing vibration and cabin noise (*ASbVN*). The air-borne noise, as expressed in the second term of Eq. (2), is the product of the near-field volume velocity level around the PTU housing (*NFVVL*) and the acoustic transfer function between the PTU housing and cabin (*ATFbPC*).

$$SPL = \sum_{i=1}^m (OVL \times ASbVN_i) + \sum_{j=1}^n (NFVVL_j \times ATFbPC_j) \quad (2)$$

m: Total number of vibration transfer paths

n: Number of PTU gear noise-radiating surface segments

It is apparent from Eq. (1) that methods for improving the *OVL* include reducing the *TE*, *MF*, or *GtHFRF*. In the past, however, development gave priority to reducing *TE* levels and reducing variation rather than modifying the frequency characteristics of structures. Regarding the reduction of *SPL*, as shown in Eq. (2), in order to reduce the structure-borne noise as discussed above, the main approach in development has been to change the frequency response characteristics of the body-side transmitting parts to adjust the *ASbVN*, thereby satisfying the target values for the system as a whole. Recently, however, market demand for reduction of cabin noise level in 4WD vehicles is so high that the conventional approaches described above are not always sufficient to determine the specifications of the system with positive prospects. Therefore, prediction technology that uses CAE analysis is also necessary for *OVL*, so that frequency characteristics, such as *MF* and *GtHFRF*, can be investigated at the basic layout stage early in development and the specifications required to achieve the targets can be determined on the basis of quantitative judgment.

3. Performance Target of NV Design Technology

In establishing the technology for prediction using CAE analysis, the following targets for predictive accuracy were set, based on the performance sought for this technology as a tool.

- (1) Peak frequency prediction accuracy within $\pm 5\%$ of the frequency in the actual vehicle in order to enable decoupling from the body-side transmitting-part resonance.
- (2) Vibration level prediction accuracy within ± 2 dB of the level of housing vibration necessary to distinguish subjective rating point difference of the cabin noise.
- (3) Considering the natural vibration characteristics of the standard propeller shaft used at Honda, the frequency range that ensures the above predictive accuracy should be from 400 to 1600 Hz.

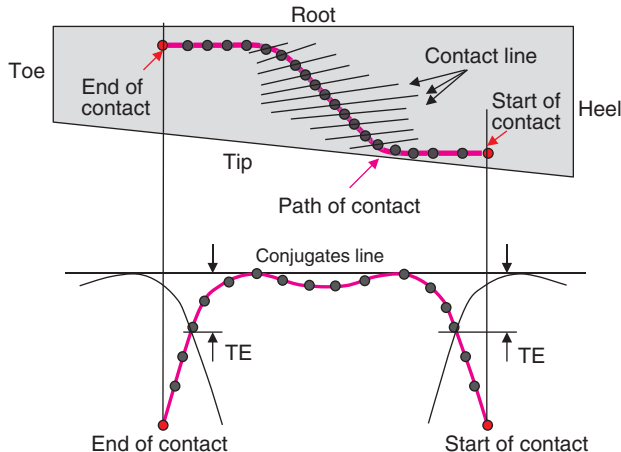


Fig. 2 Transmission error of hypoid gear

4. PTU Gear Noise Analysis Model

In order to predict the PTU housing vibration level and corresponding peak frequencies with sufficient accuracy to enable determination of the desired specifications, a finite element analysis model (FEM model) was created. As shown in Eq. (1), calculation of the PTU housing vibration requires MF and $GtHFRF$ to be calculated. In order to accurately calculate the MF in the FEM model for this purpose, it is necessary to have a drivetrain model of the drive side and driven side that includes the mesh points for the PTU hypoid gears. At the same time, in order to accurately calculate the $GtHFRF$, the housing also needs to be modeled so as to include the transmission.

In order to ensure the required prediction accuracy for the frequency range described above, the analysis mesh segment size should be fine to enable expressing the detailed shape of the structure accurately. Then the number of analysis mesh will be increased and the size of model, which influences the calculation time, increases as a whole. Additionally, model calculation time should be considered when determining the parameters of the FEM model. Ideally, the calculation should be completed within several hours to enable efficient countermeasure identification. After taking these various factors into consideration, it was decided to carry out the PTU gear noise analysis using frequency response analysis based on linear eigenvalue analysis in the frequency domain.

4.1. Hypoid Gear Mesh Analysis Model

In order to obtain the MF and $GtHFRF$ of the PTU, an analysis model of the hypoid gear mesh was created. The scope of the analysis model was extended from the mesh points of the hypoid gears inside the PTU to the final gear of the transmission on the drive side, and to the hypoid drive gear in the rear differential through the propeller shaft on the driven side. The main components of the analysis model of hypoid gear mesh are shown in Fig. 3.

When creating the FEM model of hypoid gears, the gear bodies, which were defined by rotating the profile through the root diameter of hypoid gears, were modeled using hexahedral elements in order to achieve a balance between securing the prediction accuracy with regard to bending mode and torsional mode and shortening the calculation time. In order to correct for the mass corresponding to the gear teeth and the inertia around the rotating shaft, the model was configured with a shell element attached to the hexahedral elements described above. The created FEM model is shown in Fig. 4(a).

For the model of the hypoid gear meshing point, on the other hand, a quintuple-node model was configured that takes the rigidity of the hypoid gear teeth into account. A local coordinate system was configured for the purpose of defining the forced displacement input in the direction of the line of action that is determined by the gear dimensions and tooth rigidity. A conceptual drawing of the gear meshing point model that was created is shown in Fig. 4(b). In the

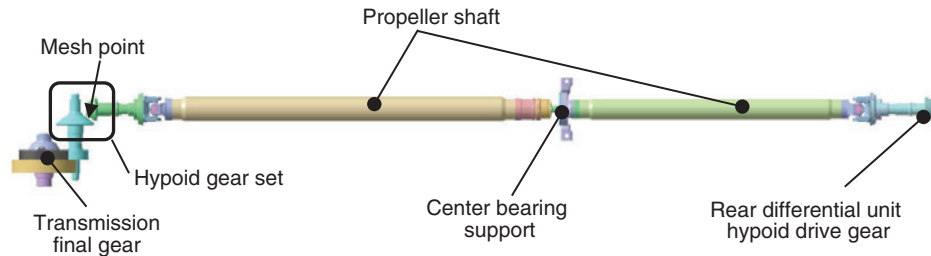


Fig. 3 FEM model for MF analysis

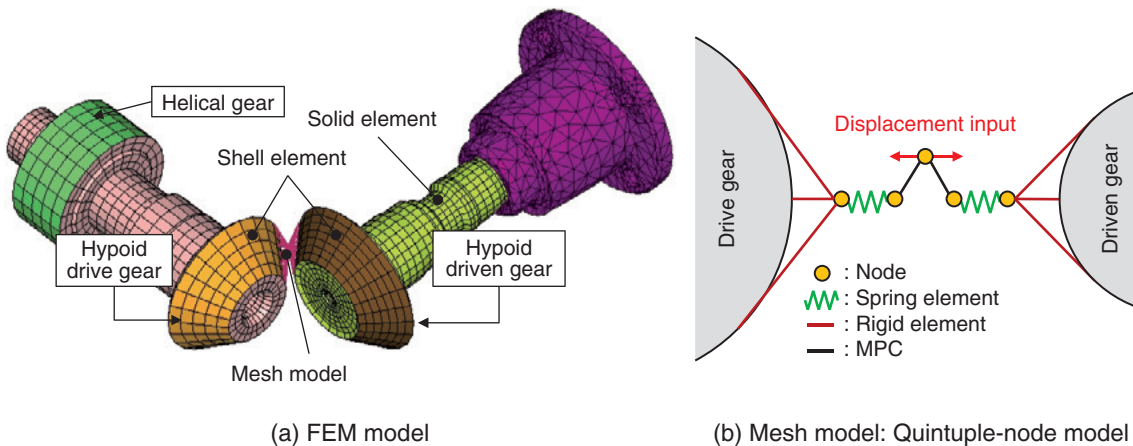


Fig. 4 Hypoid gear mesh model

housing vibration analysis model, which is to be described below, when unit forced displacement input is applied to this gear meshing point, the multi-point constraint force (MPC force) generated at the same meshing point will be the *MF*.

The tooth rigidity used in the created FEM model was identified and defined by comparison of the PTU housing vibration calculation figures derived from the housing vibration analysis, described below, and the measurement results. The peak frequency obtained from the housing vibration analysis by changing the tooth rigidity and from the housing vibration measurement results were compared, with the results shown in Fig. 5. Two types of PTU with differing dimensions of hypoid gears installed in vehicles equipped with V6 engines were used to confirm the relative positioning of their peak frequencies. The PTUs that have respective peak frequencies in housing vibration measurement results at 1100 Hz and 800 Hz were subjected to comparison of estimated peak frequency values obtained when the tooth rigidity was changed. This confirmed that peak frequency obtained by measurement and calculation by using a tooth rigidity value are largely the same. Consequently, it was decided to apply this value for tooth rigidity in vehicles equipped with V6 engines.

4.2. Housing Vibration Analysis Model

In order to calculate the housing vibration that occurs in the PTU when unit forced displacement input is applied to the hypoid gear meshing point, an FEM model of the drive train was created that includes the transmission. The scope of the analysis model was extended from the engine to the rear differential, including the drive shafts, as shown in Fig. 6.

In order to assure prediction accuracy with regard to torsional rigidity, which is important when calculating *MF*, the model was configured to be able to recreate the vibration characteristics of the propeller shaft joints and bearings under actual operating load conditions. As shown in Fig. 7(a), the

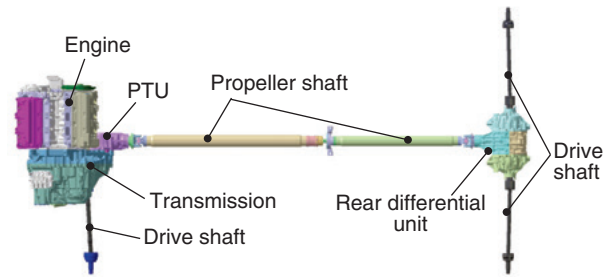


Fig. 6 FEM model for OVL analysis

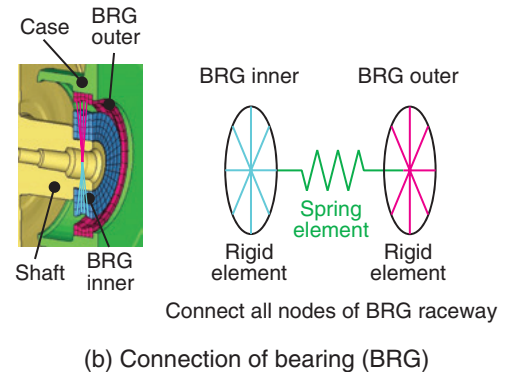
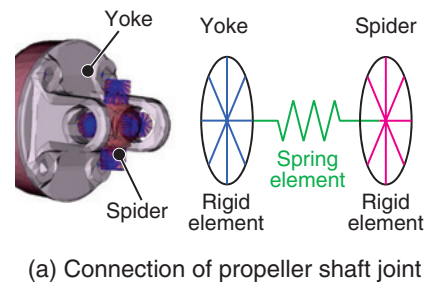


Fig. 7 Parts modeling

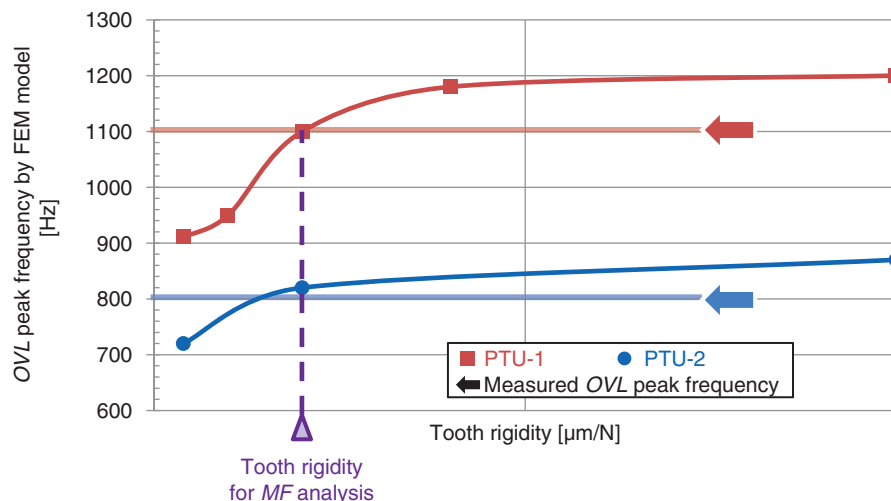


Fig. 5 Correlation between tooth rigidity and OVL peak frequency in calculation

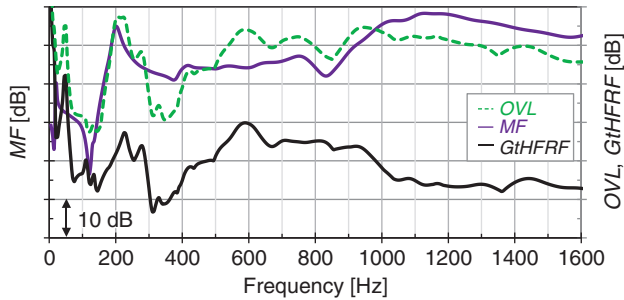
propeller shaft joints have a yoke side and spider side, joined by a spring element. The rigidity value for the spring element used here was identified and configured by correlation with the results of frequency response function (FRF) tests for the joint between yoke side and spider side. As shown in Fig. 7(b), the built-in PTU bearings include inner and outer bearings that were modeled using hexahedral elements and joined using a spring element. The spring element rigidity value used here was derived by static rigidity analysis of the displacement amount with respect to actual operational load in the direction of each load, and that rigidity value was reflected in the model. The FEM models of transmission and PTU housing for *GtHFRF* calculation were constructed along the established guidelines that had verified its prediction accuracy in the past⁽³⁾ and used normally in the gear noise marketability development, and used.

The created FEM modeling method was used to calculate the housing vibration in a PTU applied in vehicles equipped with V6 engines, and the results are shown in Fig. 8. The PTU housing vibration, together with *MF* and *GtHFRF* calculation results, are shown in Fig. 8(a). A model with the drive-side and driven-side mesh points decoupled was also created in order to analyze the factors

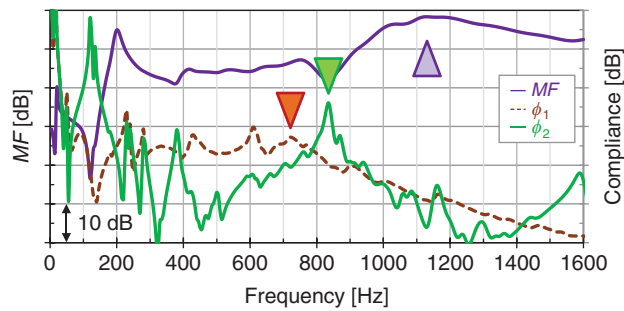
in *MF* peak generation. The results for calculation of ϕ_1 and ϕ_2 compliance are shown in Fig. 8(b). The analysis was carried out with a focus on the *MF* peak that exists in the vicinity of 1200 Hz, which is a resonance frequency of the body-side transmitting parts in the target model. As shown in Eq. (1), the *MF* is the reciprocal of the product of ϕ_1 and ϕ_2 , and it was found, therefore, that the *MF* peak at 1150 Hz is influenced by the 715-Hz mode on the drive side and the 836-Hz mode on the driven side. The calculation results for each mode are shown in Fig. 8(c). In both cases the modes were torsional modes, and it was found that the *MF* peak at 1150 Hz was generated by the torsional mode of the gear on the drive side and the torsional mode of the propeller shaft joint on the driven side.

4.3. Analysis Model Accuracy Verification

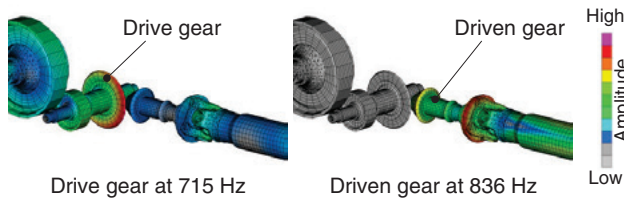
In order to verify whether the FEM model calculation method has the prediction accuracy capable of determining specifications at the layout stage, prior to fabrication of a prototype, a comparison was made of the FEM model calculation values and the vibration measurement results. Since the *MF* cannot be readily measured in an actual vehicle, the FEM model calculation values for *GtHFRF* and PTU housing vibration were compared with the measurement results for verification purposes. Figure 9 shows the results of a comparison made using a PTU that is applied in vehicles equipped with V6 engines. It was confirmed that both the *GtHFRF* shown in Fig. 9(a) and the PTU housing vibration shown in Fig. 9(b) reproduce the waveforms in the vicinity of the peak frequencies within the defined frequency evaluation range.



(a) OVL and MF, *GtHFRF*

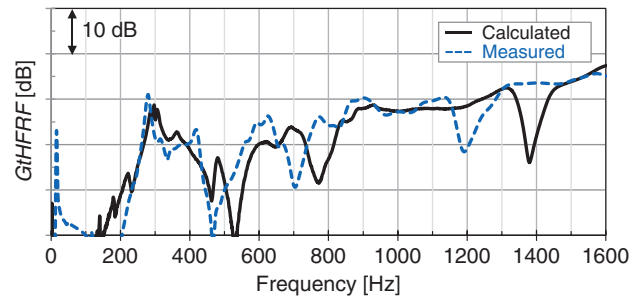


(b) MF and compliance

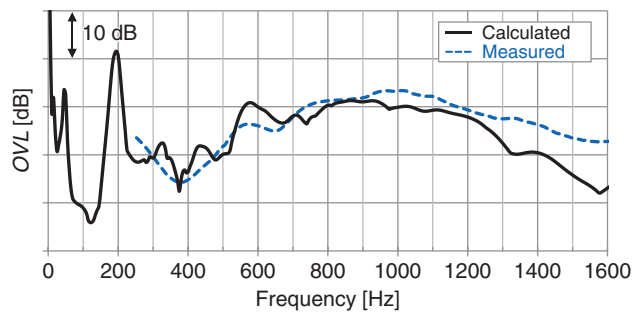


(c) Mode shape

Fig. 8 Calculated results



(a) *GtHFRF*



(b) OVL

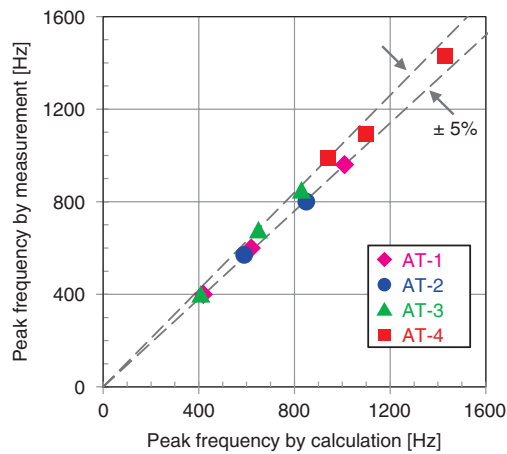
Fig. 9 Comparison of calculated results and measured data

5. PTU Gear Noise Analysis Model Verification

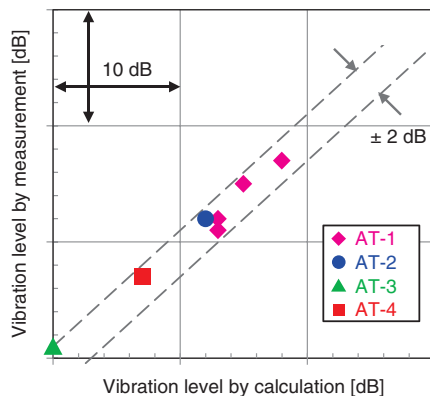
In order to verify the usefulness of a PTU gear noise analysis model in PTU development, a comparison was made of housing vibration calculation values and housing vibration measurement values using differently constructed PTUs. This was done to verify whether or not the target prediction accuracy had been achieved. An investigation was also made of specifications with altered *MF* caused by changes made to the shape of an existing PTU, and a prototype was fabricated. In order to verify the feasibility of investigating specifications using a PTU gear noise analysis model, a comparison was made of housing vibration before and after the shape change between measurement and prediction by calculation.

5.1. Prediction Accuracy Verification

A comparison of housing vibration calculation values and vibration measurement values was made using PTUs with different specifications. Four PTU specifications for automatic transmissions in existing Honda products were used for the comparison, and the correlation between peak frequencies that present PTU gear noise issues and peak vibration levels was confirmed. The peak frequency comparison results are shown in Fig. 10(a) and the peak



(a) Peak frequency



(b) Peak level

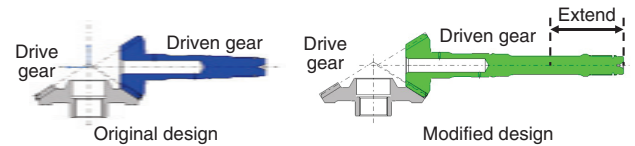
Fig. 10 Verification of prediction accuracy

vibration level comparison results in Fig. 10(b). The Fig. 10 results confirmed that frequency prediction accuracy within $\pm 5\%$ and vibration level prediction accuracy within ± 2 dB was achieved in the defined frequency range of 400 to 1600 Hz, which were set as the prediction accuracy targets for the analysis model of PTU vibration.

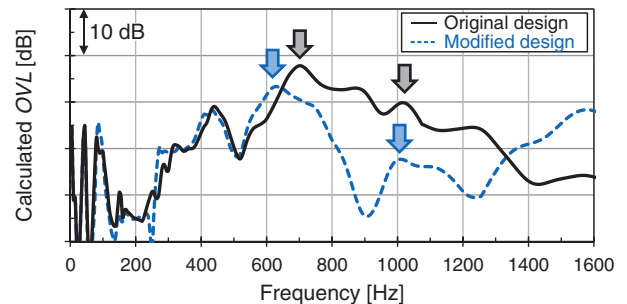
5.2. Verification of Feasibility by Actual Unit Testing

A new specification that changed the *MF* by altering the shape of the driven gear was created, and a comparison was made of the resulting housing vibration calculation values and vibration measurement results. The shapes of the compared gears are shown in Fig. 11(a). Figure 11(b) shows a comparison of the housing vibration calculation results, while Fig. 11(c) shows a comparison of the housing vibration measurement results between the two specifications. When the housing vibration calculation results and housing vibration measurement results from the two specifications are compared in Fig. 11, it is apparent that the vibration peak frequencies and the amount of change in the vibration level in the vicinity of 700 Hz and in the vicinity of 1000 Hz produce the same results.

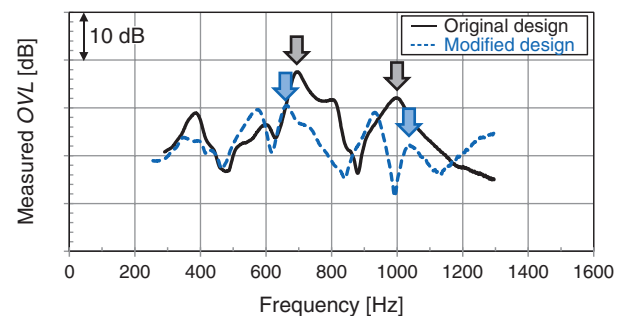
The above verification results confirm that PTU housing vibration calculation results derived using the PTU



(a) Designs for validation



(b) Comparison of calculated OVL



(c) Comparison of measured OVL

Fig. 11 Validation result of application

gear noise analysis model can be used to investigate and determine specifications in the early stages of design.

6. Conclusions

An FEM model was created of the entire drive train, from the engine to the rear differential and including the drive shafts, and the PTU housing vibration caused by hypoid gear mesh was estimated. The model of the hypoid gears was made of hexahedral elements and shell elements. The gear meshing point model was created with a quintuple-node model that takes tooth rigidity into account, and a local coordinate system was configured. A comparison was made of the housing vibration calculation results obtained using the FEM model and the housing vibration measurement results, and the results achieved the following.

- (1) In the frequency range from 400 to 1600 Hz, prediction accuracy achieved a vibration peak frequency error within $\pm 5\%$ and a vibration peak level error within ± 2 dB. This established a technology for quantitative prediction that can be used to judge specifications for PTU layout at an early stage of development.
- (2) Even with specifications involving a shape change, housing vibration calculation results obtained using an FEM model presented waveforms similar to those from actual unit vibration, confirming the usefulness of the analysis model.

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Hybrid System Heat Management that Contributes to High Performance for New NSX

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ABSTRACT

A hybrid system with three motors was developed to realize the high power train system power and vehicle dynamic performance that are the vehicle concepts of the new NSX. Efforts were made to enhance the cooling performance in order to simultaneously reduce the size and increase the power of each hybrid system component. To achieve high cooling performance compared to that of the conventional hybrid system, the direct drive motor is directly cooled by the engine cooling water, an oil cooler has been added to the Twin Motor Unit, the size of the dedicated radiator for the Power Drive Unit has been increased, and the Intelligent Power Unit uses an air conditioner cooperative battery cooling system.

As a result, thermal feasibility of the hybrid system during high-load driving was achieved. The power train system, which consists of the engine and three motor systems, achieved the high power of 427 kW. In addition, the motor assist of the hybrid system compensated the turbo lag, which is an issue for supercharged engines, enabling rapid response acceleration. Furthermore, the longitudinal and lateral driving force allocation control performed by the hybrid system realized a good balance between cornering performance and high-speed stability.

1. Introduction

It has been advocated for some time that issues such as environment, energy, and food should be addressed from a global perspective. Among the various environmental issues, reduction of both CO₂ emissions and dependence on petroleum are pressing issues, and automobile companies worldwide are making efforts to enhance automobile fuel economy.

A new power train was developed for the new NSX based on these premises. This new power train comprises a high power engine, a transmission, and a hybrid system consisting of three motors, a Power Drive Unit (PDU), and an Intelligent Power Unit (IPU). The high system power and torque of this newly developed power train enable to manifest rapid response acceleration performance. In addition, the SPORT HYBRID SH-AWD, which is a 4WD system consisting of three motors, performs longitudinal and lateral driving force allocation control that enables to manifest high maneuverability. Meanwhile, the hybrid system also realizes high fuel economy performance.

Figures 1 and 2 show the layout of the power train system mounted in the new NSX, and Table 1 lists the specifications. The twin-turbocharged V6 3.5 L engine has a longitudinal midship layout and drives the rear wheels using a direct drive motor directly connected to the crankshaft and

a 9-speed dual clutch transmission (9DCT). A Twin Motor Unit (TMU) that drives the right and left front wheels with separate motors is mounted on the front axle of the vehicle. An IPU with a high voltage battery and high voltage distribution parts is mounted behind the seats, and a PDU



Fig. 1 Overview of layout

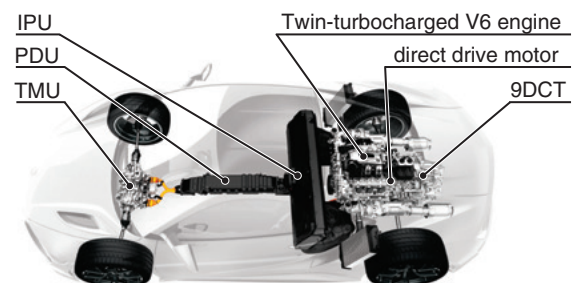


Fig. 2 Power train system components

* Automobile R&D Center

Table 1 Specifications of power train system

Power train system	SPORT HYBRID SH-AWD Maximum power 427 kW Maximum torque 646 Nm
Engine	Twin-turbocharged DOHC V6 3493 cm ³ 373 kW at 6500-7500 rpm 550 Nm at 2000-6000 rpm
direct drive motor	Water-cooled motor and generator directly connected to crankshaft 35 kW at 3000 rpm 148 Nm at 500-2000 rpm
Transmission	9DCT
TMU	Twin traction motor and generator unit 27 kW at 4000 rpm x 2 73 Nm at 0-2000 rpm x 2

that supplies and controls the power to the three motors is located below the center console between the seats. This realizes a layout with the main components close to the center of the vehicle.

Efforts have been made to achieve a layout with a low center of gravity while reducing the size and weight and increasing the average power of each component of the new NSX hybrid system. Achieving suitable cooling performance was an issue when increasing the average power. This paper introduces the vehicle systems used to enhance the cooling and power of the hybrid system mounted in the new NSX.

2. Hybrid System

The main components of the hybrid system are the direct drive motor, TMU, PDU, and IPU, as shown in Fig. 3. The direct drive motor is directly connected to the engine and performs power generation, regeneration, and driving. The TMU drives the right and left front wheels and performs regeneration using separate motors. The IPU mainly consists of a high voltage battery, and performs electric power charging and discharging. The PDU is connected between the three motors and the IPU, and performs AC-DC power conversion and control.

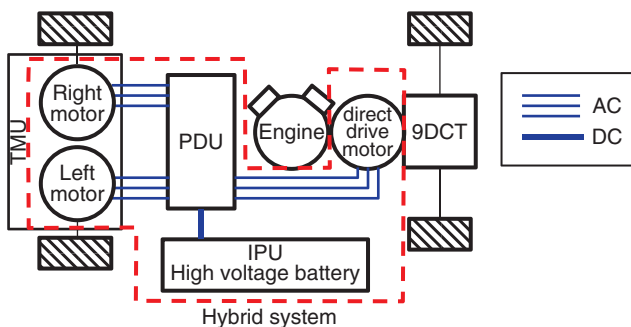


Fig. 3 Hybrid system components

2.1. direct drive motor

The direct drive motor is located between the engine and the transmission, and uses a structure with the rotor directly connected to the crankshaft (Fig. 4). This is to cooperate with the engine and make use of the linear torque characteristics of the motor, which compensates for the turbo lag and achieves rapid response acceleration. Cooling is realized by a water jacket for stator structure that uses the engine cooling water (LLC) to provide cooling performance as shown in Fig. 5. In addition, the insulator was changed from a conventional assembly type to an insert molding type as shown in Fig. 6 to reduce the thermal resistance to the stator core, which is the heat transfer path with the coil, which is a heat-generating location. Figure 7 shows the relationship between the average power and the average vehicle speed. Here, the driving mode, which includes the typical fuel economy modes of city driving mode and highway driving mode, is labeled City mode, and the high-load driving mode on a circuit is labeled Heavy load mode. The dots show the operating points of the developed system, and the cooling performance of the conventional hybrid system was set to include City mode. The developed system was confirmed to both enhance the average power by 40% compared to the conventional hybrid system and to satisfy the cooling performance in Heavy load mode. This enabled sufficient performance even during high-load driving.

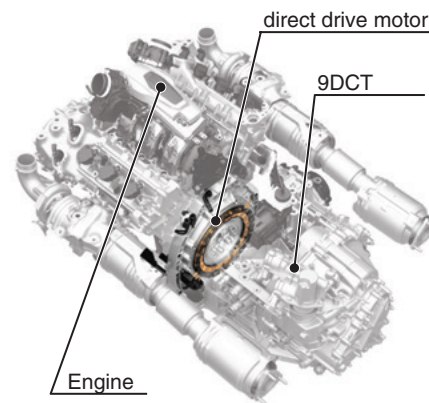


Fig. 4 Location of direct drive motor

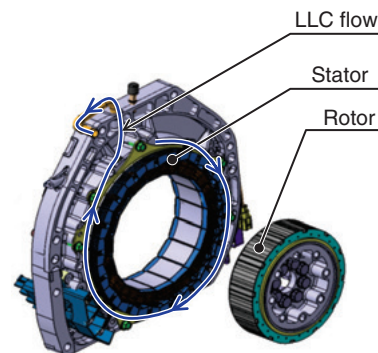


Fig. 5 Structure of direct drive motor

2.2. IPU

The high voltage battery needs high power and high capacity to realize high system power and enhance fuel economy. However, increasing the amount of batteries mounted leads to an increase in the vehicle's weight. Therefore, it is necessary to simultaneously increase the power and reduce the weight in order to enhance the vehicle dynamic performance. In addition to the conventional method of using the air inside the cabin to cool the battery cells, a system that introduces air from the air conditioner to cool the battery cell is also used to maintain an appropriate battery cell temperature and enhance power performance during high-load driving (Fig. 8). Also, a lithium ion battery cell and module were developed that are smaller and lighter in weight compared to the conventional hybrid system (Fig. 9). These technologies enhanced power by up to 15% compared to the conventional hybrid system. The developed system was confirmed to both enhance the average power by 80% compared to the conventional hybrid system and to satisfy the cooling performance during high-load driving in Heavy load mode.

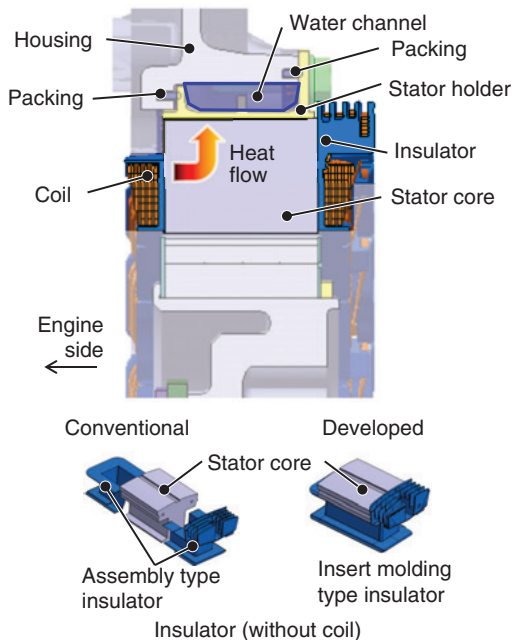


Fig. 6 Section view of direct drive motor

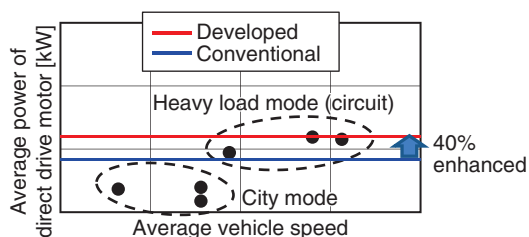


Fig. 7 direct drive motor performance

2.3. TMU

The TMU located in the front of the vehicle incorporates two motors and a gearbox, and can control the torque separately for the right and left front wheels during driving and also during regeneration. The yaw moment can be effectively generated by controlling the right and left wheel torque. This enables to achieve higher cornering performance compared to the mechanical SH-AWD, which uses the yaw moment produced by the difference in driving torque of the right and left wheels (Fig. 10).

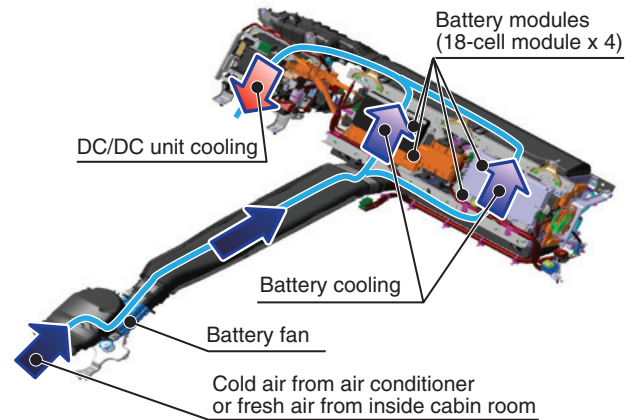


Fig. 8 Overview of IPU cooling system

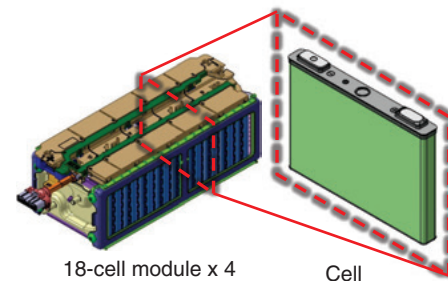


Fig. 9 Structure of battery module and cell

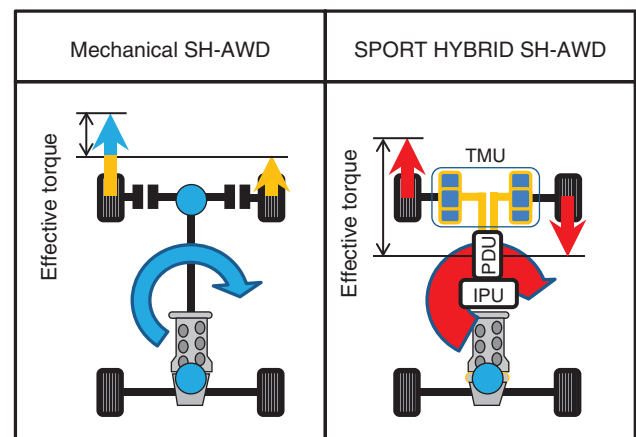


Fig. 10 Difference between SH-AWD systems

The high heat load is supported and cooling performance is provided by installing a TMU cooler (Fig. 11) and having the wind produced by driving flow to the TMU main unit. Figure 12 shows the structure of the TMU left motor, and Fig. 13 shows the average power enhancement results. Cooling uses the wind produced by driving, so the average power characteristics curve depends on the vehicle speed. The developed system was confirmed to both enhance the average power by 95% compared to the conventional hybrid system and satisfy the cooling performance when driving in Heavy load mode.

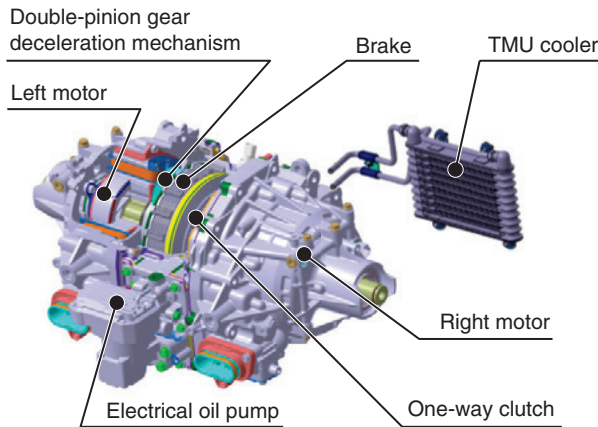


Fig. 11 Overview of TMU

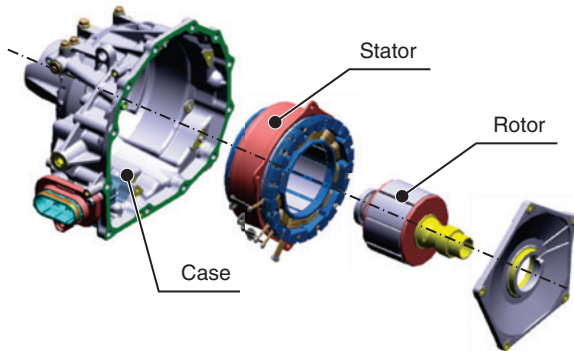


Fig. 12 Structure of TMU left motor

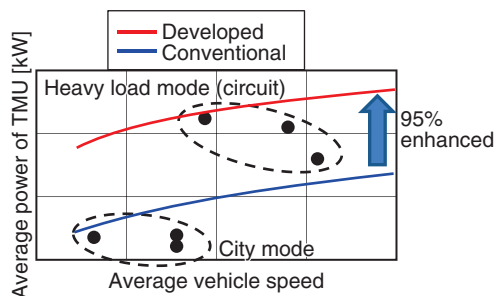


Fig. 13 TMU performance

2.4. PDU

The PDU controls the total three motors of the direct drive motor and the TMU (Fig. 14). Cooling capability was enhanced to support the increased inverter heat generation by increasing the size of the dedicated radiator (Fig. 15). The PDU dedicated radiator layout was modified to optimize the amount of air introduced to the engine radiator and air conditioner condenser in order to increase the utilization rate of the air introduced from the front bumper. Figure 16 shows the simulation results. The developed system was confirmed to both enhance the average power by 80% compared to the conventional hybrid system and satisfy the cooling performance when driving in Heavy load mode.

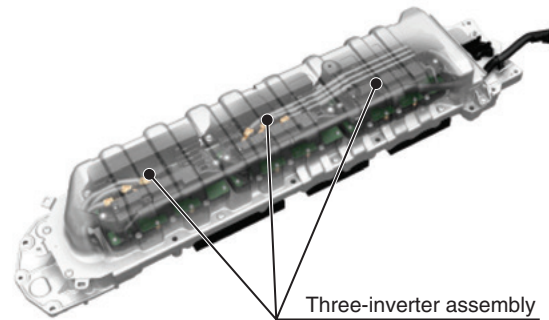


Fig. 14 Overview of PDU

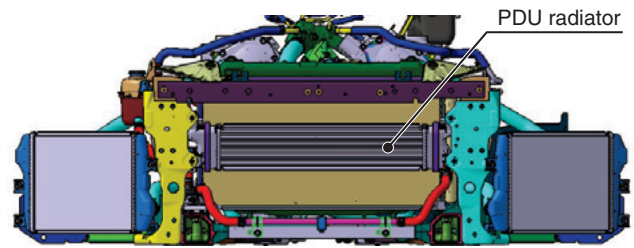


Fig. 15 Section view of PDU radiator

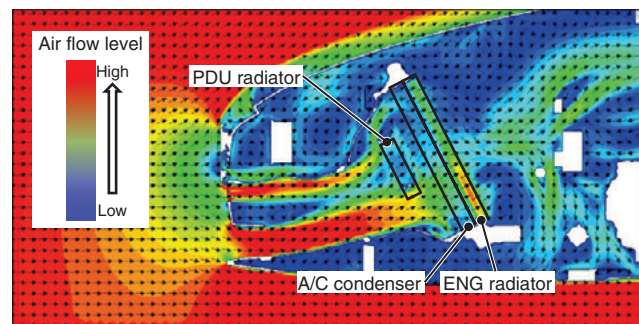


Fig. 16 Air flow for PDU radiator (simulation)

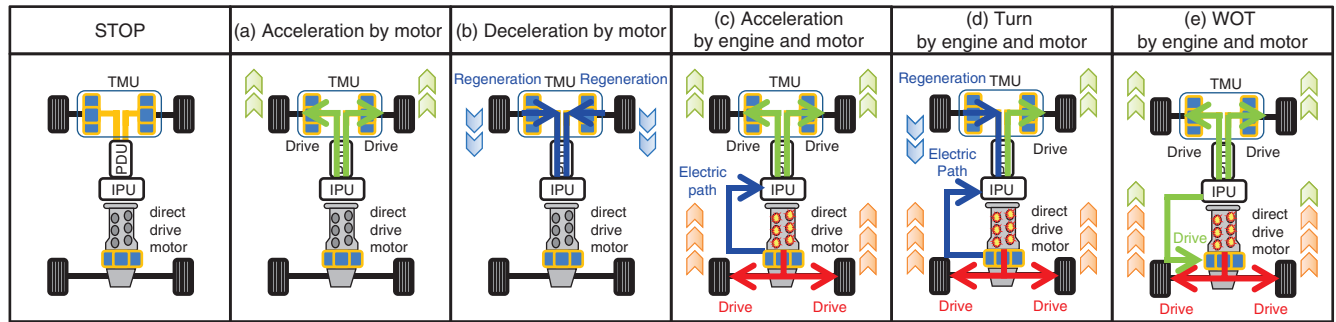


Fig. 17 System operation

3. System Operation

3.1. Normal Operation

Figure 17 shows the typical driving modes of the SPORT HYBRID SH-AWD system. In EV driving mode, the rear wheels are cut off from the engine and only the front wheels are driven by the TMU [Fig. 17(a)].

When decelerating, the TMU generates power by regenerative braking and charges the battery [Fig. 17(b)]. In hybrid driving mode, the engine directly drives the rear wheels, and the direct drive motor performs power generation and charging as appropriate in accordance with the battery charging status [Fig. 17(c)]. When turning, the TMU motor for the wheel on the outside of the turn is driven by the energy regenerated by the TMU motor for the wheel on the inside of the turn, and the yaw moment is generated by the previously mentioned difference in driving torque [Fig. 17(d)].

3.2. Wide Open Throttle (WOT) Operation

When high driving force is called for, the TMU and direct drive motor are driven using the electric power charged in the battery, and the engine and three motors produce rapid response acceleration [Fig. 17(e)]. At vehicle speeds of 200 km/h or more, the TMU is disengaged by a clutch to protect the motor from over speed. Figure 18

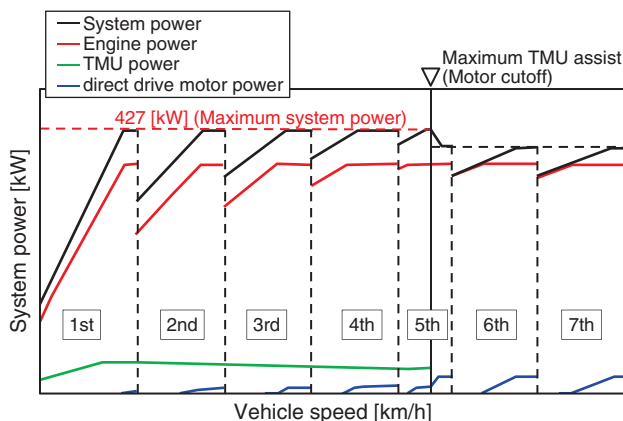


Fig. 18 System performance at WOT

shows the system power. This figure shows the vehicle speed and the power of each power train component during each transmission step at WOT, and shows that a maximum system power of 427 kW is achieved.

4. High-load Driving and Thermal Feasibility

4.1. Realization of Rapid Response Acceleration Performance

Figure 19 shows the hybrid system operating status when starting at WOT. The turbo lag compensation assist and steady assist performed by the TMU and direct drive motor enhanced the power rise during WOT acceleration by 57% (Fig. 20). This helps to enhance both acceleration from 0 km/h to 100 km/h and intermediate acceleration performance.

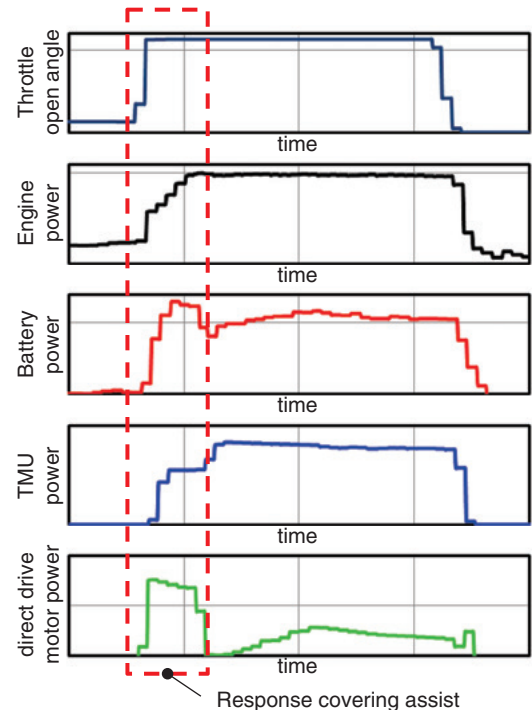


Fig. 19 Power of power train system

4.2. Realization of High Cornering Performance

The lateral driving force allocation control performed by the hybrid system realizes high cornering performance. Figure 21 shows the simulation results of US/OS characteristics relative to lateral acceleration during a 30R(R0) turn. Longitudinal and lateral driving force allocation control help to suppress understeer and increase the lateral acceleration limit, which as a result also enhances cornering performance.

4.3. Realization of Thermal Feasibility during High-load Driving

Enhancement of the cooling performance of each hybrid system component enabled driving without reducing the hybrid system power even during high-load driving. Figure 22 shows the effect of the hybrid system when driving in Heavy load mode as an example of the results. The enhanced rapid response acceleration performance and cornering performance described above were confirmed in simulations to reduce the lap time by 1.8%.

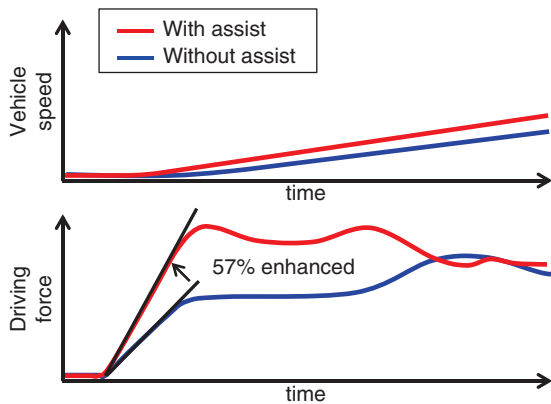


Fig. 20 Effect of motor assist on driving force at WOT

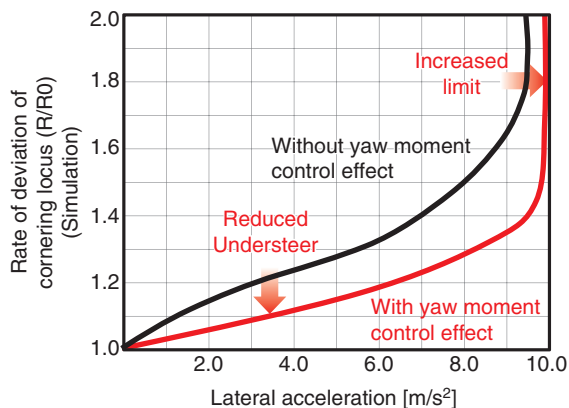


Fig. 21 Effect of hybrid system on US/OS Characteristics

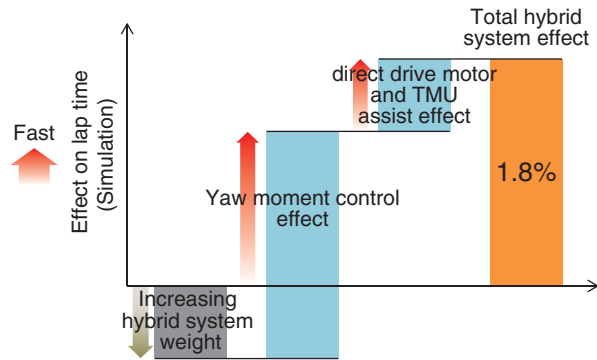


Fig. 22 Effect on lap time

5. Conclusion

A high-power, rapid-response power train was developed that achieves the following items in the hybrid system for the new NSX.

- (1) Thermal feasibility of the hybrid system when driving in Heavy load mode was achieved.
- (2) The combination of three motors and the engine achieved a maximum system power of 427 kW.
- (3) The assist of the direct drive motor compensated for the turbo lag of the supercharged engine and enhanced the power rise by 57% during WOT acceleration.
- (4) Lateral driving force allocation by the hybrid system achieved a good balance between cornering performance and high-speed stability.

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Keisuke URUSHIHARA

Development of Antenna for Global Telematics

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Takayuki SONE**

ABSTRACT

Based on a concept of global compatibility, a telematics antenna unit has been developed that integrates antenna elements for mobile communications and for satellite positioning in order to respond to the increasing global application of telematics services.

Taking into consideration the differences in the frequencies used by each mobile network provider in any specific country and the frequency range stipulated by regulations, a bowtie antenna was employed as the antenna for mobile communications. This made it possible to realize an ultra-wide-band characteristic from 698 to 3800 MHz. The antenna for satellite positioning is compatible with both the US GPS and Russian GLONASS systems, and the use of a built-in signal divider and power supply selector switch has made it possible to split satellite signals between the telematics system and other systems. The volume of the antenna unit has been reduced by 50% against conventional antenna units, increasing the degree of freedom available for fitting in the instrument panel.

1. Introduction

Telematics is well known as an information service employed in the automotive and transportation industries. The word “telematics” itself was coined from a combination of “telecommunications” and “informatics.”

Today, attention is being focused on examples of the large-scale collection of driving logs from individual vehicles, and their use in big data analyses for the public benefit. One such case is the social contribution made following the Great East Japan Earthquake by the use of a service employing Honda’s InterNavi Floating Car System⁽¹⁾ to provide map data concerning roads that were in use by system users, enabling rapid communication of information regarding passable roads to other users⁽²⁾.

Current telematics services can be broadly classified as follows:

- (1) Transmission of information that is of use to vehicle users while driving, including information on traffic congestion and weather information;
- (2) Serving as a means of providing information to national and regional emergency response systems, for example as an emergency reporting system; and
- (3) Maintenance and management of vehicle performance, including electric vehicle battery data and charging station data.

Emergency reporting system is one of the means of

informing emergency lifesaving organizations as described above, thereby promoting formulation of official standards and/or establishment of mandatory regulations.

In Europe, the European Road Transport Telematics Implementation Coordination Organization (ERTICO), a public-private sector organization, has been the central actor in the formulation of European technological standards⁽³⁾ based on multi-stage verification of systems in public proving trials (e.g. HeERO1/HeERO2 and eCall). These standards make the fitting of telematics units mandatory in new model vehicles from March 31, 2018.

Separately to the European standards, Russia has also made it mandatory to fit telematics systems in all new model vehicles from January 1, 2015, and in all newly marketed vehicles from January 1, 2017. The use of the Russian satellite positioning system GLONASS to provide vehicle position data for emergency reporting is an essential condition for these telematics systems.

In response to this global diffusion of telematics services, the specifications of the conventional antennas used for telematics have been adapted to the characteristics of the frequencies used by mobile network providers in different countries and regions. As a result, the number of variations in antennas developed for specific countries and regions has increased in direct proportion to the global diffusion of telematics, and this has simultaneously increased costs for users.

* Automobile R&D Center

** YOKOWO CO., LTD.

2. Development Goals

In order to address these issues, the research discussed in this paper set out to develop a new type of telematics antenna based on a concept of global compatibility, a unit able to be used in any country or region, and one that could assist in controlling the increase in antenna variations with the diffusion of telematics.

The antennas employed in telematics services are made up of an antenna for mobile communications (TEL ANT), making it possible to connect to mobile wireless telecommunications networks, and an antenna for satellite positioning (GNSS ANT), making it possible to obtain vehicle position data. The development targets for the new antenna were set as follows:

- (1) TEL ANT: Able to cover basically the entire frequency band specified by the Long-Term Evolution (LTE) standard, which is currently being advanced globally;
- (2) GNSS ANT: Compatible with the Russian satellite positioning system in addition to the conventionally used US system, and able to share satellite signals with other systems that employ satellite positioning; and
- (3) Realization of reduced size in order to increase the degree of freedom of fitting in the instrument panel.

3. TEL ANT

3.1. Issues of Conventional TEL ANT

Since the appearance of car telephones, onboard TEL ANT have been fitted in areas including the trunk lid, the rooftop, and the instrument panel. The main antenna elements in use for onboard TEL ANT are $\lambda/4$ monopole elements, $\lambda/2$ T-monopole elements, $\lambda/2$ dipole elements, and elements derived from these. The linear antenna elements resonate with standing waves⁽⁴⁾.

Due to their principle of operation, resonant antennas have a resonant frequency, and are restricted to use within a frequency band in which they are able to display their prescribed performance. In terms of the figure given by their upper limit frequency divided by their lower limit frequency, the antennas are generally used within a range of around 1.05 to a maximum of 1.1.

Government authorities in each country and region of the world grant licenses to mobile network providers for the frequency bands that can be used for mobile communications based on the global standards specified by the Third Generation Partnership Project (3GPP). These frequency bands are broadly divided into low bands (below 1 GHz) and high bands (1 GHz and above), and the bands used depend on the communications environment and the nature of the communications.

For the third-generation mobile phones that have been the mainstream since 2000, the main frequency ranges in use in the North American region are the low band from 824 to 894 MHz and the high band from 1850 to 1990 MHz. In the regions of Europe and Asia, the main

frequency ranges are the low band from 880 to 960 MHz and the high band from 1710 to 1880 MHz or from 1920 to 2170 MHz. These frequency bands are all in a frequency ratio of 1.1 or below. Resonant antennas with their resonant frequencies adjusted to each frequency band are employed as TEL ANT⁽⁵⁾. Two methods of manufacturing antennas are in use: A method that uses two elements, for the low and the high bands, respectively (Fig. 1); and a method that uses only a single element, a low band element, with the high band resonating as the third harmonic of the low band.

The wavelength of radio waves is calculated by dividing the speed of light (3.00×10^8 m/s) by the frequency of the wave. For example, the wavelength at 824 MHz, the lowest frequency of the low band, is 364 mm. The basic length of a TEL ANT element that resonates with this wavelength would be 182 mm in the case of a $\lambda/2$ dipole element, and 91 mm in the case of a $\lambda/4$ monopole element.

The frequency range used by the majority of fourth-generation mobile phones is broad, with the lower limit for the low band set at 698 MHz, and the high band ranging from 1427 to 1510.9 MHz, from 1744.9 to 2200 MHz, and from 2500 to 3800 MHz. The wavelength at 698 MHz is 430 mm. The basic length of resonating TEL ANT elements for this wavelength would lengthen the unit by 215 mm in the case of a $\lambda/2$ dipole element, and 107 mm in the case of a $\lambda/4$ monopole element.

As indicated above, mobile network providers are allotted specific frequency ranges from these frequency bands and are licensed to use these ranges by government authorities. When Honda establishes telematics services in different countries, the resonant frequencies of the antenna elements that are employed are adjusted to the frequency bands for which the mobile network providers that the company contracts with hold licenses.

As this indicates, the number of variations of conventional TEL ANT increases with the number of mobile network providers with which contracts are

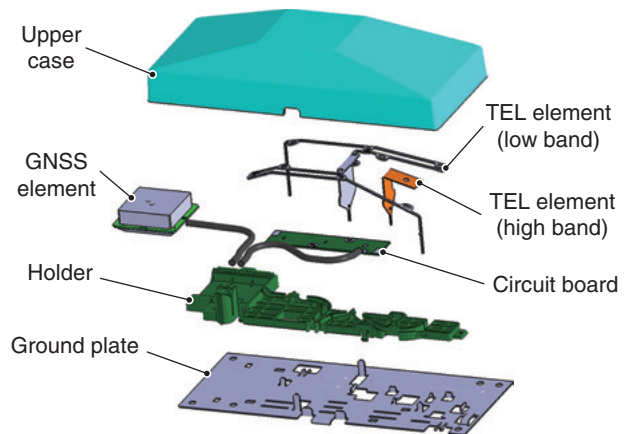


Fig. 1 Conventional antenna

established. Even if the contracted mobile network provider is not changed, if the company newly adds a frequency to its range, it will be necessary to either add or readjust an antenna element, which will further increase the number of TEL ANT variations.

3.2. Self-similar TEL ANT Elements

It is necessary for antenna elements to display a level of performance making it possible to apply them irrespective of which mobile network provider in any specific country a contract is established with. However, it is not an easy matter to obtain characteristics from conventional resonant antennas, which are operated at a frequency ratio of around 1.1, making it possible to apply them across the entire range of frequency bands. It was therefore decided that self-similar rather than resonant elements would be employed as the form of operation for the TEL ANT elements. Taking the degree of freedom of positioning the TEL ANT in the instrument panel into consideration, the use of a self-similar bowtie antenna would present the advantage of not having a solid, three-dimensional structure, but of having a pair of flat discs as its basic shape.

Examples of the use of bowtie antennas in ultra wide-band radar applications using millimeter wave pulses, for example underground exploration radar, have been reported⁽⁶⁾⁻⁽⁸⁾.

Biconical antennas, broadband antennas formed from two cones, have the basic shape of a pair of triangles arranged such that their vertices face each other (a planar projection configuration), like a bowtie. The actual dimensions of the antennas are known to affect the frequencies able to be employed (Fig. 2). The gain characteristics of the antennas in relation to frequency can be adjusted by modifying the hypotenuses of the triangles into quadratic curves or semi-circles⁽⁸⁾.

Because the polarized waves of the radiated electric field travel in the same direction as the axial direction of the triangular discs (the direction of the axis of rotation of the cones), the vertically polarized waves that are the main type used by second- and third-generation mobile phones were

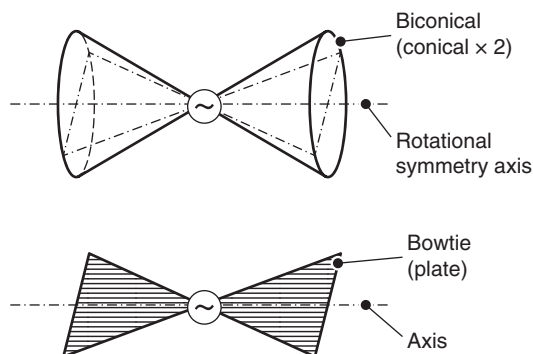


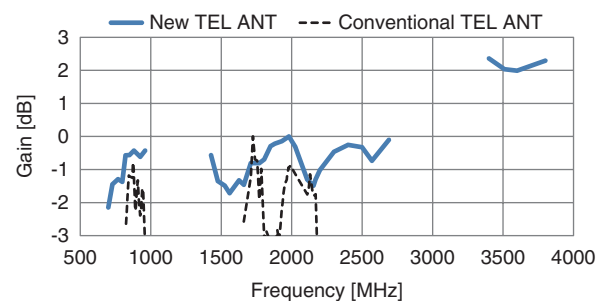
Fig. 2 Bowtie antenna

focused on, and the use of a vertical axis of alignment was selected as the basic form for the antenna.

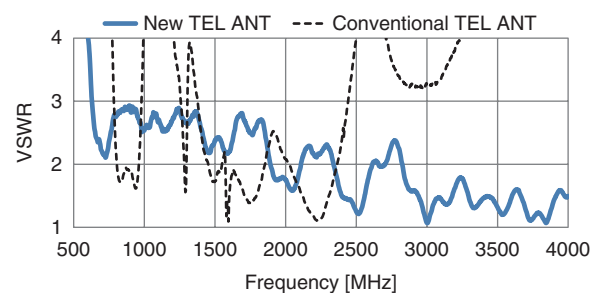
If it was not necessary to house the TEL ANT together with the GNSS ANT in the same case, a simple flat disc shape, like the shape of the antenna element, could be used for the external shape of the case; further consideration was necessary when the two antenna elements were housed together.

The use of a bowtie antenna as the basic structure of a new TEL ANT would make the antenna compatible with the 698 to 3800 MHz frequency range scheduled for use by fourth-generation mobile phones, producing a frequency ratio of 5.4. In the case of conventional TEL ANT, gain declines rapidly outside the resonant frequency. Changing the frequency-gain characteristic of the new TEL ANT made it possible to realize an ultra-wide-band characteristic that maintains gain within a 2 dB amplitude in the range from 698 to 2700 MHz (Fig. 3). In order to simplify comparison of frequency-gain characteristics, in Fig. 3 the maximum gain in the range from 698 to 2700 MHz has been shown as a standard 0 dB.

The voltage standing wave ratio (VSWR) is an indicator expressing the impedance matching between an antenna and the feeder line. The ideal ratio is 1, and the radiation efficiency and other performance parameters of the antenna decline as this ratio increases. The figure increases rapidly and performance declines outside the resonant frequency in the case of conventional TEL ANT. The new TEL ANT realizes an ultra-wide-band characteristic in which VSWR is below 3 across the range from 698 to 3800 MHz.



(a) Gain (V-Pole)



(b) VSWR

Fig. 3 Frequency characteristics

4. GNSS ANT

GNSS antennas have long been employed in car navigation units. This has facilitated the civilian use of the Global Positioning System (GPS) operated by the United States. When car navigation units are used together with Telematics Control Units (TCU) to provide vehicle position data, it can be necessary to employ multiple GNSS ANT in the same vehicle.

In addition, in some cases there is an obligation to use a national satellite system, as in the case of Russia's GLONASS mentioned above. The frequencies for civilian use of GPS in the United States and GLONASS in Russia are 1575.42 ± 1 MHz and 1601.72 ± 4 MHz, respectively. Both systems use the L1 band, but there is a difference of approximately 30 MHz between them. Because of this, it was necessary to regulate the characteristic of an interference wave filter built into a low-noise amplifier (LNA) integrally supported directly below the GNSS element in order to make it possible to receive both frequencies.

Japan's Quasi-Zenith Satellite System (QZSS) is another satellite positioning system currently in operation, but the QZSS frequencies are basically identical to the GPS frequencies, making it possible to use the same antenna elements as are used for GPS.

In order to respond to the differences in specifications in relation to the use of the elements with navigation systems, a GNSS ANT element with a built-in GNSS signal divider was employed. A Wilkinson divider was used, implemented by forming an additional distribution circuit pattern on the circuit board of the LNA positioned directly underneath the GNSS element. This made it possible to share the GNSS ANT when a car navigation unit and the TCU were used simultaneously, eliminating the need to fit multiple GNSS ANT in the same vehicle (Fig. 4).

The LNA positioned directly below the GNSS element is operated using power supplied by the TCU or the car navigation unit. Car navigation units mainly supply a source voltage of between 4.5 and 5.0 V. In some cases, the voltage supplied by the TCU differs from the voltage supplied by the car navigation unit. This is because, taking emergency reporting of vehicle data as a representative case, it is necessary to attempt to ensure a minimum continuous operating time for the TCU using power from its inbuilt battery even if the power supply from the vehicle is completely exhausted; in such cases, it is normal to reduce power consumption by reducing the source voltage.

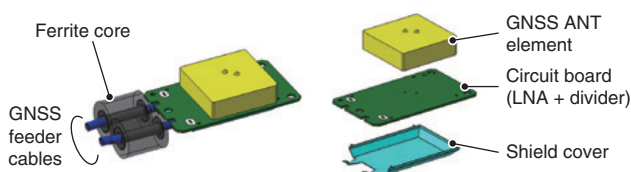


Fig. 4 GNSS ANT element and circuit board

The car navigation unit and the TCU monitor the current supplied to the LNA, and have been provided with a function for the detection of connection errors, disconnection, short-circuits, and other malfunctions. When there is a difference in supplied voltage between the units connected to the antenna with a built-in GNSS signal divider, it is not easy to attempt to ensure the correct functioning of monitoring of the supplied current when a simple backflow prevention device is employed as the means of responding to backflow to the power supply. A power supply selector switch has therefore been positioned on the LNA circuit board. When two systems are connected simultaneously, one is used as a power source for the LNA, and the other is connected to a dummy load (Fig. 5).

When only Unit #1 or Unit #2 in Fig. 5 is connected, the connected unit supplies power to the LNA. When Unit #1 and Unit #2 are simultaneously connected, Unit #1 is used as a power supply for the LNA, and Unit #2 is connected to the resistor R, the dummy load.

This helps to ensure the operation of both the backflow prevention function and the supplied current monitoring function even when there is a difference in the voltage supplied by the units connected to the antenna.

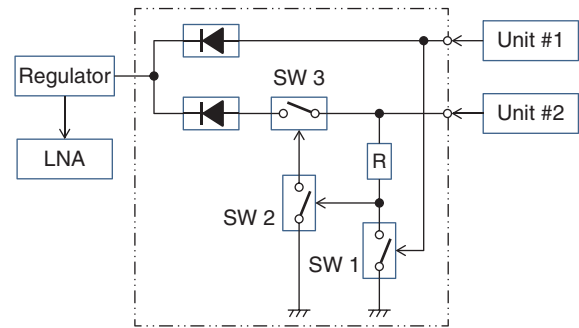


Fig. 5 Power supply switching circuit

5. Size Reduction

As indicated above, the axis of alignment of the triangular discs forming the bowtie TEL ANT element is a vertical axis. By contrast, the GNSS ANT element is a patch antenna with a built-in LNA, and is aligned horizontally, with the surface of the patch in the direction of the open vertex. When the alignment of the antennas was unified, an inverted L or T shape was produced, with the GNSS ANT element positioned along the upper section of the TEL ANT element. In this configuration, the horizontal width and height were determined by the TEL ANT element, and depth was determined by the GNSS ANT element. If both antenna elements were simply fitted together within the case, the space between the lower section of the GNSS ANT element and the TEL ANT element would be dead space. This would reduce the efficiency of space utilization,

and reduce the degree of freedom available in fitting the case in the instrument panel. To address this issue, the internal layout of the case was examined [Fig. 6(a)].

It is known that it is possible to reduce the size and adjust the wide-band characteristic of bowtie antennas via measures including modifying the shape of the elements or adding slots⁽⁶⁾. A configuration in which the upper element of the bowtie antenna was folded down was selected; a horizontal section was created that was aligned with the depth dimensions of the GNSS ANT element from the position at which the upper element of the TEL ANT element was folded down to the height of the GNSS ANT element, and finally the TEL ANT was folded upwards to the height of the GNSS ANT element. By this means, the sides of the GNSS ANT element were enclosed by two areas of the folded section of the TEL ANT, separated by predetermined intervals [Fig. 6(b)]. There was no necessity for the lower section of the bowtie antenna to overlap with the GNSS ANT element. Because of this, it was decided that the lower section of the antenna could be extended outside the case rather than being enclosed within it. The mounting section was extended downward from the bottom of the case, and the lower element of the bowtie antenna was inserted into it to hold it in place.

Multiple slots were added to the lower element, and some of these slots also served as holes to make it possible to secure the element in place.

The configuration described above made it possible to reduce the height of the case, while also creating a structure to hold the GNSS ANT element, increasing the space utilization efficiency in the case.

Coaxial cables are normally used as the feeder cables for high-frequency power from considerations of interference from radio disturbance, loss from power leakage, ease of wiring, and cost of manufacture.

Coaxial cables are unbalanced feeder cables, consisting of an external conductor and a core conductor. Bowtie antennas, however, are balanced antennas, with a basic shape formed from a pair of symmetrical elements. In cases in which balanced and unbalanced devices are connected, the use of a balance-unbalance transducer, or balun, is

available as a method of conversion between balanced and unbalanced⁽⁷⁾. However, it is not easy to apply a balun for the wide-band range represented by a frequency ratio of 5.4, due to the fact that the configuration of the unit tends to become more complex. In addition, it was feared that due to the use of a configuration that reduced size, in which the GNSS ANT element was fitted to a section of the TEL ANT element, leakage current might be induced in the external conductor of the GNSS ANT coaxial cable. The coaxial cables for both the TEL ANT and the GNSS ANT were therefore fitted with ferrite cores in order to control leakage current.

With regard to the shape of the ferrite cores, the internal diameter of the cores was determined by the finished exterior shape of the cable, and the external diameter and axial length of the cores were determined by magnetic properties. The case, which had been reduced in size by means of the process discussed above, contained one TEL ANT and two GNSS ANT, meaning that space would also be necessary for three ferrite cores. In creating the space for the external diameters of three ferrite cores, the cores were arranged on upper and lower levels, in order to control any increase in the size of the case. Space for the axial length of the cores was created by offsetting the axis of the bowtie antenna against the center of the case in the direction of lateral width. The effect of this offset of the axis of the bowtie antenna on its performance characteristic fell within a range that could be responded to by means of measures such as adjustment of the hypotenuses of the element [Fig. 6(c)].

These measures realized a reduction of approximately 50% in volume against a conventional antenna unit fitted in the instrument panel, increasing the degree of installation freedom.

Because it is possible to employ a unit without a built-in GNSS signal divider when it would not be used together with a car navigation system, there are three variations of the new antenna unit: (a) A unit with a GNSS ANT signal divider; (b) A unit without a GNSS ANT signal divider; and (c) A unit featuring a TEL ANT only.

The units with and without GNSS ANT signal dividers can be distinguished externally by the number of coaxial cables and the number of connector poles (Figs. 7 and 8).

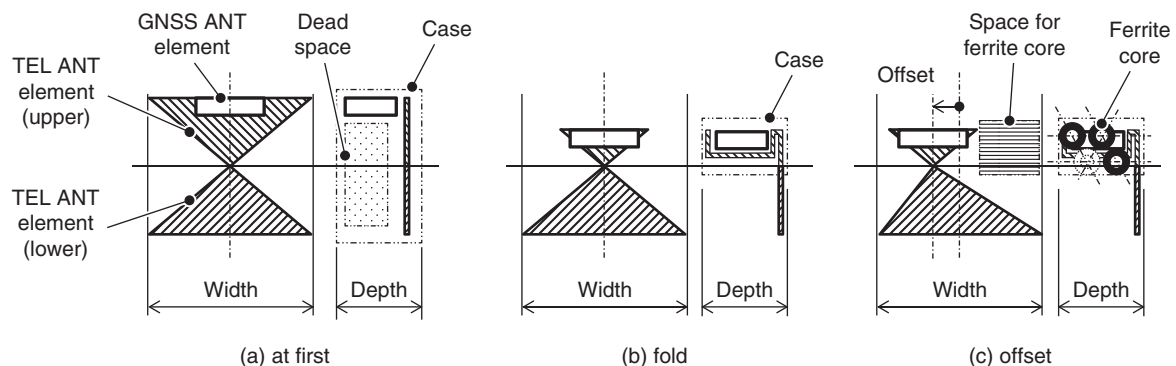


Fig. 6 Configuration concept for TEL ANT and GNSS ANT elements

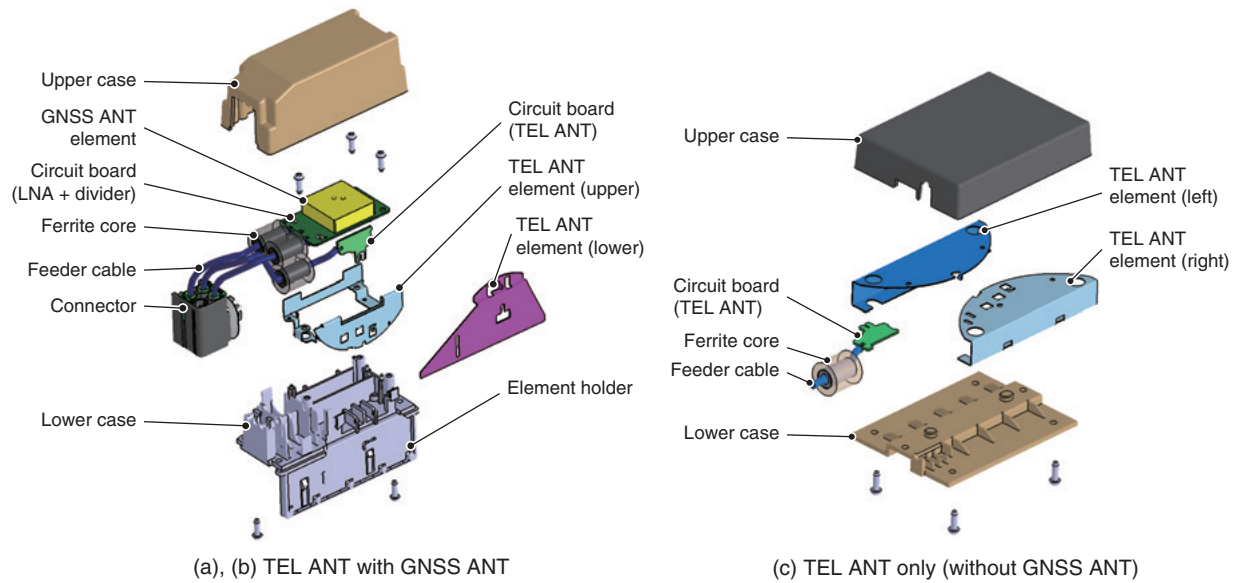


Fig. 7 Configuration of new antennas

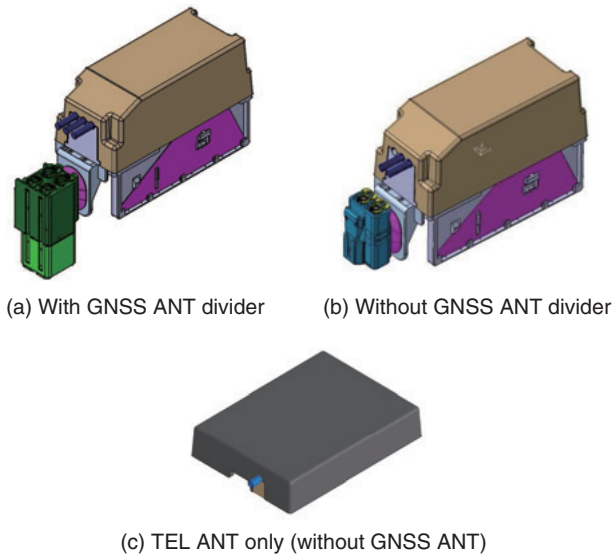


Fig. 8 Appearance of new antennas

6. Conclusion

A new telematics antenna unit has been developed that is capable of global utilization, irrespective of the frequencies licensed to a contracted mobile network provider.

The following development targets were set and achieved based on a concept of global compatibility.

- (1) A bowtie antenna was employed for the TEL ANT, compatible with a wide-band range of 698 to 3800 MHz (a frequency ratio exceeding 5), making it possible to cover the entire frequency range used in the LTE format.

- (2) The GNSS ANT is compatible with the Russian GLONASS satellite positioning system in addition to the US GPS system; providing the circuit board of the in-built LNA with a signal divider and a power supply selector switch has made it possible to split and share satellite signals with other devices using satellite positioning systems.
- (3) The volume of the unit has been reduced by 50% against a conventional unit, increasing the degree of freedom available in fitting the unit in the instrument panel.

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Heavy Rare Earth-free Hot-deformed Magnet for Traction Motor

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ABSTRACT

A technology has been developed making it possible to do away with the use of the heavy rare earths dysprosium and terbium, which are added to the magnets employed in traction motors for application in electric vehicles and hybrid electric vehicles in order to increase heat resistance. The research focused on the hot-deformation method of magnet manufacture, which offers greater potential for the realization of heat resistance than the sintering method, the main method of manufacturing the magnets currently in use. The magnetic properties of the developed magnet were boosted by reduction of the temperature for hot-deformation and the optimization of the rate of hot-deformation and the composition design of the magnet material. These approaches made it possible to develop a completely heavy rare earth-free magnet able to be employed in mass-production vehicles.

1. Introduction

Neodymium magnets, formed from an alloy of a rare earth, iron, and boron, were invented by a Japanese researcher in 1982⁽¹⁾. Because they display the highest maximum energy product $[(BH)_{\max}]$ among existing permanent magnets and are able to be manufactured in high volumes using a sintering method, neodymium magnets have found use in a wide range of applications. The neodymium magnets used in EV and HEV are also manufactured using a sintering method, but unlike the magnets used in home electronic appliances, these magnets are exposed to high-temperature and demagnetizing field environments. As a result, high coercivity (H_{cj}), an indicator of a high level of heat resistance, is demanded of these magnets. Heavy rare earths, which increase the anisotropy field of the main phase of the magnets, are therefore added in order to increase H_{cj} . In the case of the heavy rare earth dysprosium (Dy), 5-10 wt% is added; in the case of terbium (Tb), 1-5 wt% is added⁽²⁾. However, the amount of heavy rare earths contained in ores is less than 10% that of light rare earths, and regions of heavy rare earth production are limited. Taking a future increase in the number of EV into consideration, reduction of the volume of use of

heavy rare earths will be essential from the perspectives of the burden on the environment, the risk associated with scarce resources, and cost. It will therefore be necessary to determine a method of increasing H_{cj} other than by the addition of heavy rare earths to the magnet material.

Figure 1 shows a schematic image of the crystalline microstructure of a magnet. The microstructure is made up of a main phase and the grain boundary phase that encloses it. The arrows show the easy axis of magnetization of the main phase crystals. It is known that H_{cj} can be increased by refining the main phase crystals or increasing the thickness

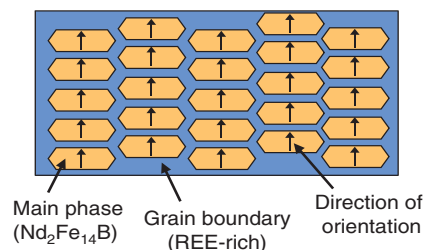


Fig. 1 Schematic image of crystalline microstructure of magnet

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of the grain boundary phase in order to magnetically isolate the main phase crystals⁽³⁾⁻⁽⁵⁾.

However, refinement of the magnetic powders used as raw materials in the sintering process causes oxidation, and in addition is not easy in practice due to the fact that when heated to temperatures of 1000°C or more, the crystals grow to around 5 μm. The research discussed here therefore focused on the hot-deformation method. In this method, the magnet raw materials are melted and rapidly quenched, forming ribbons of crystals on the order of nano-meter (nm)⁽⁶⁾. The material is then hot-deformed at the low temperature of 700°C, producing a microstructure 10% or more finer than the sintering microstructure, on the order of several hundreds of nm⁽⁷⁾. However, due to the specific characteristics of the process of manufacturing hot-deformed magnets, it is not easy to produce magnets with high magnetic properties in high volumes, and the magnets have previously found application only in a comparatively limited range of fields.

2. Development Goals

Figure 2 shows the magnetic properties of sintered magnets, a conventional hot-deformed magnet, and the hot-deformed magnet developed in this research.

The horizontal axis shows H_{cj} at the maximum temperature of a traction motor during operation, and the vertical axis shows remanence (B_r). The performance range necessary for the traction motor is shown outlined by the red broken line. Among the sintered magnets, the addition of heavy rare earths (chiefly dysprosium) increases the anisotropy field, allowing the magnets to realize the demanded performance, while the heavy rare earth-free sintered magnet does not. While the conventional hot-deformed heavy rare earth-free magnet displays higher H_{cj} than the rare earth-free sintered magnet, the level is insufficient for application in a traction motor. The research therefore set out to boost the properties of the magnet by optimization of the production conditions and design of the composition, in order to realize a performance range suitable for use in a traction motor.

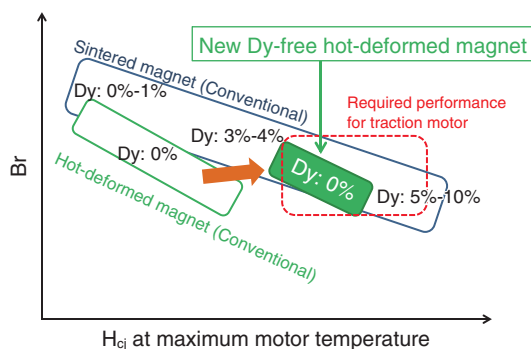


Fig. 2 Relationship between magnetic properties

3. Magnet Manufacturing Methods and Associated Issues

A variety of magnet manufacturing methods exist⁽⁸⁾. Figure 3 compares the characteristics of sintering, the representative method of manufacture of neodymium magnets, and hot-deformation, the method focused on in the present research.

3.1. Sintered Magnets

To produce the magnetic powders that form the starting material for sintering, alloys are melted and cooled into thin sheets, following which they are mechanically crushed to produce a powder ranging in particle size from 3 μm to 5 μm. This powder is cold pressed to form a pressurized powder body. The powder is then poured into the cavity of a die and cold-pressed under an applied magnetic field for crystal alignment. Because each particle of the magnetic powder is a single crystal, orientation is a simple matter, and there is a high degree of freedom in the shape of the pressurized powder body. It is therefore possible to form large blocks, and productivity is high. The pressurized powder body is next placed in a heating oven and aged to complete the magnet.

3.2. Hot-deformed Magnets

The raw material alloys used in the hot-deformation process are melted and rapidly quenched at speeds from 10⁵ °C/s to 10⁶ °C/s in order to form ribbons. Rapid quenching of the material results in the formation of fine crystals of around 40 nm in diameter. These ribbons are crushed to form a polycrystalline powder with a particle size of around 150 μm. This is the starting material magnetic powder. Because the fine grains in the powder are arranged isotropically, it is necessary to orient the grains and align the easy axis of magnetization. However, because it is not the case that each of the particles in the powder is a single

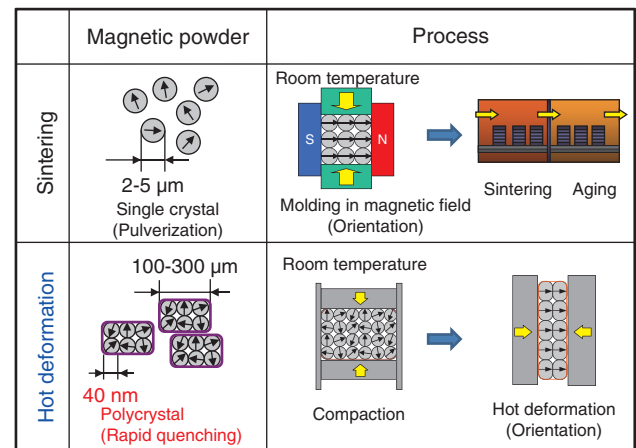


Fig. 3 Magnet manufacturing method comparison

crystal, as in the sintering method, the crystals cannot be oriented using a magnetic field. The crystals are therefore oriented by heating the material and subjecting it to a deformation process. Figure 4 shows the mechanism of this orientation⁽⁹⁾⁻⁽¹¹⁾.

When the crystals are heated, growth is prioritized in a direction perpendicular to c-axis, the easy axis of magnetization, and the crystals become flattened. Following this, when a load is applied on a single axis, torque acts on the flat crystals, and they rotate, becoming oriented in the direction of pressurization⁽¹⁰⁾. Based on this mechanism, pressure is applied to the pressurized powder body on a single axis by heating and extrusion, to form oriented, plate-shaped magnets. However, because it is necessary to uniformly apply pressure to all areas of the pressurized powder body, there are certain restrictions on the shape of the pressurized powder body in order to produce a uniform magnet. The control of variations by setting the conditions of the deformation process therefore represents an issue. In this process, while B_r increases as a result of the orientation of the crystal grains, heating results in crystal growth, reducing H_{cj} . It is essential to consider this trade-off in attempting to boost the properties of the magnet. The fact that high- H_{cj} magnets with microstructures similar to that of the developed magnet generally display a low level of magnetization also represented a concern, and it was necessary to investigate this effect.

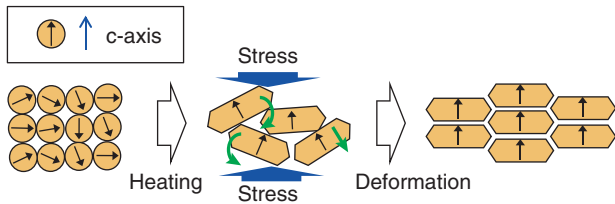


Fig. 4 Model of anisotropic crystal growth

4. Boosting Properties of Hot-deformed Magnet

4.1. Hot-deformation Conditions

Figure 5 shows scanning electron microscope (SEM) photographs of the Dy-free magnet with modified characteristics developed in this research for different hot-deformation temperatures. These results show that as the temperature increases, crystal growth proceeds and the shape becomes flatter, promoting increasing orientation. As indicated above, however, it is necessary to reduce the hot-deformation temperature in order to maintain the microstructure of the magnet. In the case of the developed magnet, therefore, in addition to reducing the hot-deformation temperature in order to refine the crystal grains, the rate of the deformation process was set so as to obtain a relatively high level of crystal orientation in comparison to the conventional method even under the lower-temperature conditions.

4.2. Composition Design

The main phase of a neodymium magnet is an intermetallic compound with the stoichiometric proportions $RE_2T_{14}B$ (RE: Rare earth; T: Transition element). However, because the magnet also has a grain boundary phase, the Total Rare Earth (TRE) in the starting material alloy is greater than the stoichiometric proportion. Figure 6 shows SEM photographs of a low-TRE, low- H_{cj} conventional

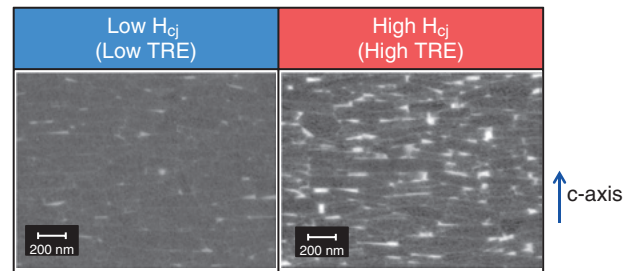


Fig. 6 Crystalline microstructure of hot-deformed magnet

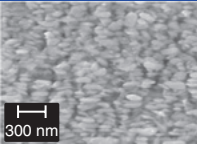
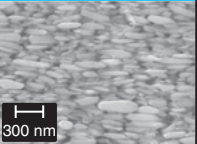
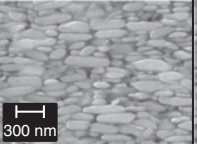
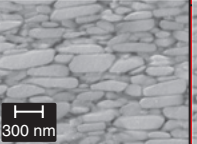
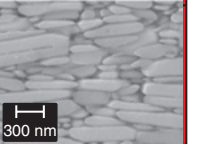
No.	No.1	No.2	No.3	No.4	No.5
SEM image					
Grain size	126 nm	203 nm	295 nm	386 nm	571 nm
Deformation temp.	700°C	725°C	750°C	775°C	800°C

Fig. 5 Grain size of hot-deformed magnet for differing deformation temperatures

magnet, and a modified magnet with high TRE and high H_{cj} . The thickening of the grain boundary phase (the white areas in the photographs) magnetically isolates the main phase, increasing H_{cj} . Increasing TRE within a range in which there is no major decline in the ratio of the main phase has boosted the properties of the magnet.

4.3. Boosting Magnet Properties

Figure 7 shows the magnetic properties of a conventional hot-deformed magnet and the magnet developed in the research discussed here. In the case of the developed magnet, the hot-deformation temperature was reduced, the conditions of the deformation process were optimized, and the composition of the material was designed in order to optimize the grain boundary phase. The refinement of the crystal grains and the realization of increased magnetic isolation of the main phase have increased H_{cj} . In addition, B_r has been increased by maintaining the microstructure while increasing the level of orientation.

4.4. Temperature-dependence

H_{cj} normally declines at high temperatures, and the rate of this decline is dependent on the grain size⁽⁴⁾. The correlation between grain size and the temperature coefficient of H_{cj} (β %/°C) as a secondary effect of the refinement of the grains was verified (Fig. 8).

Figure 9 shows examples of the effect of increasing the temperature coefficient of H_{cj} . The H_{cj} of the hot-deformed magnets close to ambient temperatures is lower than that of the sintered magnet, shown as the solid line. However, at higher temperatures, the hot-deformed magnets display equivalent or greater H_{cj} than the sintered magnet. This is because the temperature-dependence of H_{cj} in the hot-deformed magnets is lower, and the ratio of decline in H_{cj}

is therefore lower. The lower temperature-dependence of H_{cj} in the hot-deformed magnets represents an advantage at high temperatures, when demagnetization becomes an issue in traction motors.

4.5. Magnetization

Figure 10 shows the initial magnetization curve (the first quadrant of the hysteresis curve) for a sintered magnet and a hot-deformed magnet. As the magnetizing field is increased in strength from the zero point of the curve, the sintered magnet becomes saturated and is completely magnetized at around 500 kA/m. In the case of the hot-deformed magnet, the initial magnetization curve displays

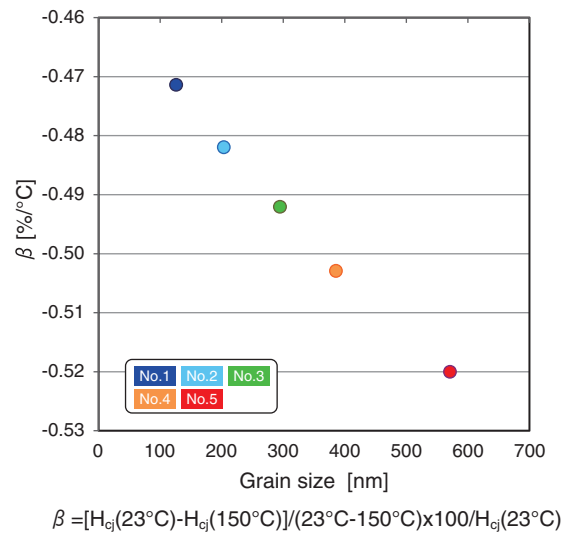


Fig. 8 Relationship between grain size and temperature coefficient of H_{cj} (β)

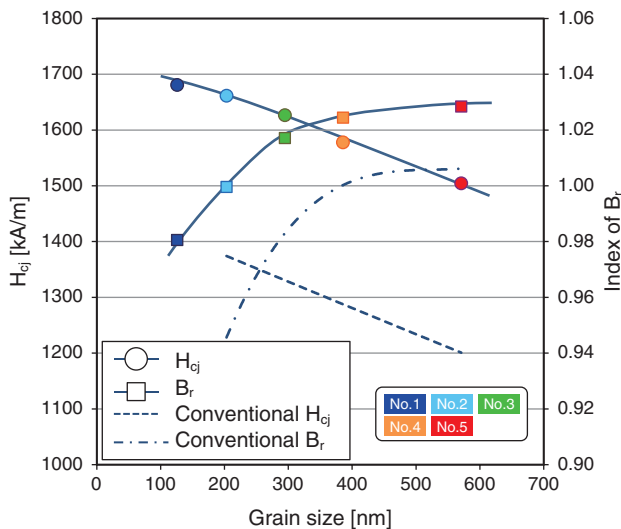


Fig. 7 Relationship between grain size and H_{cj} /grain size and B_r

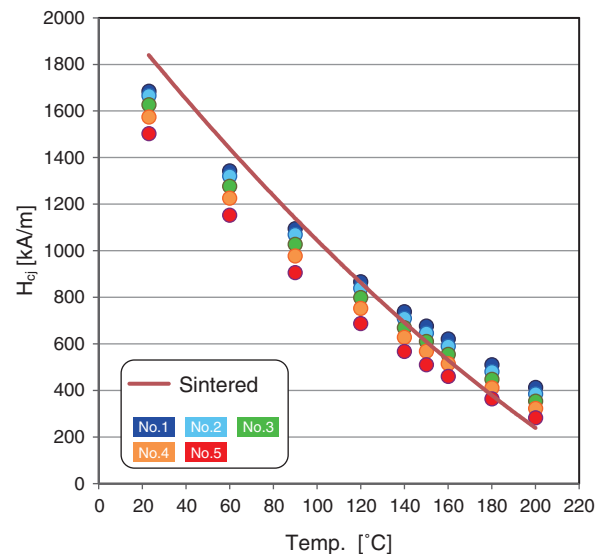


Fig. 9 Temperature-dependence of H_{cj} in hot-deformed magnet and sintered magnet

two stages, and an effective magnetic field equivalent to or greater than the coercivity of the magnet would be necessary for complete magnetization.

Because the crystal grains in the sintered magnet are large, a single grain represents a multi-domain structure. When a magnetic field is applied, the grains readily magnetize due to domain wall displacement. By contrast, because the crystal grains in the hot-deformed magnet are small, both single-domain structures and multi-domain structures exist in the magnet. The two-stage initial magnetization curve is a result of the fact that the grains in the multi-domain structures are magnetized first, followed by those that are single-domain structures.

Figure 11 shows the results of study of the magnetic domain structure of each magnet using magnetic force microscopy. The sintered magnet is characterized by multi-domain structures, in which multi-domains divided by domain walls exist on each grain. In the hot-deformed magnet, by contrast, the majority of grains are single-domain structures without domain walls. This

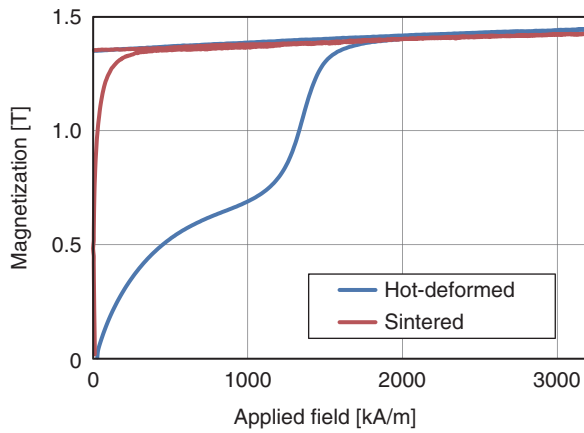


Fig. 10 Magnetization profile

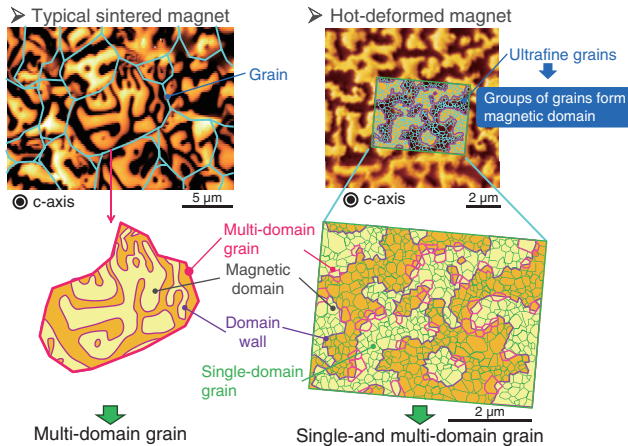


Fig. 11 Magnetic domain structures (Magnetic force microscope image)

further substantiates the difference observed in the initial magnetization curves of the magnets.

The results discussed above indicated that a larger applied magnetic field would be necessary in order to magnetize the hot-deformed magnet, making it necessary to consider the production technology and respond via the voltage setting of the magnetization power source.

4.6. Realizing Uniformity of Properties

The ability to form stable products following the modifications to the production process was verified. Magnets were cut from a formed magnet, and the magnetic flux originating in B_r was measured for each magnet (Fig. 12). With regard to variations in magnetic flux, optimization of tool design and formation conditions during the hot-deformation process made it possible to realize a process capability index (C_p) of 5.90 in relation to the range demanded for HEV.

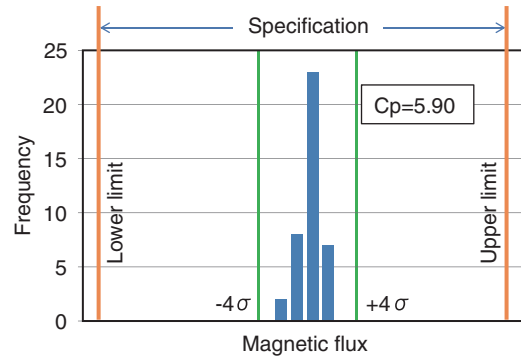


Fig. 12 Dispersion on magnetic flux

5. Conclusions

The research discussed in this paper developed a heavy rare earth-free, hot-deformed magnet for a traction motor. Refinement of the magnet microstructure through hot-deformation at a low temperature, the realization of a high level of orientation through the optimization of the rate of the deformation process, and the magnetic isolation of the main phase through design of the grain boundary phase increased H_{cj} and B_r . The ability of the method to output a stable product in mass production was verified. The development of the new magnet will make it possible to mass produce traction motors for electric vehicles displaying a level of performance equivalent to or higher than conventional traction motors without the use of high-cost heavy rare earths, the production of which is unevenly geographically distributed.

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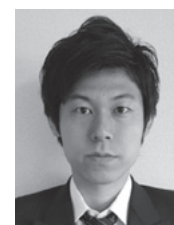
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Development of High-Rigidity Polypropylene Material and Clear Coat for Lightweight Bumper Fascia

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ABSTRACT

A polypropylene material and clear coat were developed for the purpose of reducing bumper fascia weight.

In order to reduce bumper fascia weight, a polypropylene material was developed that would make it possible to thin the average wall thickness of 3.0 mm down to 2.0 mm. The developed material has high flowability to enable injection at 2.0 mm, and steps were taken to augment its rigidity by making it a high-rigidity material. At the same time, attention was also paid to the reduction in impact resistance caused by the higher rigidity, and to the fact that it would be further reduced after coating. That reduction in impact resistance was therefore limited by developing not only a material but also a coating for the purpose. Of the primer, base, and clear layers that make up the bumper fascia coating, the origin of cracking is in the clear layer. The main component of the clear layer is acrylic resin, and the glass transition temperature of this resin was raised while also adding an admixture of resin particles with a diameter of 0.1 μm or less. This was done to make the coating hard and brittle, increasing the number of cracks in order to distribute the stress.

As a result, a weight reduction of 23% or more relative to preceding materials was achieved in the bumper fascia of the 2016 model CIVIC.

1. Introduction

There are high levels of concern about reducing carbon dioxide emissions in order to protect the global environment. In the lifecycle of a motor vehicle, CO₂ emissions during driving make up a high percentage, and reductions in CO₂ emissions are being sought by means of improved fuel economy. Achieving reductions in vehicle body weight is considered important for the purpose of improving fuel economy, and many parts are being examined to this end.

The combined weight of the front and rear bumper fascia for a single vehicle is around 8 kg, making these large trim parts where weight reduction could be expected to have an impact (Fig. 1). Methods used to achieve such a weight reduction include, for example, using material with a lower specific gravity and reducing wall thickness. Since the material being used is polypropylene (PP), which already has a low specific gravity, reports of measures in this area mainly involve technology for reducing wall thickness⁽¹⁾.

Since reducing wall thickness lowers moldability, rigidity, and impact resistance, ways of enhancing performance of thin-wall parts by means of parts design,

material, and manufacturing methods are being investigated. In materials, in particular, investigations are being made of the properties and proportional balance of the three components that make up PP material, namely PP resin, talc filler admixture, and rubber.

Injection molding is used to mold the bumper fascia, but when wall thickness is reduced, the flowability in the mold is reduced, lowering the moldability. In order to heighten moldability, therefore, it is necessary to heighten the PP material flowability.

When the bumper fascia wall thickness is reduced, the rigidity is lowered so that the pushing force on the



Fig. 1 Front and rear bumper fascia

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fascia when applying wax causes elastic buckling in the parts. Therefore high rigidity material is necessary. Furthermore, the properties of PP material change with the temperature, so that the impact resistance of the material in low-temperature environments is lower than at normal temperatures⁽²⁾. There would be concern that the parts could be damaged by external force in the kind of low-temperature environments found in North America and Russia in wintertime, when the impact resistance of the parts would be lowered, and it is therefore necessary to heighten the impact resistance.

On the other hand, as shown in Fig. 2, PP material rigidity and impact resistance are in an inverse relationship. Moreover, impact resistance at low temperatures after coating is lower than before coating. This means that it is no simple matter to achieve a balance between material rigidity and post-coating impact resistance at low temperatures, and so to obtain a large weight reduction effect, by means of PP material development alone. It was reasoned, therefore, that if a coating that would limit the reduction in impact resistance at low temperatures could be developed, then a balance between rigidity and impact resistance could be achieved. This paper introduces the new development of PP material for use in reducing wall thickness as well as of a coating that limits the reduction in impact resistance at low temperatures.

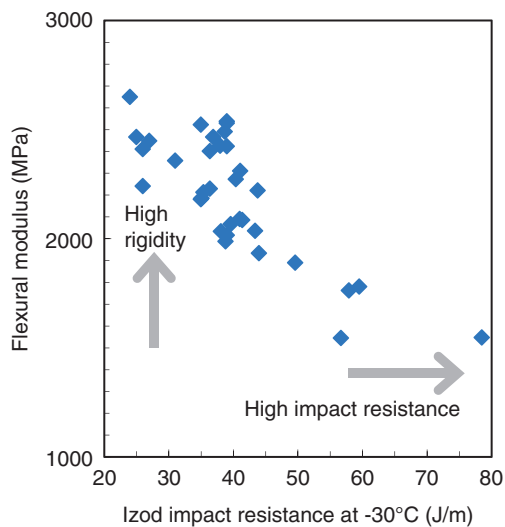


Fig. 2 Relationship between impact resistance and rigidity

2. Conceptual Approach of Coating for Limiting Reduction in Impact Resistance

The coating on ordinary bumper fascia is composed of three layers. These are the primer coat, which assures adhesion of the coating to the PP material, the base coat,

which provides the color, and the clear coat, which protects the coating from ultraviolet radiation (Fig. 3).

The post-coating impact resistance at low temperatures was evaluated using a modified Dupont impact tester according to paragraph 6⁽³⁾ of JIS K5600-5-3 (Fig. 4). A test plate cooled down to -30°C has a weight of 1 kg dropped onto it from a set height, and if the test plate does not break apart, it is considered up to standard. The drop height is

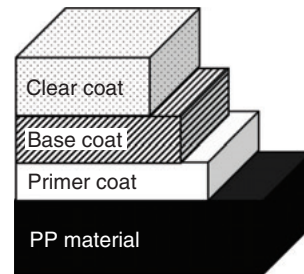


Fig. 3 Construction of bumper fascia coatings

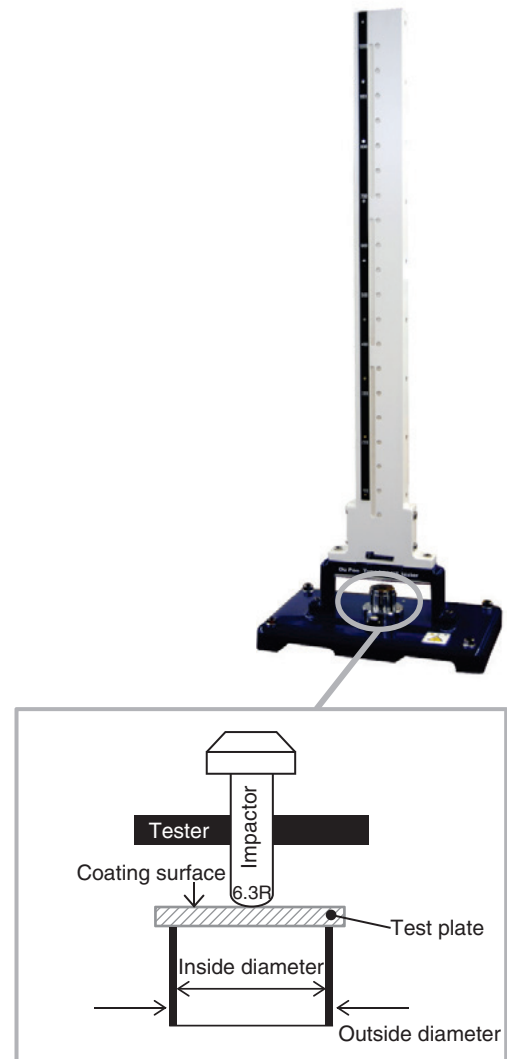


Fig. 4 Modified Dupont impact tester

raised 10 cm at a time, and at the height where the test plate breaks apart, it is considered to fail the test. The maximum height where no breaking apart occurs is taken as the impact value. The ways in which the bumper fascia are used was studied and an impact value target was set at which the parts would not break in the actual use environment.

The fracture surface of test plates that broke apart in the post-coating low-temperature impact test were observed using a scanning electron microscope (SEM), and the results are shown in Fig. 5. It was apparent that the cracking originated in the coating and advanced to the surface of the PP material, then propagated to the bottom surface.

Figure 6 shows the relationship between the three coating layers and impact resistance. The material without any coating, with only the primer coat, and with the primer coat and base coat, exhibit no difference in their impact resistance. When coated with primer, base, and clear coats, however, the impact resistance is lower.

Based on the fracture surface observation results together with the relationship between the various coats and the impact resistance, it was reasoned that breaking apart occurs as follows. An external force causes the test plate to deform. Unable to follow this deformation, the clear coat surface cracks, the cracking propagates to the base, the primer, and the PP material, in that order, resulting in the PP material breaking apart. Since the origin of the cracking is in the clear coat, the possibility of changing the resin properties in the clear coat so as to limit the lowering of the impact resistance was investigated.

Two types of clear coat resin properties were considered for the purpose of limiting the propagation of cracking. The first was a soft type that would conform to the deformation under external force. The second was a hard type that was intended to prevent the development of certain specific types of cracking that advance faster than others by instead making the clear coat more susceptible to cracking and increasing the number of cracks in order to distribute the stress, thereby limiting the development of cracking. The soft type would become sticky when the clear coating surface grew softer in the summer heat, making it difficult

to clean, and there was concern that discoloration would reduce the market appeal of its external appearance. It is no simple matter to configure resin properties so as to achieve a balance between clear coat staining properties under high temperatures and impact resistance under low temperatures.

The hard type makes the clear coat more susceptible to cracking and this causes the coating to lose some of its flexibility. There was concern that cracking of the coating

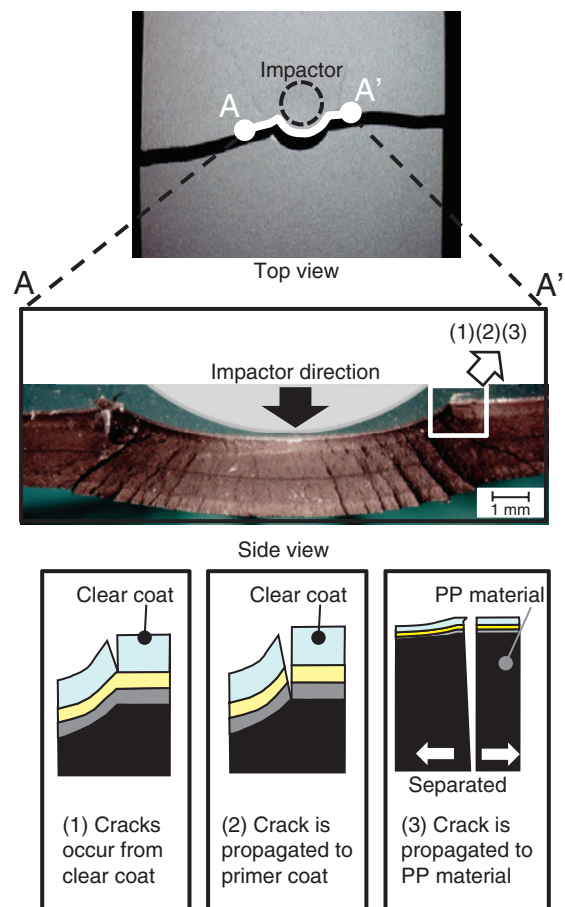


Fig. 5 SEM photograph of broken panel

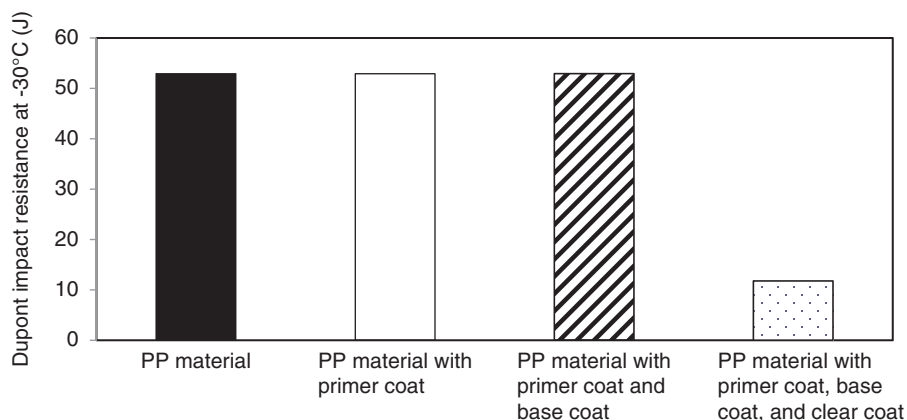


Fig. 6 Impact resistance of 3.0 mm PP material with coatings

could occur when installing or removing the bumper fascia, and that this would reduce the market appeal of its external appearance. It was reasoned, however, that the resin properties could be configured if the fascia could be designed not to cause cracking of the coating in a bending test that simulated the installation and removal work.

In light of the above, a hard type of stress-distributing clear coating was chosen in order to achieve a balance between functionality on a par with conventional fascia and limitation of the lowering of impact resistance.

3. Development Goals

The target for reduction of wall thickness was determined by studying the weight and average wall thickness of bumper fascia on existing mass-production vehicles. The target for weight reduction was set as 20% or more and average wall thickness as 2.0 mm, which would be competitive with other manufacturers.

(1) Flowability

In order to reduce the average material wall thickness from the conventional 3.0 mm to the thinner 2.0 mm, a target of approximately 50% greater flowability was adopted so that the PP material would flow even at a thickness of 2.0 mm. The melt flow rate (MFR) was used as the index of flowability.

(2) Rigidity

In general, rigidity is in direct proportion to the cube of

plate thickness. In order to assure rigidity in material with an average wall thickness of 2.0 mm that is on a par with material with wall thickness of 3.0 mm, and to achieve a 20% reduction in weight, the specific weight of the material was set to 1.04 g/cm³ or less and the flexural modulus was set to 2200 MPa or greater. Measurement of the flexural modulus was carried out in accordance with ASTM D790⁽⁴⁾.

(3) Impact resistance

The impact value of PP material with and without coating was compared. As shown in Fig. 7, the conventional material (a) with coating, the impact value of the PP material is approximately 80% lower than PP material without coating. (b) When the wall thickness is reduced from 3.0 mm to 2.0 mm, the impact resistance of the PP material is reduced. And (c) when the PP material is made a high-rigidity material, the impact resistance is reduced relative to the conventional material. (d) When PP material that is made with a thin wall and high rigidity has a conventional coating applied, its impact value falls short of the target. (e) Estimating the amount by which impact resistance is reduced in PP material that is made with a thin wall and high rigidity, it was decided to set a limit so that the amount of that reduction would not exceed 50%. The purpose of this limit is to assure post-coating impact resistance at low temperatures.

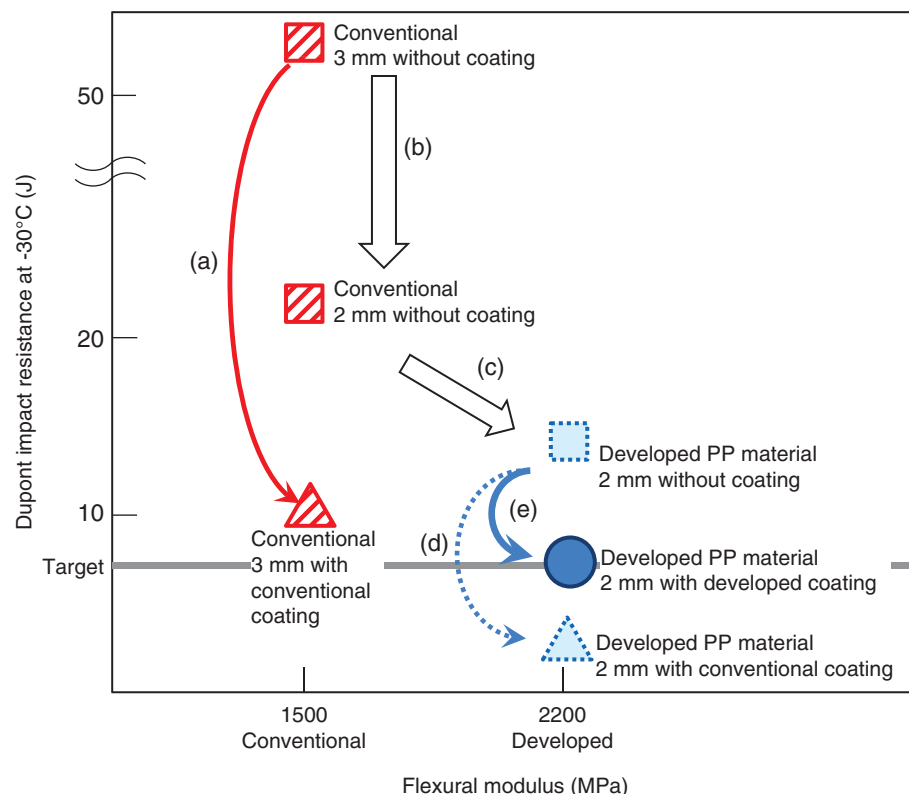


Fig. 7 Relationship between flexural modulus and Dupont impact resistance

Table 1 Properties of conventional and developed PP material

Properties		Conventional	Target value	Developed
Moldability	Melt flow rate (g/10 min)	28	≥ 42	44
Rigidity and weight reduction	Flexural modulus (MPa)	1500	≥ 2200	2280
	Specific gravity (g/cm ³)	0.95	≤ 1.04	1.04

4. Developed Specifications

4.1. PP Material with High Rigidity and High Flowability

The PP material contains a mixture of three components, which are PP resin, talc, and rubber. In order to realize a balance of the target specific gravity and rigidity, the amount of talc, which is a component enhancing rigidity, was increased, while the amount of rubber, which reduces rigidity, was reduced.

Increasing the amount of talc in conventional PP material causes the specific gravity to increase. However, the increase in rigidity achieved by that greater amount of talc is insufficient to achieve the target for rigidity in balance with the increased specific gravity. Therefore the possibility of using a different type of talc in the developed material was investigated. In general, when the admixture contains the same amount of talc, the rigidity-enhancing effect will be greater when the aspect ratio is higher. Therefore a talc with a higher aspect ratio was selected and an amount approximately twice that in conventional material was added to the mixture.

The rubber component on the surface becomes elongated during injection molding and has the effect of enhancing the adhesion of the coating. Therefore there is concern that reducing the amount of rubber would diminish the adhesion. In order to assure the adhesive strength of a stable coating, the amount of the rubber component was reduced approximately 30% relative to the conventional material. Figure 8 shows the ratio of the three raw material components in the PP material.

The heightened flowability was achieved by reducing the average molecular weight of the PP resin, which is the largest component in the PP material admixture, thereby reducing the viscosity of the material. Table 1 shows a comparison of the developed material and conventional material.

4.2. Stress-Distributing Clear Coating Specification

A clear coating of thermosetting urethane is used on the bumper fascia. The acrylic resin that is the main component of this clear coating was designed to be hard and brittle so that the application of external force would cause many cracks in the coating. Specifically, the acrylic resin was made to have a higher glass transition temperature (T_g) than conventional material.

A hard particulate resin was also added to the mixture to function as a starting point for cracking when the coating is deformed. There was concern that using particles of a large diameter in the particulate resin would diffuse light and reduce the luster of the clear coating. Particles with a diameter of 0.1 μm or less, which would be able to maintain the luster, were therefore added to the mixture.

As shown in Fig. 9, raising the acrylic resin T_g and including particulate resin in the admixture enhanced the impact resistance. Use of this clear coating made it possible to limit the reduction in post-coating impact resistance to approximately 50% as compared with approximately 80% with the conventional clear coating (Fig. 10).

The cross-sections of the conventional clear coating and of the stress-distributing clear coating after impact testing were examined by SEM. Figure 11 shows that the cracking of the conventional clear coating due to stress is concentrated at one location. The crack is sharply pointed and is propagated deeply into the base material. The stress-distributing clear coating, however, shows multiple cracks occurring, and the cracking also extends only to shallow depths in the PP material. This indicates that the stress has been distributed and cracking of the material has been limited.

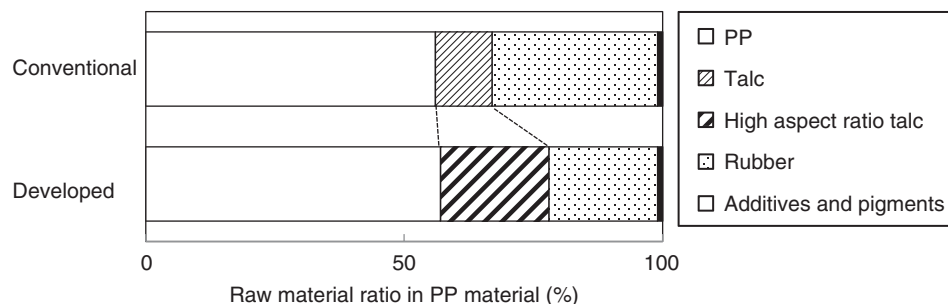


Fig. 8 Comparison of raw material ratio

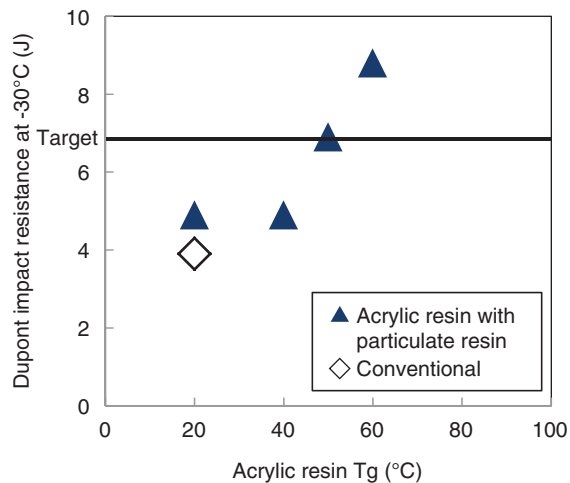


Fig. 9 Relationship between acrylic resin Tg and Dupont impact resistance

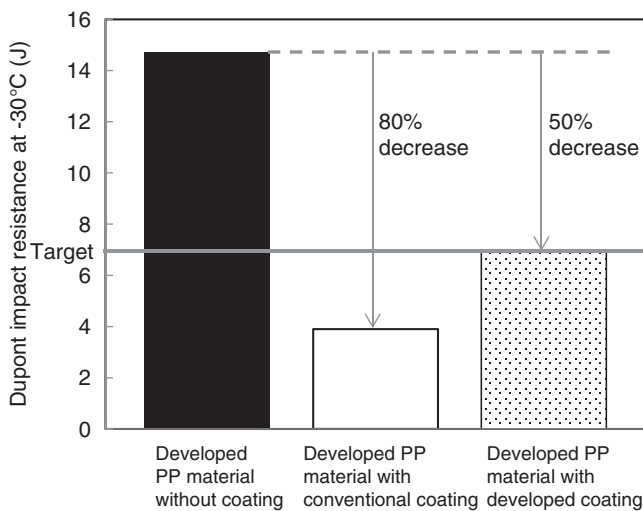


Fig. 10 Dupont impact resistance of developed 2.0 mm PP material with developed coating

5. Product Performance Evaluation

The component performance of bumper fascia with a stress-distributing clear coating on high-rigidity, high-flowability PP material was investigated by means of a pendulum impact test, measurement of the amount of deformation under pushing force, and a component installation and removal test.

Envisioning how a vehicle would be used in a low-temperature environment, the vehicle was fully chilled in a -30°C environment. The bottom portion of the bumper fascia was then subjected to a pendulum impact test, and it was confirmed that damage did not occur.

With regard to elastic buckling of a part caused by pushing force, the amount of deformation that occurred under a fixed load was measured and confirmed to be below the standard value.

With regard to cracking of the coating, verification was conducted by installing and removing the bumper fascia. This confirmed that the market appeal of the part's external appearance was not diminished by cracking.

A thin-wall, lightweight bumper fascia that does not sacrifice the impact resistance and rigidity of the parts was developed. Application of the fascia started with the 2016 model CIVIC. A 23% reduction was achieved in the total weight of the front and rear parts together.

6. Conclusion

The combination of the PP material with the clear coat, both shown below, achieved a balance of rigidity and low-temperature impact resistance while also successfully reducing the bumper fascia wall thickness.

- (1) With respect to the PP material, the viscosity of the PP resin was reduced, thereby enhancing its flowability during injection molding. A talc with a high aspect ratio was also selected, thereby achieving a balance of the target specific gravity and rigidity values.
- (2) With respect to the clear coat, the acrylic resin Tg was

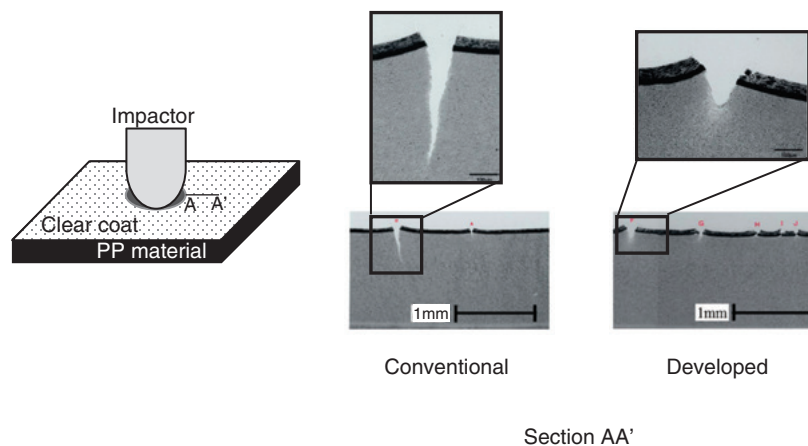


Fig. 11 Section AA' of coated PP after impact test, taken using SEM

raised and particulate resin with a diameter of 0.1 μm or less was mixed in. These measures were used to create a stress-distributing specification with an increased number of starting points for cracking when deformed by external force.

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Emi NOMI



Ken NAKANE

Technology for Joining of Dissimilar Material with Thermoplastic Polymeric Resin Using Atmospheric Gas Phase Modification of Metal Surfaces

Hiroshi AKITA*

Shinichi KURODA**

Takahiko KAWAI**

ABSTRACT

A technology was developed for metal surface modification treatment to be used on a car body production line for weld-joining parts made of thermoplastic resin with metal parts. A glass membrane with a high hydroxyl group density of 1.4×10^{-9} mol/cm² was successfully formed on an aluminum alloy surface by configuring the conditions for the atmospheric pressure plasma chemical vapor deposition process. The obtained surface was confirmed to have wettability to melted 6-nylon. In addition, an amorphous layer was observed to have formed near the interface portion of the thermoplastic resin thermally welded to it. The effect of these results was that a high level of join strength equal to that in existing items with roughened metal surface aiming for an anchor effect was achieved with items of dissimilar material joined by thermal welding.

1. Introduction

The recent rise in worldwide demand for improved fuel economy in automobiles is the context for increasing investigation of the application of composite materials for the purpose of achieving lighter-weight vehicle bodies. Among them are carbon fiber-reinforced thermoplastics (CFRTP), which are carbon fiber composite materials with a matrix of 6-nylon or other such thermoplastic resin. These CFRTPs are receiving attention for their high specific strength and specific rigidity as well as from the viewpoint of life cycle assessment⁽¹⁾. In their application to vehicle bodies, there is concern about deterioration of the material's mechanical properties due to the environment of use, and about the cost of the material, so structures that combine CFRTPs with metal materials are frequently used. This involves the joining of dissimilar materials, for which the thermal welding ability of the thermoplastic resin that is the matrix material for CFRTPs is utilized to simplify the construction of parts and the process of manufacturing. Such simplification is desirable in terms of achieving lighter weight and reducing costs.

The technology for weld-joining dissimilar material with thermoplastic resin involves roughening by inscribing fine holes and grooves in the metal surface ranging from

several nanometers to several tens of micrometers in size. The pits are filled with melted thermoplastic resin by injection molding, which then solidifies by cooling, in the so-called anchor effect that provides a mechanical join. There have been many recent cases of application of this method. For example, there has been widespread use of technology for integrated forming of thermoplastic resin and light alloy plate using the anchor effect in the process of manufacturing components for compact mobile electronic equipment. However, these surface roughening treatments require chemical treatment by solution processes in which components are immersed in chemicals in order to form the holes and grooves on the metal surface. Due to the long time taken by the processes and the added complication of facilities for disposing of effluent and other such factors, these solution processes cannot readily be introduced to automobile body production lines. Furthermore, these solution processes are originally a technology intended for batch treatment of large numbers of relatively small parts simultaneously, and they are not well suited to localized treatment of only the necessary locations on the surface of large automotive parts. Applying a roughening treatment to the larger surface that includes portions not required for joining would necessitate the use of larger amounts of chemicals as well as larger treatment facilities. This would

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increase process costs, making this approach undesirable. One technique for roughening a metal surface without depending on solution processes uses laser machining equipment, but fine machining in three dimensions at high speed requires equipment with high power output and complex controls.

One conceivable method for achieving dissimilar material weld-joining in automotive parts other than by the mechanism of mechanical joining is by the application of chemical bonding force. In ordinary adhesive bonding, a hydrogen bond or a covalent bond is formed between the adhesive components and the solid surfaces. A join made by thermal welding of thermoplastic resins that does not involve a chemical reaction can make use of the chemical bonding force of the hydrogen bond.

In order to manifest the hydrogen bonding force, the presence of anisotropy functional groups such as hydroxyl groups or amide groups is necessary both on the solid surface and in the thermoplastic resin. A polyamide resin such as 6-nylon includes amide groups in the basic structure of the molecular chain, but anisotropy functional groups are not by their nature found on the solid surface of an inorganic material such as aluminum alloy. It is therefore necessary to place them there *de novo* by means of chemical modification of the surface.

This raises two issues. The first issue is raising the wettability of the solid surface with which the thermoplastic resin has fused thermally. To effectively manifest the chemical bonding force requires wettability to the solid metal surface, but the thermoplastic resin changes from the chainlike state of its molecular structure to a highly viscous fluid when it melts, so its wettability is diminished in comparison with a thermosetting adhesive that has a low molecular weight before it hardens.

The second issue is achieving a stable bonded state. Thermoplastic resins that have crystallinity, such as 6-nylon, tend to separate or experience loss of join strength with solidification by cooling during the welding process or with subsequent changes in the temperature of the usage environment, so that they do not readily achieve stability in their bonded state. This is because, when the progressive crystallization of the melted nylon extends to the weld interface portion, its flexibility is lost so that it becomes unable to absorb the thermal stress in the weld interface that is caused by the difference in thermal expansion between the dissimilar materials. Technology has been given practical application to prevent interface separation. It involves coating the metal surface with a flexible non-crystalline resin to a thickness of approximately 100 μm . Then a layer of thermoplastic resin is applied over that surface by injection molding, forming the shape of an integrally formed component. Finally, it is heat-treated and the non-crystalline resin is cross-linked to assure the join strength. This technology for creating a non-crystalline resin layer requires a special grade of resin material, in addition to which the process is complex and time-consuming.

2. Development Goals

In order to enable localized thermal welding of dissimilar materials with CF RTP components on the automobile body production line, a method for surface modification of metal parts in atmosphere was investigated.

The object was to utilize the chemical bonding force resulting from the hydrogen bond in the thermoplastic resin weld to obtain stable join strength equal to that of mechanical bonds obtained by the anchor effect. Attention was given to the following points:

- (1) Increase the hydroxyl group density at the bond interface;
- (2) Increase the thermoplastic resin wettability at the bond interface; and
- (3) Form a non-crystalline layer at the interface in order to increase the stability of the bond.

3. Method of Achieving Aims

In order to enable thermal welding of the thermoplastic resin, the introduction of high-density hydroxyl groups to the metal surface was adopted as the policy for investigation of surface treatment technology. The interaction between metal surface hydroxyl groups and the thermoplastic resin increased the wettability of the melted resin, which was noted above as the first issue, manifesting greater hydrogen bonding force so as to obtain greater join strength. The effect this interaction has of restricting polymer chain mobility was utilized to suppress the progressive crystallization of the thermoplastic resin in the weld interface portion. This formed a flexible and amorphous thermal stress relaxation layer, suggesting that stabilization of the bond, the second issue, could also be addressed.

As a method for introducing hydroxyl groups to the metal surface, the focus was placed on the atmospheric pressure plasma approach, which enables high-speed processing at atmospheric pressure.

Atmospheric pressure plasma processing ordinarily obtains a plasma gas flow by converting a portion of atmospheric gas to plasma by electric discharge or heat and directs that plasma gas flow onto the target object. This method causes oxidation-reduction or other such chemical processes to occur at atmospheric pressure⁽²⁾.

Siloxane or another such precursor is introduced into that plasma gas flow where it decomposes through the action of the plasma, and the highly chemically active substance that is generated is sprayed onto the target object and polymerized so that a membrane of glass or other substance is formed on the surface of the target object. This surface modification technology is the chemical vapor deposition (CVD) process⁽³⁾. The energy level of the excited species – meaning the atoms and molecules that were excited by the electrical discharge – will vary with the type of atmospheric gas. On the downstream side of the plasma gas flow, the energy level of the excited

species decreases as they undergo progressive relaxation or collide with molecules of oxygen, nitrogen, water, and so on in the atmosphere, causing excitation of those they collide with^{(4),(5)}. By using this property, the atmosphere in which the precursor undergoes a decomposition reaction can be controlled so that a different degradation product can be obtained from the same precursor. As a result, glass membranes with different properties can be created for different purposes.

An example of existing research is the report from Ihde and others regarding the properties of two types of glass membrane formed on the surface of an aluminum alloy (Al 2024-T3) with hexamethyldisiloxane (HMDSO) as a precursor using the atmospheric pressure plasma CVD process⁽³⁾. The first was a highly homogeneous glass membrane with little organic residue from the precursor that was obtained when the processing conditions included the use of dry air as an atmosphere gas. This membrane has physical properties that suit it as an anti-corrosion coating for aluminum alloy. The second was created using the same apparatus with dry nitrogen (N₂) as an atmosphere gas and with the location where the precursor is interfused with the plasma gas flow moved several millimeters downstream from the plasma source. The glass membrane obtained under these processing conditions has a chemical composition that includes approximately 2.5 times more organic constituents than the first membrane⁽³⁾. Research has also been done on the adhesion of coatings and adhesives to these glass membranes, and the first membrane in particular has been proposed for application as an adhesive primer for thermosetting urethane adhesive in automobile windshields⁽⁶⁾.

This kind of investigation has not yet been carried out on the thermal welding ability of thermoplastic resin. In the present research, attention was focused on the methyl groups derived from the organic components in the surface of the second membrane, i.e., the HMDSO precursor.

The methyl groups that exist in the surface portion of the glass are known to be caused to alter into hydroxyl groups (silanol groups) by the oxidative reforming that is caused by the atmospheric pressure plasma process⁽⁷⁾.

It was reasoned that using the atmospheric pressure plasma CVD process to form a glass membrane with an abundance of methyl groups on the metal surface to start, and then to cause oxidative alteration of it by atmospheric pressure plasma processing, would yield a glass membrane with a high density of hydroxyl groups on its surface.

4. Tests

4.1. Surface Modification Treatment of Aluminum Alloy

An Openair plasma system (FG5001 plasma generator, PFW10-PAD/RD1004 plasma jet nozzle, and PAD1 polymer coating controller) made by Plasmatec GmbH were used for the atmospheric pressure plasma CVD processing.

Figure 1 shows a schematic diagram of the device. The device is based on an atmospheric pressure plasma jet device. While atmospheric gas at atmosphere pressure is passed through a tube made of conductive metal, a high-voltage pulse is applied to an insulated electrode inside the tube to cause an arc discharge, and plasma is generated. The gas flow that includes this plasma is blown through the plasma nozzle at the tip of the tube and onto the surface of the target object. The device that does this is the atmospheric pressure plasma jet device. This plasma nozzle is installed with a cover nozzle that has a channel for liquid in it, as shown in Fig. 2. The precursor substance is injected through this channel into the plasma gas flow to mix with that flow, making it possible for the atmospheric pressure plasma CVD process to occur.

The metal substrate to which the atmospheric pressure plasma CVD process is applied is made using rolled aluminum alloy (Al 5052) material. This alloy surface is not cleaned using solvent or other such material. Instead a plasma gas flow generated using air as the atmosphere gas is blown against the surface so that oil or other contaminants adhering to it are oxidized and removed.

Next an atmospheric pressure plasma CVD process using HMDSO as the precursor substance is carried out and a glass membrane is formed on the substrate surface. The atmospheric pressure plasma CVD process is carried out under two sets of conditions that differ in the type of atmosphere gas and whether or not the nozzle has an extension. For each of those, another version is also made in which the process is applied post-oxidation with the

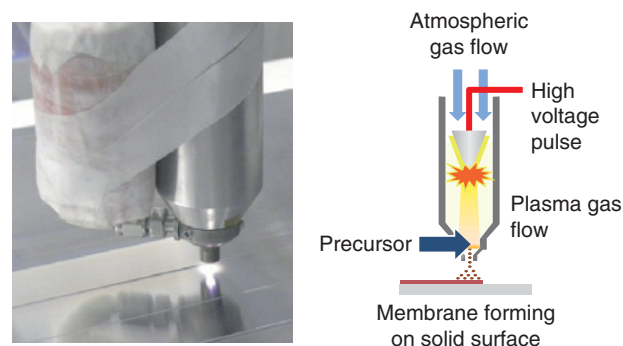


Fig. 1 Diagram of atmospheric pressure plasma CVD process principle

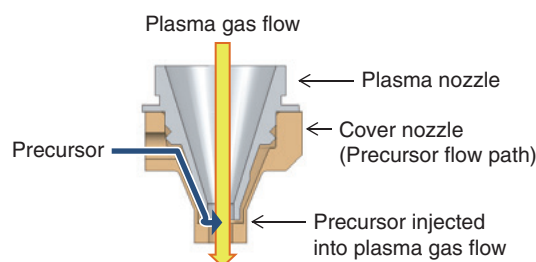


Fig. 2 Plasma CVD nozzle (original form)

Table 1 Atmospheric pressure plasma CVD process conditions

Membrane type	Atmospheric pressure plasma CVD		Post processing
	Gas	Nozzle extension	
A	Nitrogen	4.5 mm	-
B	Air	-	-
C	Nitrogen	4.5 mm	Plasma oxidation
D	Air	-	Plasma oxidation

atmospheric pressure plasma. In this way, a total of four types of glass membrane are created as shown in Table 1.

Specifically, N₂ was used as the atmosphere gas for the atmospheric pressure plasma CVD process under the first set of conditions. In addition, as shown in Fig. 3, a shim and pipe-shaped extension part are added to the cover nozzle so that the location where the precursor is mixed together with the plasma gas flow is moved 4.5 mm downstream. Using this method, a sample in which glass membrane (A) had formed on the surface of the aluminum alloy was obtained.

In the second set of conditions, air was used as the atmosphere gas for the purpose of comparison. The atmospheric pressure plasma CVD process was carried out using the original specification nozzle, without extension parts, to create glass membrane (B). The above two processes were carried out with a plasma voltage of 283 V and plasma current of 13 A, distance from the nozzle tip to the substrate surface of 4 mm, and rate of nozzle movement in the horizontal direction of 20 mm/min as the plasma generating conditions.

After that, additional membranes (C) and (D) were created by generating a flow of plasma gas with air as the atmosphere gas and without introducing any precursor to it. The flow is respectively directed onto the surface of membrane samples (A) and (B), subjecting the organic residue constituents to post-oxidation treatment. This oxidation treatment was carried out with plasma voltage of 301 V and plasma current of 20 A, with distance from the nozzle tip to the substrate surface of 7 mm, and with rate of nozzle movement in the horizontal direction of 20 mm/min as the plasma generating conditions.

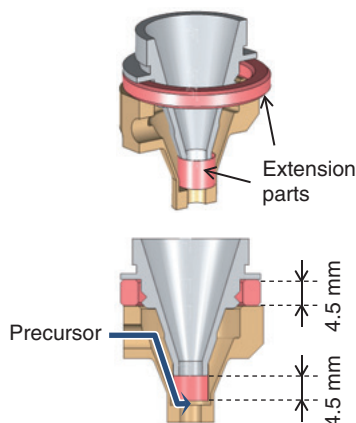


Fig. 3 Plasma CVD nozzle extension

4.2. Glass Membrane Property Analysis

Scanning electron microscopy (SEM) and atomic force microscopy (AFM) were used to observe the glass membrane shape and to measure the roughness of the surface.

Positron annihilation lifetime measurement was conducted using the positron beam method to determine the average micropore radius distribution on the silicon oxide (SiO_x) framework. A ²²Na-based positron beam was used as the positron beam source, and BaF₂ scintillator and photomultipliers were used as a gamma ray detector.

X-ray photoelectron spectroscopy (XPS) was used to measure the element existence ratio on the surface of the glass membrane. Monochromatic aluminum was used as the X-ray source with pass energy of 160 eV.

The ion chromatography method was used to measure hydroxyl group density on the surface of the glass membrane. Specifically, this involved thermal decomposition of a sample of a brominated silicon compound solution with hydroxyl groups on the surface subjected to derivatization treatment. The gas this generated was absorbed into an alkali aqueous solution and the amount of bromine in the solution was measured by ion chromatography. A per-surface-area figure for the hydroxyl group density was calculated from the substrate dimensions.

4.3. Joining of Dissimilar Materials by Thermoplastic Resin Weld

A lap shear-strength test specimen was created using thermal welding to join the aluminum alloy subjected to the atmospheric pressure plasma CVD process with the CF RTP, and the strength of the join was measured. Aluminum alloy test specimens were prepared that were not subjected to the atmospheric pressure plasma process, that had membrane (C) formed on the surface, that had membrane (D) formed on the surface, and that had been subjected to metal surface roughening processes for the purpose of utilizing the already existing anchor effect. In the processes selected for metal surface roughening, an injection molding grade of 6-nylon was used to apply four types of process with surface roughness in different sizes to aluminum alloy. One of these used laser machining to inscribe grooves with a width and depth of approximately 50 μm with a pitch of 200 μm in a grid pattern. In the other three types, a chemical process applying an anodizing process, acid solution, or alkaline solution was carried out to apply finer sizes of roughening and to generate micropores.

Joining by thermal welding was carried out using the metal insert injection molding method. The molding used a specialized metal mold with a cavity in which an aluminum alloy test specimen in strip form and 100 × 25 × 2.0 mm in size could be set, as shown in Fig. 4. The remaining space inside the cavity was shaped in strip form so as to overlap by 12.5 mm longitudinally with the test specimen. Pellets of CF RTP grade 6-nylon containing 15 wt% carbon fiber (CF) were injection-molded into that space with a cylinder temperature of 260°C and a mold temperature of from 160

to 180°C under dwelling pressure of 30 MPa. This injection molding yielded an aluminum alloy plate and 6-nylon plate joined by thermal welding for use as a lap shear-strength test specimen.

All the test specimens were fabricated to a single standard with $n = 5$ and were used for lap shear-strength testing.

SEM and energy dispersive X-ray spectrometry (EDX) were used to examine the fracture surface and perform qualitative analysis of the constituent elements in order to identify the rupture locations.

4.4. 6-Nylon Analysis of Thermal Welding Interface Portion

The crystallization state of the 6-nylon was examined by grazing incidence X-ray diffraction (GIXD) using the multi-axis X-ray diffractometer manufactured by Huber Diffraktionstechnik GmbH & Co. KG that is located in BL46XU Hutch No. 1 at the Spring-8 large synchrotron radiation facility. The sample was fabricated by forming a 6-nylon membrane layer on the substrate surface by the solution spin coating method, thermally fusing it, then resolidifying it. Since surface unevenness caused by the aluminum alloy substrate rolling process diminishes measurement accuracy, a smooth Si wafer was used for the substrate. The strength profile relative to the diffraction angle was separated into crystallized constituents and non-crystallized constituents to calculate the degree of crystallization.

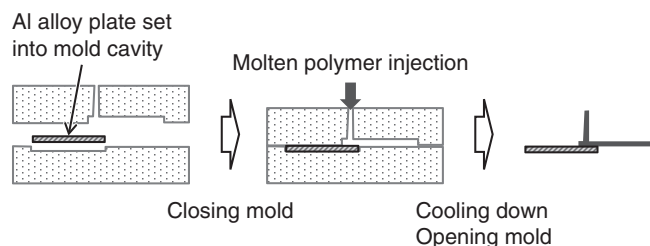


Fig. 4 Process of joining by metal insert polymer injection molding method

5. Results and Discussion

5.1. Property Analysis of the Reformed Surface

First the glass membranes (A) and (B) were analyzed and the physical properties of their respective glass frameworks were compared. Figure 5 shows an SEM image of the membrane (A) and (B) surfaces. Figure 6 shows the result from AFM observation of the membrane (A) surface. Positron annihilation lifetime measurement of the two types of membrane was conducted using the positron beam method. Figure 7 shows a comparison of the average micropore distributions on the SiOx molecular framework of the glass obtained in this way.

Membrane (B) has a homogeneous membrane structure

with a smooth surface and the micropore distribution on the SiOx framework shows a sharp peak. The structure was composed of microparticles approximately 20 nm in size, which is the mean square root value of the surface roughness measured by AFM on membrane (A). The glass frame of membrane (A) showed an irregular and broad distribution of SiOx pore diameters. This suggested that it had a frame structure that was irregular by comparison with membrane (B). In macro terms, this membrane structure has a large surface area, and in micro terms, it is characterized by an irregular molecular structure and instability. It can be inferred, therefore, that the structure is likely to undergo change in its chemical composition due to oxidative reforming.

Next, a comparison was made of the chemical

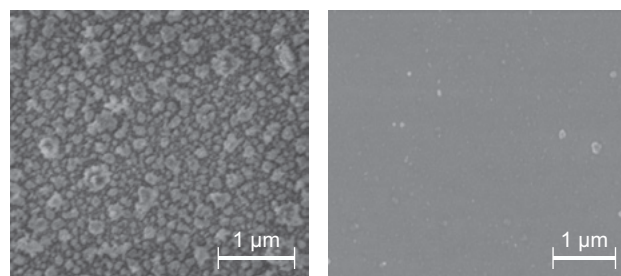


Fig. 5 SEM image of membrane A (left) and membrane B (right) surfaces

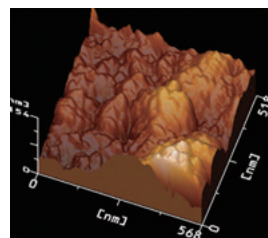


Fig. 6 AFM image of membrane A

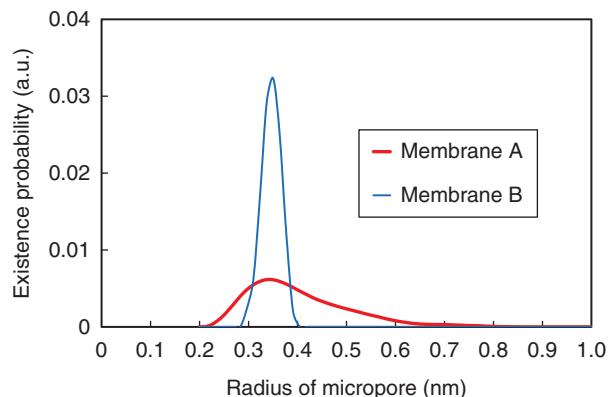


Fig. 7 Positron annihilation lifetime spectroscopy of atmospheric pressure plasma CVD glass membrane

Table 2 Property of atmospheric pressure plasma CVD glass membrane surface

Membrane type	Process conditions			Membrane properties		
	Atmospheric pressure plasma		Post processing	C/Si content (atomic %/atomic %)	Water contact angle (°)	Hydroxyl group density (mol/cm ²)
	Gas	Nozzle				
A	Nitrogen	Extended	-	1.3	160	Unmeasured
B	Air	Normal	-	0.8	80	Unmeasured
C	Nitrogen	Extended	Oxidation	0.3	2.5	1.4×10^{-9}
D	Air	Normal	Oxidation	0.6	43	2.6×10^{-10}

composition and properties of the surfaces of membranes (A), (B), (C), and (D). The fabrication conditions of the various membranes, analysis of their chemical composition by XPS, water contact angle, and surface hydroxyl group density are shown in Table 2.

As shown by the C/Si content ratio data, membrane (A) contained approximately twice as much carbon from HMDSO methyl groups as membrane (B). The change in chemical composition from membrane (A) to (C) – namely, the extent of the reduction in carbon atoms – that is due to the oxidation resulting from atmospheric pressure plasma processing, was relatively greater than the corresponding change from membrane (B) to (D). It appears likely that this is because membrane (A) has a larger surface area and the glass framework was more susceptible to oxidation. As a result, the surface hydroxyl group density of membrane (C) was greater than that of membrane (D) by a factor of five or more.

As shown by the water contact angle data, membrane (A) displayed super water repellency through the synergistic effect with a physical surface form composed of fine irregularities. On the other hand, membrane (C), which was obtained by oxidation of this surface, displayed superhydrophilic properties. As shown by the photographs in Fig. 8, a similar change in wettability was also displayed with respect to thermally melted 6-nylon.

5.2. Evaluation of Thermoplastic Resin Weld Strength

A join was not obtained by injection molding of 6-nylon using the metal mold for insert injection molding so that the 6-nylon would be in contact with an unprocessed

aluminum alloy substrate surface and membrane (D). When the mold was released, those two elements would come out as separate pieces. On the other hand, a test specimen with a satisfactory weld join, as shown in Fig. 9, was obtained when the membrane (C) treatment was applied to the aluminum alloy substrate. The test specimen also achieved a join when the metal surface roughening process was applied to the aluminum alloy substrate plate in order to make use of the anchor effect. Figure 10 shows a comparison of results from lap shear-strength testing of these specimens.

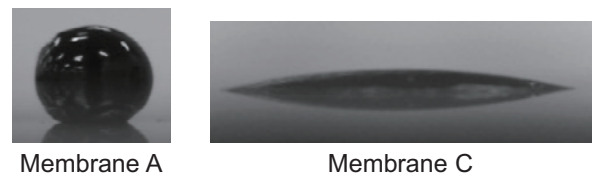


Fig. 8 Molten polyamide 6 behavior on CVD glass membrane surface



Fig. 9 Specimen of joined CFRTP and Al alloy

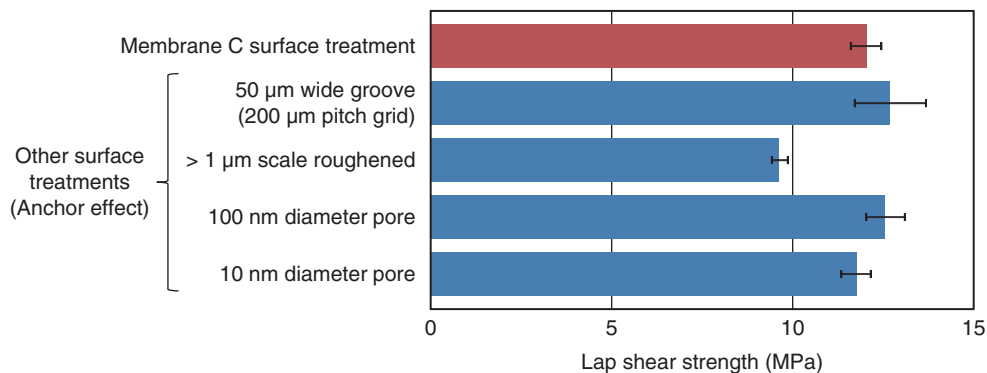


Fig. 10 Joining strength of Al alloy and CFRTP joined by insert injection molding

This confirms that the membrane (C) treatment realized weld join-strength equal to that with the physical anchor effect.

Figure 11 shows the SEM photograph of a weld joining test specimen that fractured in the lap shear-strength testing. The aluminum alloy surface was observed to have fragments of CF RTP adhering to it. EDX analysis also confirmed that carbon from the CF RTP and silicon from the CVD glass membrane were present on the fracture surface on the aluminum alloy side. These observations indicate that the rupture in the weld joint portion was not a separation of the weld interface portion or a rupture of the glass layer, but rather occurred as a material rupture within the CF RTP portion. In other words, this indicates that a thermal welding strength had been obtained that was equal to or greater than the interlaminar strength of the CF RTP.

5.3. Analysis of 6-Nylon Crystallization State in the Thermal Welding Interface Portion

A more detailed analysis was made of the mechanism of thermoplastic resin thermal welding on the membrane (C) treatment surface.

The GIXD method is capable of measurement and evaluation of the extent of crystallization in the thermoplastic resin in the weld interface region and in the bulk region, and this method was used to evaluate the crystallization state of the 6-nylon. The results this yielded are shown in Fig. 12. The horizontal axis of the graph shows the thickness of the 6-nylon membrane from the substrate surface to the measurement position. The vertical axis shows the ratio of observed X-ray crystal diffraction intensity to total scattering intensity, and a larger figure signifies a higher degree of 6-nylon crystallization in that portion. In the case of 6-nylon thermal-welded to an untreated Si wafer surface, crystallization had advanced to

the vicinity of the contact interface with the wafer. In the case of the membrane (C) treated surface, on the other hand, there was confirmed to be a layer of amorphous 6-nylon that extended to a thickness of several hundred nanometers from the interface.

5.4. Confirmation of Thermoplastic Resin Weld Stability

A weld-joined object was placed in an environment that cycled repeatedly between cooling and heating in which it was exposed to atmospheric temperatures of -30°C and 80°C for 30 minutes each for 200 cycles. As shown in Fig. 13, the join strength was not found to change. A sample of thermal-welded 6-nylon plate was also subjected to a compound cycle test of exposure to a 5% neutral salt solution spray at 35°C . Each cycle also included exposure in a dry atmosphere at a temperature of 60°C and humidity of 25% RH, and exposure in a humid atmosphere at 50°C and 98% RH. After testing for 60 cycles, no separation was observed in the weld portion.

It was confirmed from the above that a stable weld-join was obtained by the effect of thermal stress relaxation in the flexible amorphous layer formed in the weld interface.

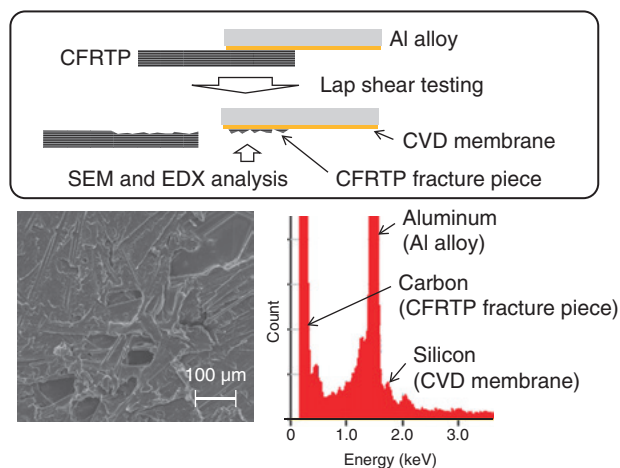


Fig. 11 SEM image (left) and EDX spectrum (right) of CF RTP fracture piece on Al alloy substrate

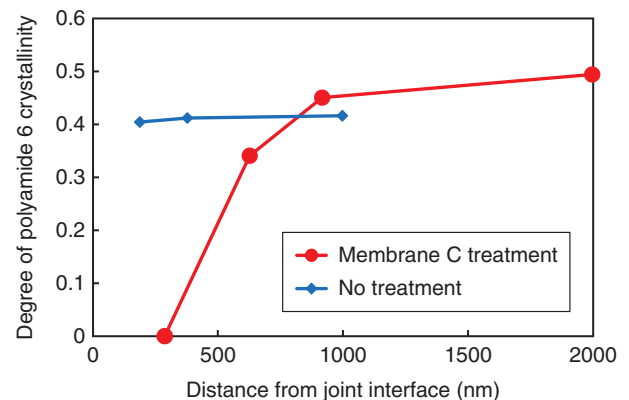


Fig. 12 Suppression of polyamide 6 crystallization by CVD membrane surface effect

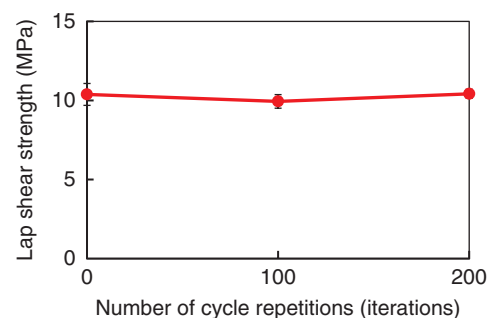


Fig. 13 Joining strength after cooling and heating cycle

6. Conclusion

A surface modification was carried out that formed a glass membrane layer on an aluminum alloy surface by a gas phase process in atmosphere. The properties of the obtained surface and the quality of the weld with thermoplastic resin were evaluated.

- (1) In the atmospheric pressure plasma CVD process, a glass membrane that contains organic constituents was formed by modification of the atmosphere in which the plasma decomposed the precursor substance. This membrane was subjected to oxidative alteration by atmospheric pressure plasma processing, yielding a membrane layer with a high hydroxyl group density on the surface.
- (2) On this surface, the melt state of 6-nylon had high wettability and the hydrogen bond could be used effectively so that a thermal welding join could achieve high join strength on a par with the mechanical anchor effect.
- (3) An amorphous layer of 6-nylon was formed in the vicinity of the weld interface portion. This was due to the effect of suppression of crystallization caused when the mobility of polymer chains of thermally fused thermoplastic resin was inhibited by interaction with solid surface hydroxyl groups. The amorphous layer, which possessed greater flexibility than the crystallized bulk portion, absorbed and relaxed the thermal stress between the dissimilar materials so that separation from the metal surface was prevented and the thermal welding join was stabilized.

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Research on Production of Cellulosic Ethanol – Development of High-Efficiency Yeast Strain using Mutagenesis and Selection and Self-Cloning, and Study of Entire Process –

Yoshiki TSUCHIDA* Norihiko TSUKAGOSHI*

ABSTRACT

A fermentation organism capable of producing a high fermentation yield in the presence of inhibitors, necessary for the realization of increased efficiency in the process of production of second-generation bioethanol from inedible plant biomass, has been developed. The construction of the organism involved a combination of mutagenesis and selection and self-cloning, and results indicated the effectiveness of this combination in the creation of fermentation organisms. Self-cloning is a form of genetic modification implemented within a scope that makes it possible to treat the organism as non-genetically-modified.

Mutagenesis and selection using biomass hydrolysates increased both the organism's tolerance to inhibitors in hydrolysates and its ethanol fermentation yield. Using the selected strain as a base, genes for the expression of transaldolase and alcohol dehydrogenase were enhanced by self-cloning. The developed strain was able to produce a higher concentration of ethanol.

An examination of the entire process led to the discovery of a biomass pre-treatment condition that would control the production of phenols, which act as inhibitors. A process using this pre-treatment condition and the developed fermentation organism would be able to produce 213 L of ethanol from 1 dry-ton of corn stover.

1. Introduction

The replacement of oil refineries by bio-refineries is advocated as a response to concerns over the depletion of fossil fuels and the necessity for the reduction of CO₂ emissions. Bio-refineries are processes that produce useful substances from biomass, a renewable resource, as the starting material. One of the most highly developed of these processes is the process of production of bioethanol. First-generation bioethanol is produced using the edible parts of sugar cane and corn plants; research is now proceeding to commercialize second-generation bioethanol, cellulosic bioethanol produced using the inedible parts of plant materials. A number of facilities able to produce several tens of millions of gallons of bioethanol per year by means of saccharification and fermentation (microbial fermentation of sugars obtained from the breakdown of biomass) were established throughout the world between 2014 and 2015. The authors conducted research on the production of cellulosic bioethanol by means of saccharification and fermentation, and constructed a fermentation organism

displaying increased tolerance to inhibitors in order to increase the efficiency of the process as a whole.

2. Overview of Ethanol Production Process

2.1. Composition of Biomass

Plant biomass is mainly composed of cellulose, lignin, and hemicellulose (Fig. 1). Cellulose is a polymer formed

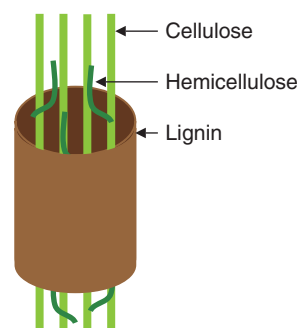


Fig. 1 Illustration of biomass structure

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by strong bonding between hexose (glucose) units via β -1,4 linkages. It supports the structure of plants as a fibrous material. Few organisms produce cellulase, the enzyme that degrades cellulose, and breaking the substance down therefore represents a challenge.

Lignin is a polymer containing numerous six-membered rings. It is strongly integrated and wraps around cellulose, forming plant structures. Hemicellulose functions to bond lignin and cellulose. Part of the hemicellulose structure contains pentose.

2.2. Composition of Process: Pre-treatment, Saccharification, Fermentation, and Condensation

Figure 2 shows a schematic overview of the bioethanol production process.

Sucrose and glucose in the juice extracted from pressed sugar cane is able to be directly used by numerous fermentation organisms. Starches in the edible parts of corn plants contain glucose units weakly bonded by α -1,4 linkages, and fermentation organisms are able to use the substances following treatment of the biomass with the low-cost enzyme amylase. Because of this, the first-generation bioethanol production process is comparatively simple.

In the second-generation bioethanol production process (termed “second-generation process” below), the integrated structure formed by cellulose, lignin, and hemicellulose is destroyed, and the cellulose is broken down and used as glucose. The challenges presented by second-generation processes originate in the strong structure of the biomass.

Second-generation processes can be broadly divided into gasification, and saccharification and fermentation methods. The saccharification and fermentation method is further divided into a number of processes.

Lignin is broken down in the pre-treatment process. Thermochemical methods are effective in the pre-treatment process, and hot water treatments, alkali treatments, and acid treatments are generally used.

In the saccharification process, cellulase is added as an aqueous solution, and cellulose is broken down into glucose. The high cost of cellulase is one of the issues of the saccharification process.

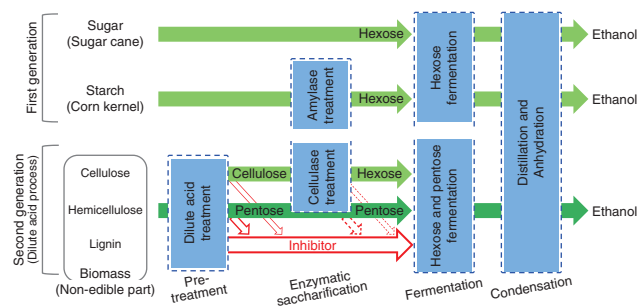


Fig. 2 Schematic diagram of bio-ethanol production process

Table 1 Characteristics of fermentation inhibitors

Category	Description	Inhibition mechanism	Countermeasure		
			Pre-treatment	Fermentation condition	Genetic modification
Phenols	Hydrophobic	Damage to membrane	Suppress production	–	–
Aldehydes	Oxidative	Oxidation of enzymes, etc.	–	–	Overexpression of ADH to reduce aldehydes
Organic Acids	Dissociation depends on pH	Damage due to change in intracellular pH	–	Fermentation pH control	Overexpression of TAL subject to damage by acetic acid

Pentose is also formed in the pre-treatment and saccharification process, chiefly originating in hemicellulose. In order to make maximum use of the biomass and increase the efficiency of the processes, it is considered necessary to use pentose for fermentation in the second-generation process. Because most organisms are unable to efficiently use pentose, this necessitates genetic modification by means of techniques such as genetic modification and mutagenesis and selection. In the fermentation process, hexose and pentose are converted into ethanol.

The condensation process involves distillation and anhydration. Because distillation uses a considerable amount of heat energy, it is desirable that the concentration of ethanol in the fermentation liquor should be high.

2.3. Fermentation Inhibitors

During the pre-treatment process, lignin and hemicellulose become denatured into a variety of substances. Some of the pentose and hexose produced becomes excessively degraded. These chemical substances include inhibitors that strongly impede the functioning of microorganisms during the fermentation process. Figure 3 shows a schematic diagram of the paths to formation of inhibitors. Because inhibitors cause a considerable decline in the yield from the fermentation process, they have a considerable effect on the ethanol production process as a whole. Table 1 provides an overview of types of fermentation inhibitors and their characteristics.

Among fermentation inhibitors, acetic acid is known

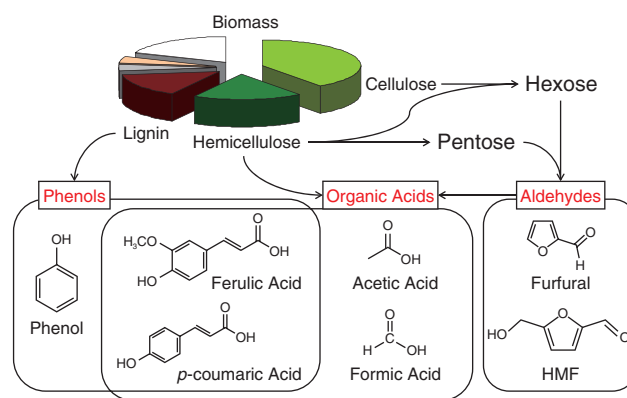


Fig. 3 Schematic diagram of production of fermentation inhibitors

to reduce the activity of transaldolase (TAL), an important enzyme in the assimilation of pentose. At the same time, the enzyme alcohol dehydrogenase (ADH) is known to reduce and attenuate aldehydes⁽¹⁾.

2.4. Types of Biomass

Research on biomass to form the raw material for the second-generation process has focused mainly on agricultural residue, including rice straw and wheat straw, corn stover (corn leaves and stalks), and bagasse (strained sugar cane lees).

In the US, where research on the second-generation process has been most vigorously advanced, expectations are high for the use of the agricultural residue corn stover (corn stalks and leaves). Estimates from data published by the United Nations Food and Agriculture Organization⁽²⁾ indicate that corn stover is the third most abundant agricultural residue in the world after rice straw and wheat straw, and it can be considered to possess considerable potential to become the main raw material for the second-generation process.

2.5. Pre-treatment Methods

A variety of pre-treatment methods are available, including hot water treatment, alkali treatment, and dilute acid treatment. Research is being advanced on dilute acid treatment methods in the US. While dilute acid treatment promotes the breakdown of hemicellulose, making the use of degradative enzymes unnecessary, it is also known to produce high quantities of the fermentation inhibitor acetic acid. High quantities of aldehydes are also observed as a result of dilute acid treatment, and pyrolysis simulations have shown this to be a result of excessive degradation of pentose and hexose.

When the volume of sugars obtained from the biomass in the pre-treatment process and the subsequent saccharification process is increased, the concentration of inhibitors also tends to increase. The fact that the pre-treatment and saccharification processes, and the inhibitor resistance of the fermentation organisms, contribute to this trade-off relationship with the fermentation yield while being mutually related necessitates the realization of fully integrated modifications.

3. Subject and Methodology of Research

3.1. Research Aim

The high cost of saccharification enzymes represents a major issue for the second-generation process. With the current level of performance of enzymes on the market as a precondition, the present research sought to reduce the volume of enzymes employed. This would necessitate powerful pre-treatment, but would also increase the volume of inhibitors produced. The aim of the research was therefore to enhance the inhibitor resistance of the fermenting organisms, that is, to increase the fermentation

yield when inhibitors were present, in order to increase the efficiency of the second-generation process.

3.2. Selection of Biomass Type and Pre-treatment Method

The selection of the type of biomass and the pre-treatment method employed determines the inhibitors, sugars, and other components of the hydrolysate supplied to the fermentation process, in addition to the characteristics of the fermentation organism demanded for the fermentation process. In order to enhance the inhibitor resistance of the fermentation organism, it is necessary to determine the target biomass type and pre-treatment method.

Corn stover was the target biomass for the present research, and dilute acid treatment was selected as the pre-treatment method.

3.3. Selection of Base Organism

The ability to naturally assimilate pentose, necessary for the realization of increased process efficiency, was prioritized in the selection of the base organism for the construction of the fermentation organism. While normal microorganisms do not possess the ability to assimilate pentose, necessitating the introduction of foreign genes via genetic modification, *Meyerozyma guilliermondii* naturally possesses this ability, making it possible to construct a non-genetically-modified organism. Even if biotechnological genetic modification was conducted, if only the genes naturally present in the organism were the subject of the process, it would be defined as self-cloning, and fall outside the purview of the Cartagena Protocol on Biosafety, which regulates genetically modified organisms, and the organism could be treated as non-genetically-modified. Given the fact that this would offer global advantages, including more ready social acceptance and simpler administrative procedures, *M. guilliermondii* was selected as the base organism for the creation of a fermentation organism.

3.4. Method of Enhancing Metabolic Pathways

It is possible to modify the reactions of a fermentation organism to sugars and inhibitors by modifying the metabolic pathways within the organism. Figure 4 shows a simplified image of the ethanol fermentation pathway in *M. guilliermondii*.

The following method of enhancing the fermentation organism's resistance to inhibitors was employed in the present research: First, a mutagenesis and selection method was applied using biomass hydrolysate, and promoters were genetically modified in those areas in which further enhancement was necessary. The mutagenesis and selection method was again applied in order to adjust the disruption of the metabolic balance caused by the genetic modification. Because promoters control the degree of expression of specific enzymes in organisms, while genetic modification would make it possible to enhance the degree of expression of the desired enzymes, it could also be expected to

disrupt the balance of the organism's network of metabolic pathways. It was predicted that adjusting the disrupted metabolic balance would make it possible to obtain a high-performance fermentation organism.

3.5. Mutagenesis and Selection

In the selective breeding of plants and animals, mutations and hybridizations are used in order to select for desired characteristics. A similar modification, involving mutagenesis and selection, is also possible in the case of microorganisms. If numerous microorganisms with mutated DNA are cultured in a medium which, for example, contains only pentose and no hexose, of all the mutant strains, only mutant strains able to assimilate pentose will survive. In addition, the fact that the organisms with the most rapid assimilation speed will overwhelm the others means that it is possible to obtain the strain with the most desirable characteristics even within the same mutation.

In order to increase the speed of mutagenesis and selection, it is necessary to artificially induce mutations with a high level of frequency. The disparity mutagenesis method makes this possible. Replication errors invariably occur when DNA is replicated in living organisms. Artificial control of this correction function makes it possible to induce mutations with a high level of frequency and at random positions in the DNA using the disparity mutagenesis method. The method uses a modified DNA repair enzyme that induces replication errors at a higher frequency, or a mutagen cocktail with the same effect.

The present research created a biomass-derived hydrolysate, and employed it in a process of mutagenesis and selection. Because this made it possible to select microorganisms displaying resistance to a real biomass hydrolysate, it was possible to create microorganisms with a high level of suitability for the process. Disparity

mutagenesis was also employed in the second process of mutagenesis and selection conducted in order to adjust the organism's metabolic networks. These processes of mutagenesis and selection using the disparity mutagenesis method were conducted by the developer of the process, Neo-Morgan Laboratory, a joint research partner with Honda.

3.6. Self-cloning

In order to further increase the inhibitor resistance of the selected fermenting organism using an actual biomass hydrolysate, genetic modification falling within the category of self-cloning was employed.

TAL occurs in the metabolic pathway for fermentation of pentose into ethanol (Fig. 4), and the reduction of this enzyme's activity in the presence of acetic acid has been reported for baker's yeast, *Saccharomyces cerevisiae*⁽³⁾. Based on metabolome analysis, it was assumed that the behaviour of TAL in the presence of acetic acid would be the same for *M. guilliermondii* as for baker's yeast. The genetic sequence in *M. guilliermondii* that displayed the closest homology with the TAL sequence in baker's yeast in a database⁽⁴⁾ was selected to enhance its expression as TAL in the organism. The goal of this enhancement of TAL expression was to increase acetic acid resistance, promote growth (promote pentose assimilation), and increase the fermentation yield. To obtain the samples used in the metabolome analysis, a culture solution was drawn off at 24 and 72 hours following the commencement of fermentation in a CS hydrolysate, and methanol was added in order to stop the biological reaction. The internal standard solution method was employed to quantify the samples.

Broadly divided, eight types of ADH are known to be produced by baker's yeast⁽⁴⁾. The considerations in selecting the ADH for enhanced expression in *M. guilliermondii* were that the reaction proceeded in a forward direction, that the enzyme possessed the ability to reduce aldehydes, and that dependence on the coenzyme NADH was assumed. The genetic sequence in *M. guilliermondii* that displayed the highest level of homology with ADH1 in baker's yeast was selected. The goal in enhancing the expression of ADH in the organism was to increase aldehyde resistance and increase the fermentation yield.

The enhancement of TAL and ADH expression in the organism proceeded as follows: A strain of *M. guilliermondii* displaying auxotrophy for uridine as the result of a natural mutation was obtained from a fluoroorotic acid containing medium. It was considered that this uridine auxotrophic strain possessed a mutation of the gene *ura3*, which codes orotidine 5'-phosphate decarboxylase⁽⁵⁾. The DNA segment shown in Fig. 5 was inserted into the site in order to simultaneously help eliminate the uridine auxotrophy by repairing *ura3* and enhance expression of TAL and ADH by means of homologous recombination. A glyceraldehyde 3-phosphate dehydrogenase promoter was employed to realize steady-state and strong expression of

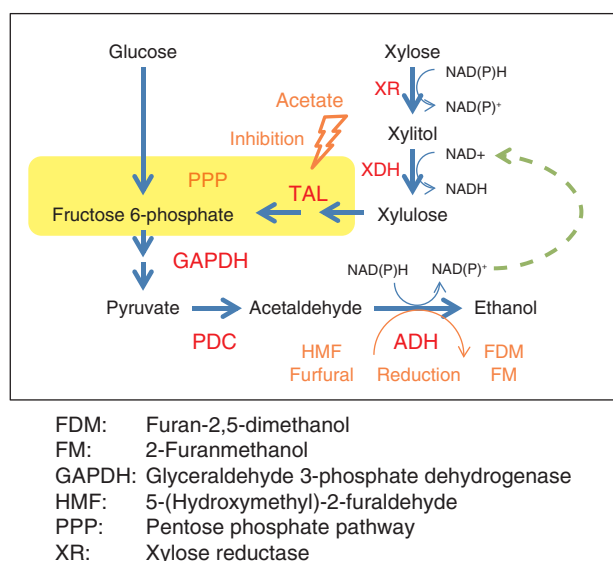


Fig. 4 Metabolic pathway of *Meyerozyma guilliermondii*

TAL. In the case of ADH, a xylose reductase promoter was employed to enhance expression of ADH in the presence of xylose. 1000 bp upstream of the initiator codon were taken as promoters, and 400 bp downstream of the termination codon were taken as terminators. Frozen-EZ Yeast Transformation II, manufactured by Zymo Research Corp, was employed for phylogenetic transformation.

3.7. Results of Mutagenesis and Selection and Self-cloning

The present research initially conducted mutagenesis and selection using a hydrolysate produced from rice straw biomass heat-treated with an aqueous ammonia solution (RS hydrolysate). This procedure produced a variety of effects, including boosting the organism's ability to assimilate pentose such as xylose and arabinose, reducing the incidence of fermentation by-products, restricting growth of yeasts and increasing ethanol production by limiting the inflow of carbon sources to the TCA cycle, and increasing expression of anti-oxidants, as determined by a metabolome analysis of the strains before and after mutagenesis and selection.

The strains produced by mutagenesis and selection were subjected to enhancement of expression of TAL and ADH realized by self-cloning. A real-time PCR analysis of the self-cloning strains showed an increase of two times in TAL expression and around 1000 times in ADH expression. In the preparation of samples for real-time PCR, an RNAqueous-4PCR Kit was used for RNA isolation and for DNase treatment, a High Capacity RNA-to-cDNA Kit was used to create cDNA, and a Fast SYBR Green Master Mix Kit was used for RNA quantification.

The metabolome analysis of the self-cloning strains indicated that the pentose phosphate pathway (PPP) had been promoted, verifying the effect in enhancing expression of TAL. The same analysis also suggested that XDH was acting as a bottleneck for PPP. This suggested that while the enhancement of ADH expression had sought to increase the supply of NAD^+ and boost XDH activity (Fig. 4), this goal had not necessarily been achieved. The fact that despite the increase of approximately 1000 times in ADH expression, the XDH bottleneck had not been eliminated, led to the conjecture that the ADH was not actually dependent on NADH.

Based on the enhanced degree of expression of ADH,

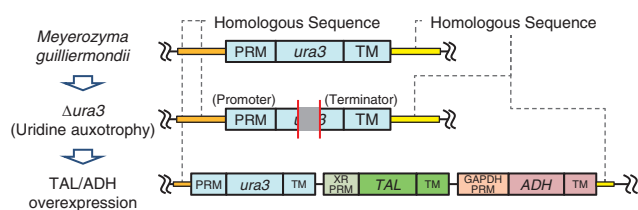


Fig. 5 Schematic diagram of DNA segment used for self-cloning

it was predicted that some imbalance would occur in the metabolism of the fermenting organism, and in fact the ethanol tolerance of all of the several self-cloning strains had declined. The mechanism of this decline in ethanol tolerance is not clear at present, but the fact that the same tendency was observed in multiple other strains displaying enhanced TAL and ADH expression strongly suggested that the self-cloning process had damaged the metabolic balance of the strains. Additional mutagenesis and selection was conducted in order to address this metabolic imbalance.

4. Performance of Fermenting Organism

4.1. Performance of Developed Fermenting Organism

In response to the decline in ethanol tolerance of the self-cloning strains, additional mutagenesis and selection was conducted with the chief aim of providing the fermentation organism with ethanol tolerance. Figure 6 shows the fermentation yield for each strain before mutagenesis and selection, after mutagenesis and selection, after self-cloning, and after the second process of mutagenesis and selection. A hydrolysate produced by applying dilute acid treatment to 20% w/w corn stover was used in fermentation tests. Because the hydrolysate contained 63.2 g/L of glucose and 34.5 g/L of xylose, including the reagent, the theoretical volume of production of ethanol was 49.96 g/L. Fermentation was conducted for 96 hr in a clear-liquid hydrolysate produced by separation of solids and fluids, and the pH was adjusted to 6.0.

The combination of positive and negative effects (promotion of the PPP, reduction of ethanol tolerance) produced by self-cloning of TAL and ADH genes alone resulted in a limited increase in the fermentation yield, but further progress was realized through the additional process of mutagenesis and selection. This demonstrated the validity of the research concept in attempting to increase the performance of the fermentation organism through a

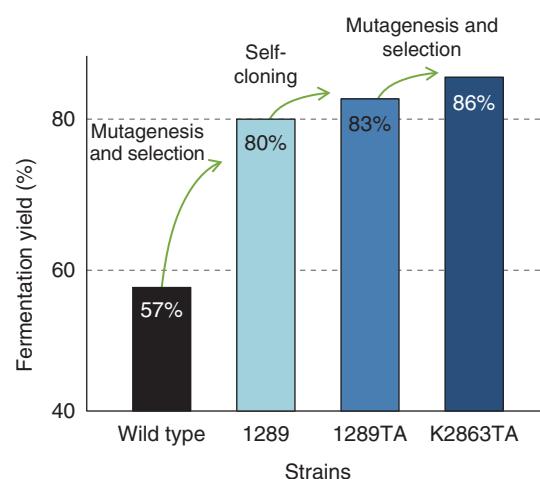


Fig. 6 Increase in fermentation yield by development of strain

combination of genetic modification and mutagenesis and selection.

4.2. Performance at Increased Scale

An ethanol production process incorporating a 5 kL fermentation tank was constructed for the research. With the increased scale of the fermentation process, factors including non-uniformity of the temperature in the tank and damage to the fermentation organisms due to agitation or high pressures at the bottom of the tank might become issues. The 5 kL process was conducted with a strain that had been selected following mutagenesis using an RS hydrolysate, like the strain 1289, and fermentation was conducted in an RS clear-liquid hydrolysate. The results obtained were almost identical to the results of a test conducted at a scale of 1 L as a contrast (Fig. 7). This result verified that the ethanol production process using the created fermentation organism could be scaled up to at least 5 kL.

4.3. Orientation of Mutagenesis and Selection and Genetic Enhancement and Realization of Increased Performance in Fermentation Organism

Fermentation tests using a single strain of the fermentation organism created via mutagenesis and selection were conducted in a slurry of corn stover subjected to dilute acid treatment. The hydrolysate with sugar concentration of more than 10% was adjusted through the addition of a reagent sugar in order to conduct tests using hydrolysates of various sugar concentrations. As Fig. 8 shows, the fermentation yield declined as the sugar concentration increased. This was due to the twin effects of an increase in the quantity of inhibitors in the hydrolysate and product inhibition, in this case inhibition by ethanol

produced by the organism. The ethanol concentration lines in the graph show the ethanol concentration in the hydrolysate following fermentation.

Figure 8 shows the line of constant production cost for the process as a whole for different fermentation yields and sugar concentrations. The closer to this line, the lower the cost at which ethanol can be manufactured. Additional mutagenesis and selection of the self-cloning strains was therefore conducted using a hydrolysate with an 8% sugar concentration, with which the fermentation yield was closest to this line. This process was successful in increasing fermentation yield at this sugar concentration.

As a response to product inhibition, mutagenesis and selection of the self-cloning strains was conducted using a hydrolysate with a sugar concentration of 11%, with tolerance to high ethanol concentrations as a selection pressure. As a result, an increase in the concentration of the produced ethanol was observed. In addition to demonstrating the necessity of setting parameters such as the composition and concentration of the hydrolysate and the concentration of the produced ethanol in advance, these cases indicate that the performance of the fermentation organism can be increased under the specified conditions.

4.4. Stress Response and Increased Fermentation Organism Performance

Integrating the results of transcriptome and DNA mutations and metabolome analyses, an analysis of the metabolic flow in the organism was conducted in order to elucidate the bottleneck in the metabolic flow. The results suggested that the developed fermentation organism went into a state of stress response when assimilating pentose. Stress response reactions seek to ensure the continued existence of the organism in the presence of stressors such as inhibitors. Product inhibition is also a cause of this stress.

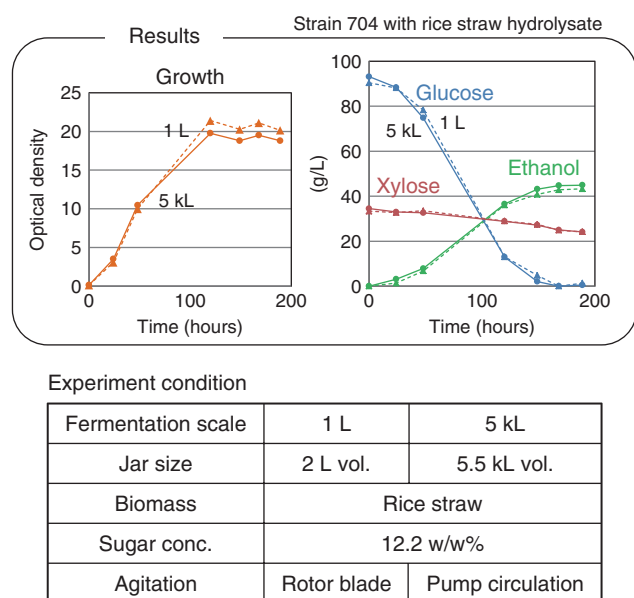


Fig. 7 Comparison of 1 L- and 5 kL-scale tests

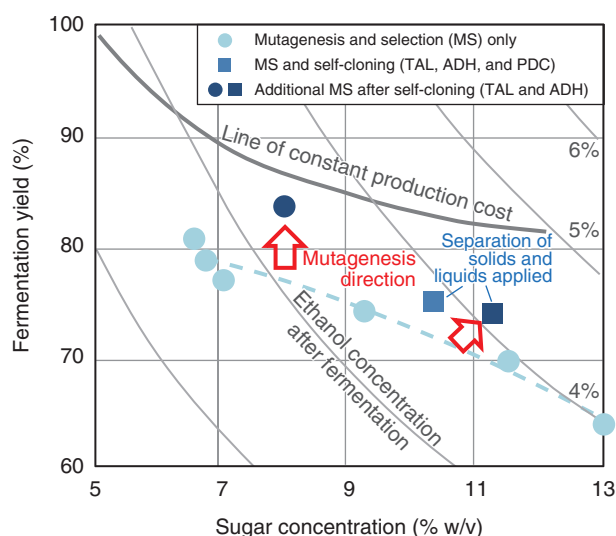


Fig. 8 Dependence of fermentation yield on sugar concentration

Death of the fermenting organisms due to the ethanol they have produced and the consequent termination of fermentation, with no reaction to product inhibition stress occurring, is a phenomenon that has been observed in baker's yeast employed in sake-making, during which fermentation produces high-concentration ethanol. It was considered that by removing this self-limitation on ethanol production due to product inhibition, that is, by forcing the organism to continue ethanol production, it would be possible to create an organism capable of the production of high-concentration ethanol. In an attempt to do so, the expression of pyruvate decarboxylase (PDC) (Fig. 4) was enhanced in addition to TAL and ADH, in order to increase the volume of ethanol production. This direction was taken because the results of a metabolome analysis had suggested that PDC represented a bottleneck following the enhancement of TAL and ADH expression. The results showed that the volume of ethanol production had been increased against the volume prior to the enhancement of PDC expression (Fig. 8), indicating the possibility that partial removal of the self-limitation on ethanol production had been realized.

It was considered that the removal of the self-limitation on ethanol production discussed above, in addition to the removal of stress responses to other inhibitors, would make it possible to create organisms that continued to ferment ethanol even in the presence of inhibitors and ethanol, and therefore to further increase the ethanol yield.

5. Fermentation Process and Overall Input and Output

5.1. Estimation of Allowable Concentration of Inhibitors and Determination of Pre-treatment Conditions

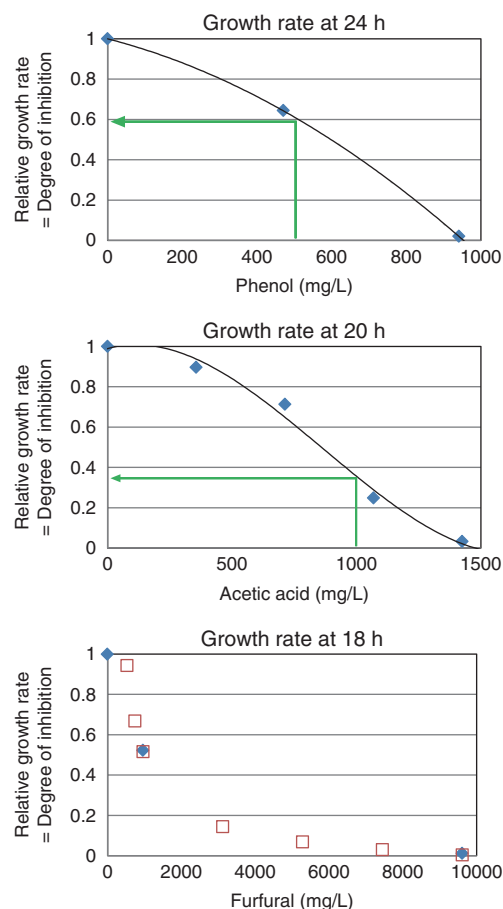
The effect of the inhibitors shown in Table 1 on retarding the growth of the fermenting organism was quantified.

First, the growth inhibition effect of each inhibitor in isolation was quantified by adding each of the inhibitors at several different levels of concentration to a synthetic culture medium considered to have no growth inhibition effect and studying the resulting degree of inhibition (Fig. 9). The fact that phenols, aldehydes, and organic acids display different inhibition mechanisms (as shown in Table 1) is reflected in the differences in the curves expressing the relationship between the concentration of the added inhibitor and the number of fermenting organisms after a fixed period of time. The effect of each inhibitor on the growth of the organisms can be read from these curves. For example, 500 mg/L of phenol added to the medium has the effect of slowing the organism's growth rate to around 0.6 times the rate in the synthetic culture medium. 1000 L of acetic acid slows the growth rate to 0.35 times the rate in the synthetic medium. The combined effect of the presence of both substances in the medium at these concentrations can be approximated as the product of these two figures,

or $0.6 \times 0.35 = 0.21$ times the growth rate in the synthetic medium. In this way, the effect of inhibitors in retarding the growth of the organisms was quantified through measurement of the concentration of the inhibitor in the hydrolysate.

This method of estimation uses the product of the concentration of each inhibitor for the sake of simplicity, and is not able to encompass the presence of all of the inhibitors. There are therefore limits to its accuracy. Because of this, an attempt was made to increase accuracy by means of parameter fitting, with parameters set as follows: First, the quantified phenols (substances that occur in a large number of types, and are therefore difficult to quantify) were multiplied by a fixed amount. The effect of Maillard reaction products, which are normally indicated as having an inhibition effect, was also set at a fixed value.

Because this estimation method made it possible to study the balance of inhibitors in a biomass hydrolysate, upper limit amounts for allowable concentrations of *p*-coumaric



Vertical axes indicate standardized growth rate.
(Culture OD with X mg/L inhibitor ÷ Culture OD without inhibitor)
Typical examples of phenols, aldehydes, organic acids are shown.
Optical density (610 nm) at ca. 20 hours was measured.
Organic acid concentration was multiplied by the dissociation constant for estimation of the concentration upper limit, in order to reflect the actual inhibition effect.

Fig. 9 Estimation of upper limit for inhibitor concentration

Table 2 Process conditions

Pre-treatment	Corn stover	Dry biomass ground to 3 mm pieces Mix at ratio of biomass : 2.5 % w/v Dilute acid = 1:2 Maintained at 170°C for 10 minutes
	Rice straw	Dry biomass ground to 3 mm pieces Mix at ratio of biomass : 25 % w/v aq. ammonia = 1:0.7 Maintained at 80°C for 3 hours
Saccharification	Substrate: 16.4 % w/w Enzyme: 0.4 mg/g-BM Maintained at 50°C for 72 hours at pH 5	
Fermentation	Substrate: 14.0 % w/w Sugar concentration: 6.2 % w/w Maintained at 30°C, at 28 mg/L/h aeration for 67 hours at pH 6	
Quasi-SSF	Saccharification and fermentation changed as follows Saccharification: 72 → 20 hours + 4 hours cooling Fermentation: 67 → 76 hours Process hours: 139 + cooling time → 100 hours	

acid and other phenols were determined. It is challenging to respond to the effects of phenols by means of fermentation conditions or genetic modifications, making it necessary to control the amount of phenols that are generated (Table 1).

The relationship between inhibitors and the amount of sugar produced for differing dilute acid treatment conditions (concentration, temperature, time) was examined via pyrolysis simulation, and pre-treatment conditions that would help to ensure that the amount of inhibitors remained below the upper limit and a high concentration of sugar was obtained were determined (Table 2).

The study of conditions in the entire process, including pre-treatment and saccharification, and measures for the enhancement of the inhibitor tolerance of the fermenting organism in parallel in this way made it possible to create a fermenting organism capable of use in the second-generation process.

5.2. Sugar Concentration of Hydrolysate and Fermentation Yield

Cost reductions in each constituent process will be necessary in order to realize practical application of the second-generation process. This necessitates increased efficiency, but in many cases efficiency in one process comes in a trade-off relationship with efficiency in another process. In addition to the relationship between inhibitor concentration and sugar concentration discussed above, other relationships within the second-generation process include the fact that it is not possible to control the total cost of the process if the quantity of saccharification enzymes is increased in order to enhance the sugar yield, and that if the sugar concentration is low, the ethanol concentration will also be low, increasing the distillation energy used.

Given this, it was decided to conduct a parameter study to determine the change in the entire cost when conditions in each process were changed, in order to identify the conditions that minimized the cost. A consideration of the line showing a constant production cost in relation to changing fermentation yields and sugar concentrations in Fig. 8 indicated that when the fermentation organisms

shown on the blue line were used, fermentation at sugar concentrations around 7 to 8% was closer to the line of constant production cost than fermentation at around 11%, and this controlled the total cost of the process. The form of the line of constant production cost shows that there is a limit to the cost reduction achievable by lowering the sugar concentration. The realization of further reductions in total cost would necessitate increasing the fermentation yield at high sugar concentrations in order to reduce distillation energy and equipment cost.

5.3. Realization of Quasi-SSF Process

Simultaneous saccharification and fermentation (SSF) is a process available for the production of bioethanol. In this process, conducting enzymatic saccharification and ethanol fermentation simultaneously in the same vessel makes it possible to reduce the time needed for the process. In addition, because fermentation is conducted using a slurry without the need for separation of solids and liquids following the saccharification process, SSF makes it possible to integrate the saccharification and fermentation tanks, and to omit the solid/liquid separation process, thus reducing initial costs.

In SSF, the conditions for saccharification and fermentation are identical. However, because there was a considerable difference between the optimum conditions for the saccharification enzyme (50°C, pH 4) and the fermentation organism (30°C, pH 6) employed in this research, saccharification and fermentation under entirely identical conditions were not practicable. The potential of a quasi-SSF process, in which saccharification and fermentation were conducted successively in the same vessel, was therefore examined. A special apparatus of 3 L was constructed for the process. Following enzymatic saccharification for 20 hr, the temperature was reduced and the pH adjusted, and the fermentation organism was added to conduct fermentation. This procedure indicated that quasi-SSF was able to reduce the time needed for the process by 39 hr and increase the efficiency of the equipment (Table 2).

5.4. Material Balance

The material balance and energy balance of the bioethanol production process is also strongly dependent on the processes other than enzymatic saccharification and ethanol fermentation. An NREL report⁽⁶⁾ was referred to in calculating the material balance of the bioethanol production process in this research. The material balance was calculated based on the assumption that all energy for the production process was supplied by methane fermentation using fermentation residues or the combustion of the residues for generation. When the total cellulose and hemicellulose content of the corn stover employed was 57% w/w, the sugar yield from enzymatic saccharification under the conditions shown in Table 2 was 63% and the fermentation yield from the quasi-SSF process was 86%.

It was calculated that following the subsequent distillation and condensation processes, 1 dry-ton of biomass would ultimately yield 213 L of anhydrous ethanol.

6. Conclusion

The research discussed in this paper produced the following results:

- (1) Using a pentose-assimilating yeast as the base organism, an ethanol fermentation organism able to be used in the second-generation process with the status of a non-genetically-modified organism was created.
- (2) Under the conditions employed in this research, including the use of the developed fermentation organism, 1 dry-ton of corn stover containing a total of 57% w/w of cellulose and hemicellulose produced 213 L of ethanol.

The research generated the following findings:

- (1) The combination of genetic modification and mutagenesis and selection is effective in the construction of fermentation organisms. The research indicated the necessity not only of modifying known enzymes, but also of modifying the entire network of metabolic pathways, including unknown enzymes.
- (2) It is not practicable to create all-purpose fermentation organisms able to respond to any hydrolysate; fermentation organisms specialized for specific biomass types and processes are necessary, and these organisms should be created following the restriction of process conditions.

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Research on Production of Cellulosic Ethanol – Creation of Novel Saccharifying Enzyme –

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Maiko FUKUURA**

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ABSTRACT

The cost of saccharifying enzymes is one of the factors hindering the practical use of cellulosic bioethanol. In an attempt to address this issue, research has been conducted to create a novel saccharifying enzyme, in parallel with efforts to reduce the quantity of the enzyme used and the cost of production of the enzyme.

Reduction of the quantity of the enzyme used involved the creation of an original saccharifying enzyme mixture that did not include any unnecessary enzymes. In addition, genetic engineering techniques were applied in order to substitute an amino acid sequence in the enzyme that formed the main constituent, increasing enzyme activity.

Reduction of the cost of production of the enzyme involved utilizing the biomass employed in the ethanol production process as a carbon source, and employing an onsite enzyme production process exploiting solid-state fermentation, a high-efficiency production method. An original enzyme-producing strain of *Aspergillus oryzae* was created in order to realize this process.

The two outcomes discussed above represent new findings with the potential to reduce the cost of saccharifying enzymes for bioethanol production.

1. Introduction

The use of bioethanol represents one response to concerns over the depletion of fossil fuels and the necessity for the reduction of CO₂ emissions. The first generation of bioethanols were produced using starch from the edible parts of plant materials. Research is proceeding in order to make practical the use of second-generation cellulosic bioethanol, produced using the inedible parts of plant materials. Saccharifying enzymes are protein catalysts that catalyze the reaction that breaks down the cellulosic biomass and forms the glucose that fermentative bacteria use to produce ethanol. Cellulose has a strong structure, and high quantities of enzymes are needed in order to break it down. Despite years of research and development efforts by specialist manufacturers, the cost of these enzymes is 10 times or more that of the saccharifying enzymes used in the production of conventional starch-based bioethanol^{(1), (2)}. The high cost of saccharifying enzymes is a factor that hinders the practical use of cellulosic biofuels.

The authors therefore advanced research towards the development of a novel and innovative saccharifying

enzyme able to reduce costs.

In addition to explaining the aims and characteristics of the research process, this paper will discuss the performance of the developed novel saccharifying enzyme and saccharifying enzyme-producing microorganism, how their use reduces costs, and the findings obtained in the research process.

2. Development Goals

The cost of saccharifying enzymes can be easily visualized by terming the cost for producing 1L of ethanol as C (Unit: Yen/L-ethanol). The cost of the enzymes can then be determined using the following equation (Fig. 1):

Here, A: Quantity of enzymes used (g/kg-biomass);

$$C = \frac{\text{Enzyme cost for 1 kg biomass (¥)}}{\text{Ethanol produced from 1 kg biomass (L)}} = \frac{A \times B \times G}{D \times E \times F}$$

Fig. 1 Breakdown of enzyme cost

* Fundamental Technology Research Center

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B: Unit cost of enzyme production (Yen/g-protein); D: Sugar content of biomass (kg-monosaccharide equivalent/kg-biomass); E: Saccharification rate (kg-recovered/kg-origin); F: Fermentation efficiency (kg-ethanol/kg-glucose); G: Specific gravity of ethanol (kg/L). The sections of the equation shaded in pink show the amount of ethanol produced from 1kg of biomass. This figure is constant, determined by the necessary conditions for the process, including the rate of conversion of biomass to glucose (the saccharification rate), and physical constants. The variable section, which can be modified in order to reduce the cost of the enzymes, is therefore the area shaded in blue, the product of the quantity of enzymes used and the unit cost of enzyme production. Two orientations, the reduction of quantity used and the unit cost of production, are available for reducing the cost of the enzyme.

The research discussed in this paper focused on both orientations in conducting biochemical research and development. Specifically, in seeking to reduce the quantity of enzymes used, the research attempted to increase the catalytic activity of the saccharifying enzyme, while in seeking to reduce the unit cost of production of the enzymes, the research attempted to increase the productivity of the enzyme-producing microorganisms. From the next chapter onwards, this paper will discuss the details of the research and its outcomes.

3. Measures to Reduce Quantity of Enzyme Used

3.1. Manufacture of Novel Enzyme Mixture

Saccharifying enzymes are secreted by microorganisms (bacteria and fungi) to enable them to consume biomass as a source of nutrition. These microorganisms are cultured on a large scale industrially, and the saccharifying enzymes that they produce are isolated and concentrated. Natural microorganisms secrete more than 30 types of enzymes simultaneously. These enzymes can be broadly divided into five groups with different functions, as shown in Fig. 2 and Table 1.

Multiple types of enzymes fall into the same groups, due to the fact that enzyme groups with slightly differing functions are necessary in order to respond to the diverse range of biomass sources occurring in the natural world. However, it is normally the case that when bioethanol is produced industrially, the biomass employed as the raw material is limited to a single type. Considerably fewer enzyme types may thus be required than the over 30 types found in natural microorganism. The present research therefore set out to reduce the quantity of enzymes used by omitting the enzymes that were unnecessary for the target biomass type. Rice straw in which the saccharification process had been promoted through immersion in ammonia water was used in the experiments as biomass.

In order to verify the working hypothesis that omitting unnecessary enzymes would make it possible

to reduce the quantity of enzymes used, unnecessary enzymes were omitted from enzyme groups secreted by three microorganisms (*Acremonium*, *Thermoascus*, and *Thermotoga*) to create an enzyme mixture tailored to rice straw. For the selection of the enzymes, a process of fractionation based on differences in the surface charge of the molecules in each enzyme and the subsequent selection of fractions shown to be effective in rice straw saccharification experiments was repeated (Fig. 3).

As a result of this process, one enzyme was selected from each of the enzyme types shown in Fig. 2 and Table 1 to create an enzyme mixture using a total of five enzymes. In addition, the ratio of constituent enzymes was changed and further rice straw saccharification experiments were conducted, in order to determine the optimum ratio. Figure 4 shows the saccharification activity of the mixture. The biomass saccharification activity of the synthetic mixture was approximately 2.5 times greater than that of a natural *Acremonium* culture solution.

These results demonstrated the validity of the initial working hypothesis that it would be possible to reduce the quantity of enzymes used by omitting unnecessary enzymes.

3.2. Enzyme Amino Acid Substitution

The research next sought to increase the activity of the enzymes making up the synthetic mixture. Amino acid substitution was employed as the method. Enzyme molecules are formed from polymers that take fixed three-dimensional structures, as shown in Fig. 5. These polymers are proteins, and their component monomers are amino acids. There are 20 types of amino acids that make up enzymes, and the three-dimensional structure and catalytic activity of the enzyme are determined by their arrangement. It is known that the substitution of part of the amino acid sequence of a natural enzyme into another sequence can result in either a decline in performance or increased activity. Tests were conducted focusing on CBH1, the main constituent (weight composition: 47%; see Table 1) of the novel saccharifying enzyme mixture discussed in the previous section. Figure 5 shows the molecular structure of CBH1. CBH1 is a polymer made up of 550 linked amino acids, with a central hollow section resembling a tunnel. Multiple polar and highly hydrophobic amino acids exist on the surface of this hollow section. The formation of non-covalent bonds with these amino acids

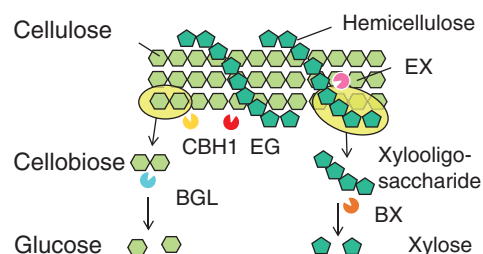


Fig. 2 Functions of components in enzyme mixture

Table 1 Composition of enzyme mixture

Enzyme group	EG: Endoglucanase	CBH1: Cellobiohydrolase 1	BGL: Beta-glucosidase	EX: Endoxylanase	BX: Beta-xylosidase
Function	Cuts the surface of crystalline cellulose to create nicks	Cleaves out cellobiose at reducing end of cellulose chain	Cuts cellobiose into glucose	Cuts hemicellulose into xylooligosaccharide	Cuts xylooligosaccharide into xylose
Original organism	<i>Acremonium</i>			<i>Thermoascus</i>	<i>Thermotoga</i>
Weight percentage (%)	24	47	24	4	1

incorporates cellulose chains into this hollow section of the enzyme, cleaving the chains. The number of possible amino acid substitutions is 19^{50} , ruling out a test of each one. Thirty sites at which amino acids on the surface of the hollow section of the enzyme were in contact with the cellulose chain were therefore identified using computer

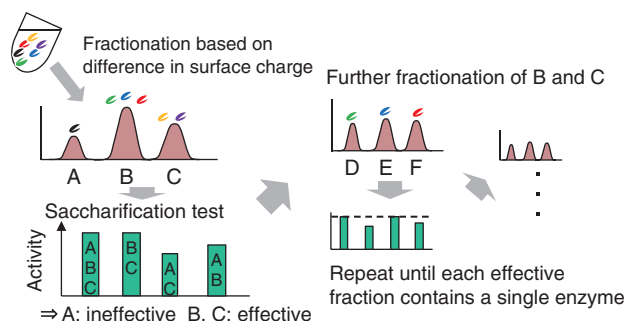


Fig. 3 Scheme of enzyme selection

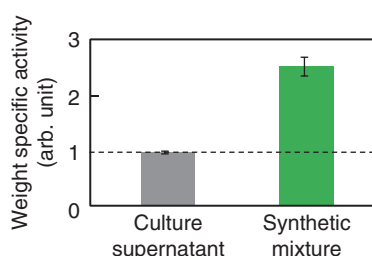


Fig. 4 Specific activity of novel enzyme mixture

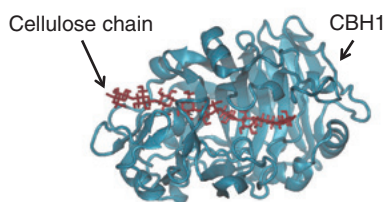


Fig. 5 Molecular structure of CBH1 and cellulose chain

modelling, and each amino acid was replaced by alanine, a separate amino acid. Changes in activity resulting from these substitutions were investigated. It was thought that because alanine did not possess the polarity or high level of hydrophobia of the amino acid prior to the substitution, the substitution of alanine would increase activity in cases in which the pre-substitution amino acid had a negative effect on activity. As Fig. 6 shows, of the 30 substitution products, three displayed higher activity than the pre-substitution wild type (WT). Figure 6 shows the six highest values for activity. With regard to nomenclature, N062A, for example, indicates that the 62nd asparagine molecule (N) from the end of the sequence has been substituted with an alanine molecule (A). This was the substitution product displaying the highest level of activity, approximately 7.8 times higher than that of the WT.

The results of a molecular dynamics simulation of the process of incorporation of the cellulose chain into the hollow section of CBH1 showed that the substitution of the amino acid that formed hydrogen bonds with the cellulose chain in the WT with alanine promoted the incorporation of the cellulose chain by the interior of the enzyme molecule, and that this was a factor in the increased activity of the substitution product.

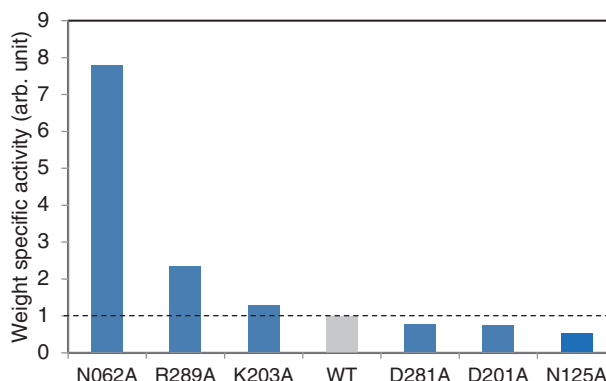


Fig. 6 Specific activity of CBH1 mutants

4. Measures to Reduce Unit Cost of Enzyme Production

4.1. Concept for Onsite Production Process

The production process shown in Fig. 7 was selected in order to make it possible to produce the novel enzyme discussed in the previous chapter at a low cost. In the normal process, a homogeneous sugar solution is used as a source of nutrition for the culturing of the enzyme-producing microorganisms, and the microorganisms are cultured in a liquid state. This technique helps to enable the mass production of enzymes of a uniform quality. Given that the purpose of the present research was to produce enzymes that would be used in the process of production of ethanol from biomass, it was thought that it would be possible to use the biomass that formed the raw material for the ethanol as a source of sugar for the microorganisms, rather than a high-cost homogeneous sugar solution, by means of annexing the enzyme production line to the main process (onsite production). In addition, because the biomass is solid, solid culturing of the microorganisms in the biomass itself would be more suited to onsite production than liquid culturing. Given that solid culturing can be conducted in an area smaller by the volume of the liquid medium than liquid culturing, solid culturing would make it possible to reduce equipment costs.

4.2. Creation of Original Enzyme-producing Microorganism

A suitable microorganism was necessary to make possible the onsite production process discussed above. *Aspergillus oryzae* was selected for the research under discussion. Solid culturing techniques using *A. oryzae* are well advanced in Japan as a result of their application in

Table 2 Comparison of candidates for enzyme production host

Organism	<i>E. coli</i>	<i>B. subtilis</i>	<i>P. pastoris</i>	<i>A. oryzae</i>
Capable of phenotypic transformation?	Yes	Yes	Yes	Yes
Capable of solid-state fermentation?	No	Yes	No	Yes
Capable of CBH1 production?	No	No	No	Yes

the production of fermented foodstuffs such as sake and miso. In addition, techniques for genomic modification and phenotypic transformation of *A. oryzae* have basically become established, making it possible to engineer the production of foreign enzymes not originally secreted by the organism⁽³⁾.

As numerous varieties of *A. oryzae* exist, research first focused on screening. Fifteen varieties of *A. oryzae* were obtained. The enzyme secretion volume of these varieties in a solid rice straw culture was compared, and the variety with the highest secretion volume was selected.

Next, CBH1, the amino acid discussed above, was introduced to the genomic DNA of this strain of *A. oryzae* using a technique known as homologous recombination, and it was determined that the organism was capable of producing it (Table 2). Three other microorganism varieties employed as a comparison did not produce CBH1, further demonstrating the validity of selecting *A. oryzae* as a novel enzyme-producing microorganism.

The enzyme secretion volume of this strain of *A. oryzae* was further increased by reading its entire genome sequence and, based on the information obtained, artificially deleting

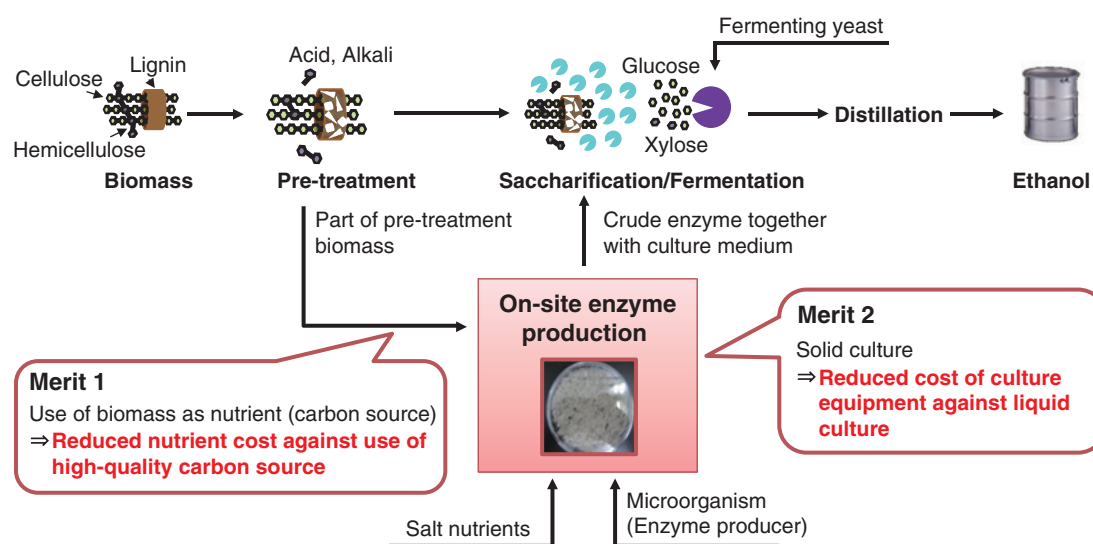


Fig. 7 Scheme of enzyme production

5. Effect on Cost

three genes considered to impede enzyme secretion. As a result, as shown in Fig. 8, it was possible to create a strain able to produce 1.5 times the CBH1 volume of RIB40, the standard strain of *A. oryzae* used in making sake⁽⁴⁾.

In addition, when the characteristics of the new strain were investigated, it was found to display tolerance to the inhibitory effect on the growth of microorganisms of the low-molecular-mass compound furfural, which detaches from lignin, a component of the biomass. Figure 9 shows a comparison of the furfural tolerance of the developed novel enzyme-producing microorganism with that of RIB40, using the volume of production of CBH1 as the index. RIB40's production of CBH1 declines to approximately 40% in the presence of furfural, while furfural has almost no effect on the novel organism. The characteristics displayed by the novel enzyme-producing microorganism can be considered to represent a considerable advantage for solid culturing of the organism in biomass.

An investigation of factors producing the organism's furfural tolerance based on the results of a comprehensive analysis of its genome and intracellular substances (RNA analysis, metabolome) indicated the possibility that there had been changes in its capacity to adapt to intracellular oxidative stress, as well as changes in the speed of the protein synthesis reaction. These results can be considered important findings about the molecular biology of *A. oryzae*.

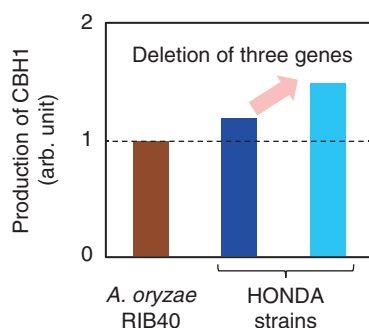


Fig. 8 Production of CBH1 by HONDA strains

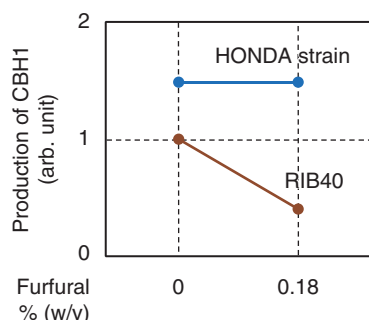


Fig. 9 Tolerance against furfural of original strain

Measures to reduce the volume of enzyme use and production cost have been discussed above. These measures have been evaluated from the perspectives of saccharification activity and production volume respectively. The higher the values of these parameters, the lower the volume of enzymes used and the lower the production cost, and therefore ultimately the lower the cost (Fig. 1).

While investigating the level of performance against the protein mass of standard market enzymes used in the production of cellulosic bioethanol, the present research found that the highest level of performance was approximately equivalent to that of a natural *Acremonium* culture solution. The novel enzyme mixture created in this research displayed 2.5 times the level of activity of a natural *Acremonium* culture solution (Fig. 4). A simple calculation indicates that it would be necessary to use 1/2.5th the quantity of this enzyme to realize the same level of saccharification performance as the highest-performing market enzyme. Assuming, because *Trichoderma*, the market enzyme-producing microorganism, is the same type of filamentous bacterium as the novel enzyme-producing microorganism (a fungus), that the unit price is the same (from Fig. 1), the cost of the enzymes produced by the novel microorganism will also be 1/2.5th that of enzymes produced by *Trichoderma*.

The amino acid-substituted mutant created in this research that displayed the highest level of activity in relation to CBH1 realized a level of activity approximately 7.8 times that of the WT (Fig. 6). Because the CBH1 WT represents 47% of the total mass of the enzyme mixture (Table 1), calculations show that the use of the amino acid substitution product displaying the highest level of activity would reduce the amount of enzyme used by 41% ($=47 - 47 / 7.8$) while maintaining the performance of the enzyme mixture. Based on the considerations indicated above, this should also reduce costs by 41%. In actuality, the volume of production of the amino acid substitution product displaying the highest level of activity by *A. oryzae* was low, and its effect on reducing the quantity of the enzyme mixture required has not been verified.

The cost-effect ratio of the use of the novel enzyme-producing microorganism cannot be discussed directly, because it is dependent on the production process. However, assuming that the same production process is employed, the enzyme-producing microorganism created in this research produces 1.5 times the CBH1 volume of RIB40, the standard *A. oryzae* strain used widely in the food industry. A simple calculation shows that the unit cost of enzyme production for the novel organism is 1/1.5.

Based on the above, the novel enzyme mixture and novel enzyme-producing microorganism created during this research can be expected to contribute to reducing the

cost of saccharifying enzymes used in the production of bioethanol.

6. Conclusion

Research has been conducted towards the realization of an innovative low-cost enzyme able to assist in the practical use of cellulosic bioethanol. This research produced the following outcomes.

- (1) A novel enzyme mixture created by removing unnecessary enzymes from a mixture produced by natural organisms displayed approximately 2.5 times the saccharification activity of a natural *Acremonium* culture solution. In addition, amino acid sequence substitution in CBH1, the main constituent of the enzyme mixture, increased catalytic activity by approximately 7.8 times.
- (2) A novel enzyme-producing strain of *A. oryzae* able to be solid-cultured in biomass was created in order to make it possible to realize an onsite production process. This strain of *A. oryzae* was able to produce 1.5 times the volume of the enzyme as RIB40, the standard strain.

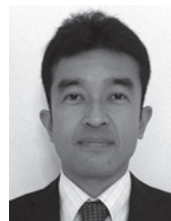
These results demonstrate that a technology has been developed that will make it possible to reduce the cost of saccharifying enzymes in bioethanol production.

The techniques employed during this research were highly reliant on genetic engineering techniques that have displayed striking progress from the 1980s onwards. In the future, the value of applying these techniques in fields other than those of the environment and energy can be expected to further increase.

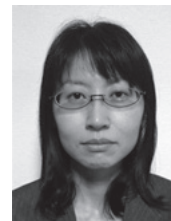
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Editorial Afterword

While the world's population continues to grow, populations are also aging, in particular in the advanced nations. The speed of development of information and communication technologies has far outstripped the speed of human mobility, and the technologies continue their evolution without pause.

The field of mobility is the scene of active development of a diverse range of methods to reduce the burden of mobility on the global environment, and of extensive creation of new value through the realization of increased digitalization and smarter functions. Efforts are also being made to develop the necessary technologies and services for these processes.

The technologies that we use today are the crystallization of the efforts of our predecessors, and it is not an easy matter to go beyond their achievements. Yet we continue in our efforts, seeking to surpass our predecessors and our own former selves, believing in our role as researchers and the developers of new technologies and products. The products and services that we develop will be judged fairly but strictly by the public. It is my hope that Honda engineers will make vigorous use of the Honda R&D Technical Review as an opportunity for global communication regarding the technologies born from their development efforts. Through this forum, I want us to communicate to as many people as possible throughout Honda and the world what our aims are, what issues we face in their realization, and what methods we use to overcome those issues.

Hisato Tanaka

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