

Honda R&D

Technical Review



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Comment on the Cover

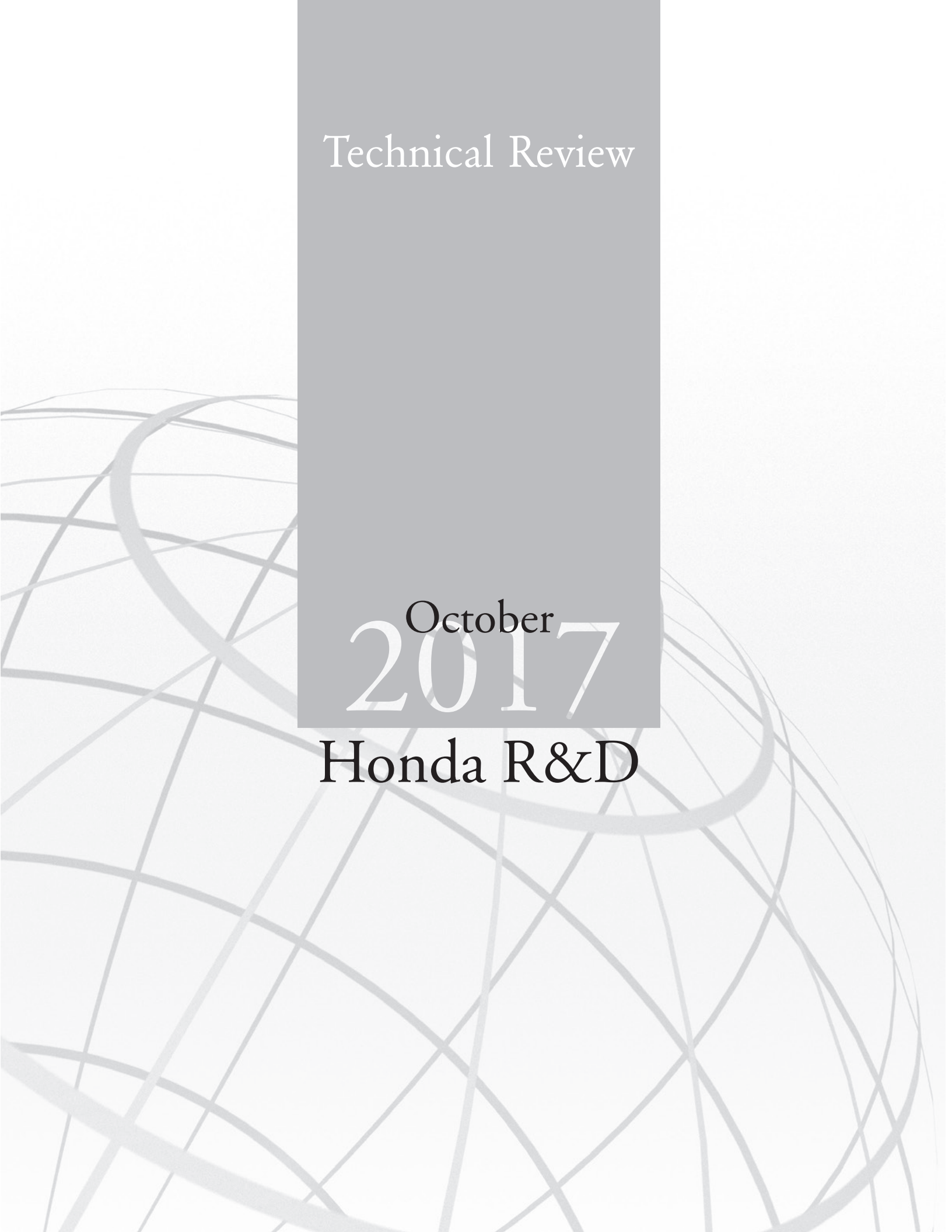
This issue's cover design shows a combustion chamber from an automotive engine.

The cylinder head combustion chamber features extremely smooth forms, forms that clearly reflect the intention of their creators.

Tracing a hand over the surfaces of this combustion chamber while imagining that the thoughts of engineers, grappling on a daily basis with fluids, have shaped these forms, is both intriguing and moving.



Power Products R&D Center
Michihito OKADO

The background features a light gray wireframe sphere on the left side. A solid gray vertical bar is positioned in the center, containing the text. The overall color palette is monochromatic, using shades of gray and white.

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Styling Design of CBR250RR

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ABSTRACT

The CBR250RR had been developed as a new 250 cc super sports model. This model targeted Indonesia where the motorcycle market of 250 cc or larger engine displacement models is being activated, as well as Japan where 250 cc motorcycle category has been established and matured. In designing this model, the basic concept was set as “Attractive styling,” “Attractive equipment” and “Attractive performance,” which are realized by its feel of presence, design and equipment that do not look inferior compared to larger motorcycles. Under this concept, we set the keyword “Speed Shape” to the designing of its styling. In order to realize that, the design team and the vehicle development team repeatedly studied from the early stage of development, and we designed it starting with the layout of the basic skeleton. In addition, this “attractiveness” was defined as the foundation of the concept in coloring as well, and five types of color lineup were prepared individually responding to a variety of customers’ preferences. Through these styling designs and coloring we achieved the desired design goal of “attractive styling.”

1. Introduction

The CBR250RR is a new motorcycle model developed by Honda as a 250 cc super sports model (Fig. 1). The name CBR250RR was once used in a road sports bike released in Japan in 1990 (Fig. 2). Speaking of CBR250RR at that era, it was a model having advanced equipment and cutting edge sporty design, and was a motorcycle that young people eagerly longed for. What inherited from this model is not only the name. The vehicle design concept of “Super sports CBR250RR worthy of being admired” itself has also been inherited.

Along with the transitions in time for a quarter century since 1990, there have been major changes in motorcycle markets on a global scale. One of those changes is the increase in sales of large motorcycles of 250 cc or more in Asian countries where people’s economic power has been enhanced. Notably in Indonesian market, where a large motorcycle market has been growing vigorously, an authentic road sports bike of 250 cc displacement has begun to be sought, especially by wealthy young group of customers.

As for the Indonesian traffic environment, it is chronically congested in city areas such as in Jakarta and it is usually experiencing flooding on roads in rainy season as well. As a means of traveling in such an environment, the mainstream motorcycles are commuter motorcycles such as scooters. At the beginning of the development of



Fig. 1 The CBR250RR

* Motorcycle R&D Center

this model, a market research was conducted in Indonesia to clarify why the sales of motorcycles having an engine displacement 250 cc or larger increased in recent years in spite of the aforementioned circumstances.

First, we visited high-class shopping malls in a big city where large motorcycles congregate, and we surveyed the riders gathered here. They are young wealthy people living in a large city, and when the traffic decreases at night, they gather on high-class shopping malls and cafés with friends by motorcycles. They are the members belonging to such a motorcycle community (Fig. 3). According to information from them, there are many such communities in Indonesia in metropolitan areas. Their behaviors are to arrange their own motorcycles side by side for boasting of in a prominent place, to enjoy conversation, and, afterwards, to flow down the streets of the night.

From the interviews and other surveys, the difference in attributes was clear between the users of commuter type motorcycles, such as scooters, who are judging the value

based on the practical usability and the users who find values in self-expressions and pay money for it.

In developing a new authentic 250 cc super sports model, it was a clear task to aim for a styling and equipment with a sense of presence that is never ever inferior compared to large sports motorcycles. In order to meet the demand those customers make, we adopted advanced and attractive equipment such as Throttle by Wire (TBW), which was first adoption in this vehicle class, and Accelerator Position Sensor (APS). In addition, it was aimed to create a product that meets user needs at the high level, by applying equipment and vehicle grade beyond the class, such as inverted front forks and aluminum swing arms, which are usually adopted in large sports motorcycles.

The direction derived from the results of these market surveys was the realization of a motorcycle highly characterized for satisfying the desire of showing off (boasting of) their motorcycles that can adequately show the attractiveness, presence and value when they show their motorcycles in the gathering places. As the concepts of the vehicle, three of them, which are “fascinating styling,” “fascinating equipment” and “fascinating performance,” have been established.

In these vehicle concepts, the term “fascinating” is commonly used. Meanwhile, many Japanese users have experienced riding various 250 cc class motorcycles so far and are familiar with this class of motorcycles. We thought that this sense of value, i.e. “fascinating,” could get empathy from such users in Japan too, and we have been confident that it is a concept common to both Indonesian and Japanese markets. With that confidence, we promoted the development. In this paper, we will mainly describe the “fascinating styling” that is one of the development concepts of this motorcycle.

2. Fascinating Styling

“Attractive styling,” which is one of the vehicle concepts, refers to styling that stands out enough for showing off. That is, the targeted styling is the one that can make the viewers of the vehicle feel “he or she is riding an amazing motorcycle.” However, when considering “showing off” a motorcycle, the points to be presented as a unique property and features of each motorcycle will be different depending on what category that motorcycle belongs to. The points to be appealed for “showing off” ought to be different between, for example, such as a tourer type motorcycle with luxurious equipment (Fig. 4) and an American cruiser type motorcycle (Fig. 5) with beautifully shining chrome plating. As for a motorcycle in the category of super sports type (Fig. 6), first priority is given to the looks of being able to run fast regardless of who see it. Furthermore, it is important to make the viewer intuitively recognize its presence and value.



Fig. 2 The CBR250RR, 1990 model



Fig. 3 Riders of motorcycle community



Fig. 4 Example of tourer type motorcycle with luxury equipment (GOLDWING)



Fig. 5 Example of American cruiser type motorcycle (VT1300CX)



Fig. 6 Example of super sports type motorcycle (CBR1000RR SP2)

3. Styling Keyword - Speed Shape -

Super cars were the first thing imagined as the most easy-to-understand example of “attractive style” to satisfy target user’s requirement for “showing off.”

Even when it is stationary, it engenders the appearance of having potential performance hidden within, and from its posture, it emits the atmosphere that it could run fast. Based on the features thus defined, the styling keyword was determined to be “Speed Shape.” Figure 7 shows the concept board of the styling design to help them understand the keyword with images.



Fig. 7 Concept board of “Speed Shape”

4. Deepened Approach for Styling Design - Efforts for Defining from the Basic Skeleton -

The word “Styling” used in this study is a process of designing for the outline enclosing the interior. In addition, elements which influence the proportions in the outline are regarded as the factors involving in the basic skeleton.

This styling keyword “Speed Shape” evolves into wedge shape, which is one of the typical examples of shape forming expression for, so-called, sense of speed. In order to achieve that wedge shape, having the front nose postured low and the tail elevated high is important (Fig. 8). In order to realize that, it was necessary to step on the basic skeleton (Fig. 9), such as the arrangement of each functional part, the mounting position of the engine and the frame enclosing them.

In many cases, in the process of a development thinking of achievement of the target performances, when styling design is to be worked on, the approximate skeleton with basic layout is already determined, or the skeleton of the other base model is to be applied. In order to realize “Speed Shape,” we thought that the entire development team, including the designers responsible for functions and performances and the test riders, needs to deeply engage in the design of the basic skeleton

We decided to start our styling design work from the basic skeleton, as it greatly affects the proportions in vehicle outline.

Over so many hours, intense discussion was conducted by the team members on the subject regarding seeming to be fast even when it is stationary. Simple questions were asked to all the team members, such as “What is the shape that makes us feel it start to move at the next moment?” or “What is the form that makes us feel the potential to run fast?”

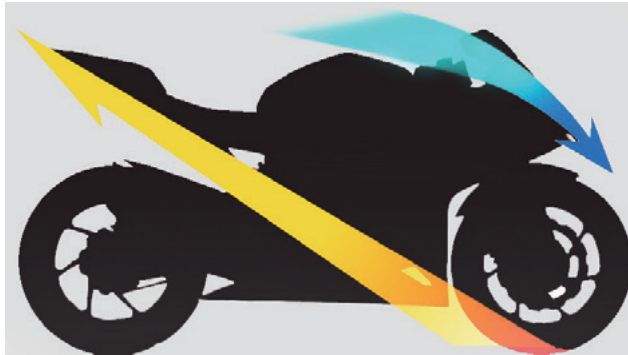


Fig. 8 Image sketch illustrating front nose postured in downward direction and vehicle tail leaping up high

The experience of sharing ideas regarding the styling design among the members, through these simple question-and-answer dialogs, contributed a lot to our process of development.

Many idea sketches were examined for the basic skeleton of the body frame structure (Fig. 10), and the best arrangement that provides required functions and



Fig. 9 Computer graphic of body structure skeleton

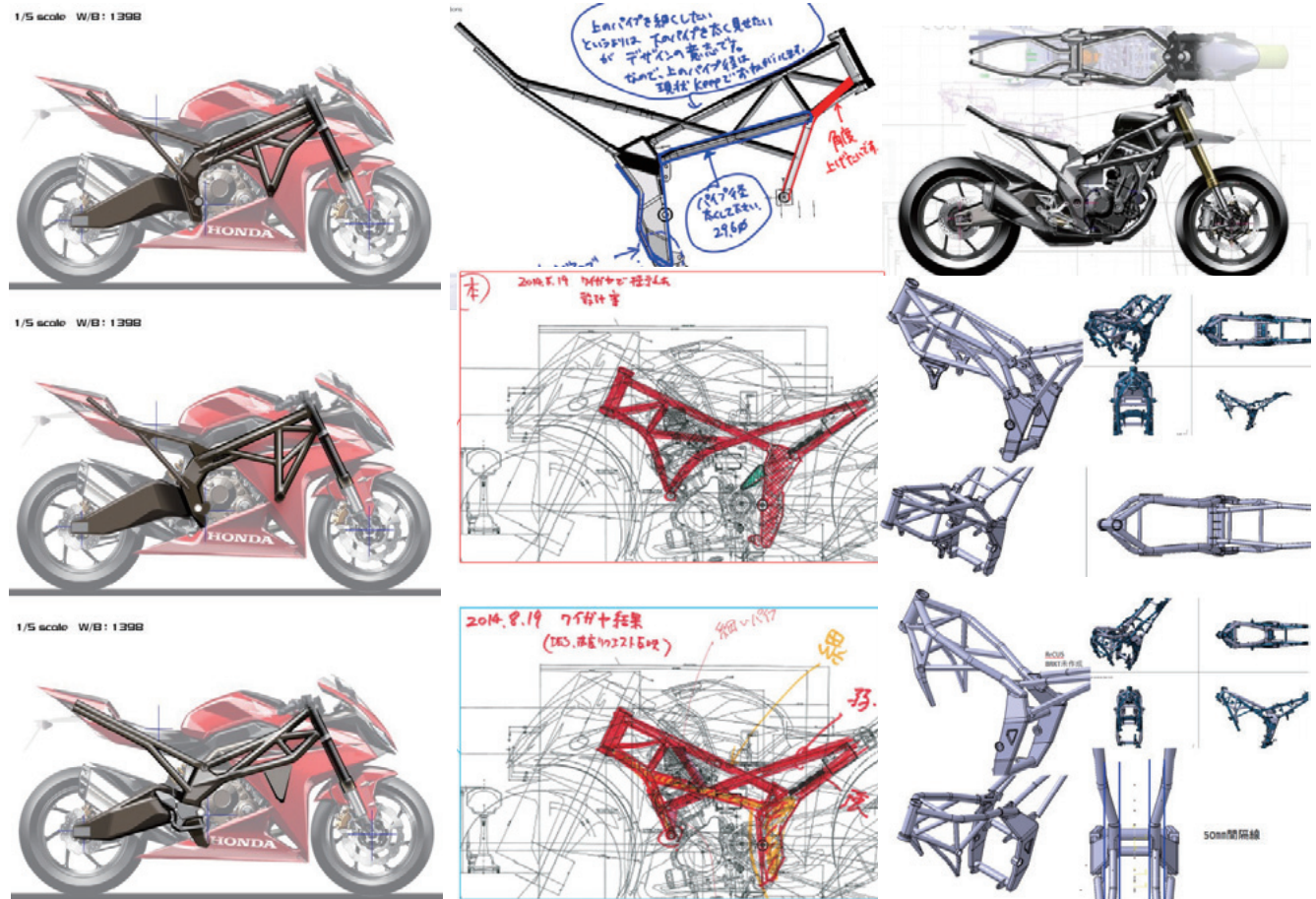


Fig. 10 Conceptual sketches for formulating frame composition

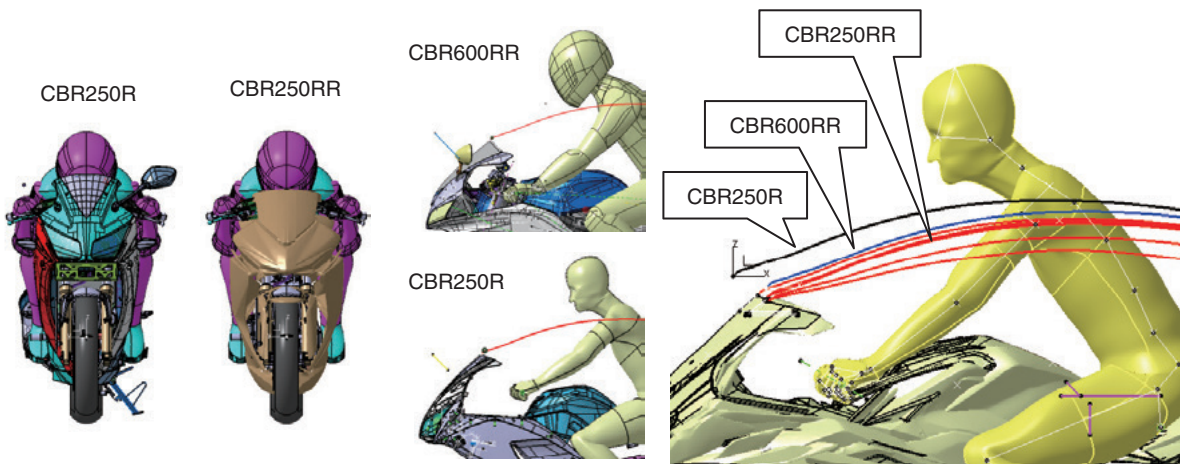


Fig. 11 Investigations through graphics drawn by conducting various analyses

performances of each part was decided utilizing CFD analyses (Fig. 11). The design approach involving all development members contributed to the achievement of the desired styling design creation that was aimed at in the initial stage of the development fostering strong teamwork, overcoming various hurdles experienced through in the process of the development.

With this basic skeleton, we developed an exterior design plan that conforms to the styling keyword “Speed Shape.”

5. Sketching

Styling sketches were drawn to express “Speed Shape.”

Attempts were made to achieve the target “the shape that looks fast even when standing still.” Considered were the styling design options hinting at motions such as the crouching start style that looked just about to leap, the stout wheel and suspension design as if they grabbed the ground surface and kicked the ground strongly to move forward.

The motorcycle in the super sport category, which is also enjoyed on race tracks, is such a vehicle that moves forward while ripping the air and clearing the corner while leaning the motorcycle from high speeds. Accordingly, the dynamic performance at the time of cornering was also taken into account in the styling design in addition to the wedge shape that rips the air. In that design method, studies were conducted for each of the fast-looking functional components, as well as for the fast-looking silhouette.

5.1. Fast-looking Functional Components

5.1.1. Importance of functional components as a design element

Studies were conducted on what kind of things were perceived fast to visualize the invisible “speed” when the motorcycle is standing still.

To begin with, studies were conducted on the MotoGP

racing machines, the pinnacle of high speed motorcycles, and the super sport models of 600 cc and 1000 cc.

In addition to the impression from the appearance with cowlings, the impression of the motorcycle when stripped was also studied. In those studies, we have reached to such a conclusion that the “fast” image of the motorcycle is created by the strong appeal of the functional components directly linked to the running performance. The basic structure is composed of the wheel and suspension components that give an impression of high stiffness, the frame body calculated to deal with various forces acting on the vehicle body, the aluminum parts to attain both lightness and strength, etc. Such functional components are a significant element of appearance that gives natural image of high performance even when not actually working.

It was therefore considered also in the development of CBR250RR that appealing of high performance functional component was an indispensable element to achieve a fast-looking styling design.

5.1.2. Designing of functional components

All the components composing of a motorcycle are a functional part having a specific role of its own. Among those, especially the frame body and the suspension parts such as the front fork and the swingarm are the key items for running of the super sport model. In this model, we aimed designing of such functional components at achieving a sense of integration with the vehicle body, and giving such an image of powerfulness that kicks the ground when standing still along with agility by aligning the swingarm upper end line with the mainframe line. The details of designing are explained in the latter chapters.

5.2. Fast-looking Silhouette

As the next step, we studies on the silhouette common to something fast.

The following design elements have been selected for

each of the one having a high maximum speed (Fig. 12), the one having an image of acceleration (Fig. 13), and the one having an image of strong traction that supports them (Fig. 14).



Fig. 12 Example of object that recollects image of highest speed



Fig. 13 Example of posture that gives feeling of instantaneous power enabling acceleration in a moment



Fig. 14 Example of powerful body posture that gives impression of legs grabbing ground and kicking out forward

5.2.1. “A shape ripping the air” – Image of maximum speed –

A silhouette having a long, pointed end permits representation of something running fast ripping through the air. In other words, the silhouette of something like a sharp knife that rips air with a blade gives the viewer an image of something running at a high speed.

Such a silhouette is referred to as “long nose silhouette.”

5.2.2. “A shape impressing explosive power that causes instantaneous acceleration” – Acceleration image –

The silhouette with the head down and gazing at the front allows expression of speed more than the silhouette after starting running. In other words, the shape just before the release of accumulated power to run allows the viewer to imagine the speed hidden inside and the explosive acceleration at the following moment. Such a silhouette is referred to as “crouching style.”

5.2.3. “A strong silhouette in that the feet grab the ground and kick the ground to leap” – Image of traction –

To induce an explosive acceleration and a speed that rips the air, it is necessary to grab the ground firmly with the feet and have a traction that kicks out the object. In other words, it is necessary to emphasize presence of the wheels to express “Speed Shape.” As the motorcycle body is relatively downsized to emphasize the undercarriage parts such as the wheels, which symbolize traction, the form of motorcycle naturally becomes trapezoidal. In that manner, a strong silhouette in which the feet grab the ground and kick out forward can be created. We refer this silhouette as “trapezoidal form.”

In addition to the importance of image of the earlier mentioned functional components, the following three were taken as the key words to visualize the concept of “speed,” and sketches were drawn accordingly.

- Long nose silhouette
- Crouching style
- Trapezoidal form

These were incorporated into the sketches as the elements of “Speed Shape.”

5.3. Incorporation into Sketch

5.3.1. Long nose silhouette that rips the air when running

Studies were conducted on how to express the stretchy, sharp silhouette ripping through the air within the limited length of the wheel base. Figure 15 shows the idea sketch in the early stage. The sharpness that looks accelerating while ripping the air is expressed by boldly incorporating the sharp air outlet duct (A) that is long in the fore and aft direction and as if ripped with a sharp knife. The line (B) stretching along the duct from the nose to the rear end of the under cowl further emphasizes the sharp line of the

air outlet duct, and expresses the stretchiness of the entire motorcycle. The line (C) from the shoulder to the middle cowl as if paired with other lines further impresses the earlier mentioned two lines, and contributes to such an image that rips everything that confronts.

5.3.2. Crouching style that impresses explosive force that brings about instantaneous acceleration

To express the crouching style, the sketches were drawn using the same lean-forward triangle (Fig. 16) that forms the basis of the styling design of CBR1000RR.

It was perceived from the said studies that while the targeted crouching style was expressed, more emphasis of lean-forward posture was necessary at this time to impress the potential of explosive force. Accordingly, it was decided to emphasize forward tilting by forming a more upright triangle that integrates a part of the front wheel. Moreover, the rear cowl section is laid in such a manner that allows clear recognition as another triangle that makes the viewer perceive a form in the same direction as the other triangle (Fig. 17). By emphasizing the up-lifting image by the contrast of the two triangles, and adequately shifting the

visual center of gravity to the lower front of the motorcycle, the posture as if accelerating instantaneously has been represented.

5.3.3. Strong trapezoidal form in that the feet grab the ground and kick to jump forward

The compactness of the upper part of the motorcycle to realize the “trapezoidal form” as shown by Fig. 18 significantly contributes to emphasize the wheels and the suspension. However, it weakens the image of “powerfulness,” which is another element to express the speed potential. The “powerfulness” signifies strong aura and presence that push aside others, and is indispensable to impress overwhelming speed.

To express the “powerfulness,” the center of the motorcycle composing of the middle cowl and the fuel tank is rendered as an integrated mass. This strong massiveness serves as an expression of powerfulness that pushes aside others. Also, while increasing the volume of the pivot plate in the center of motorcycle, the sharp-edged shape is applied to the end of the front cowl, middle cowl, and rear cowl that connect to the pivot plate

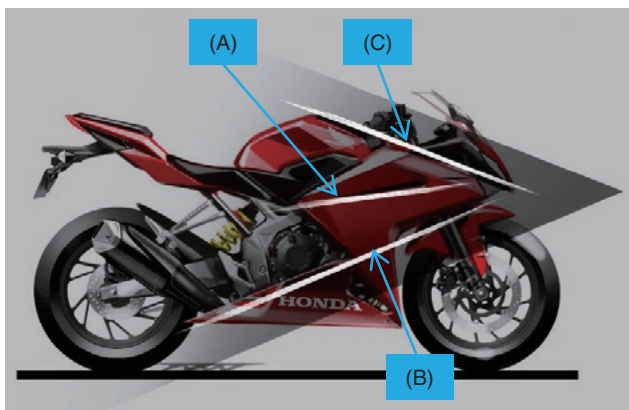


Fig. 15 Illustration of lines emphasizing long nose silhouette

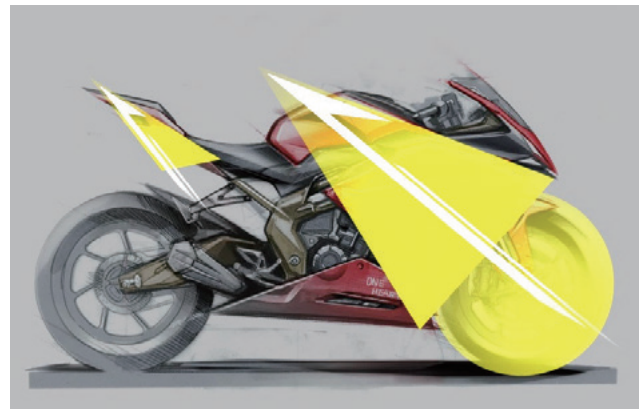


Fig. 17 Two triangles demonstrating form directed in same direction, which enhance forward slanted posture

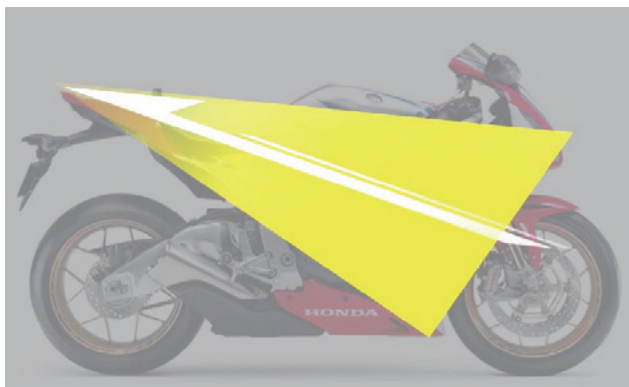


Fig. 16 Styling form symbolizing forward tilting triangle

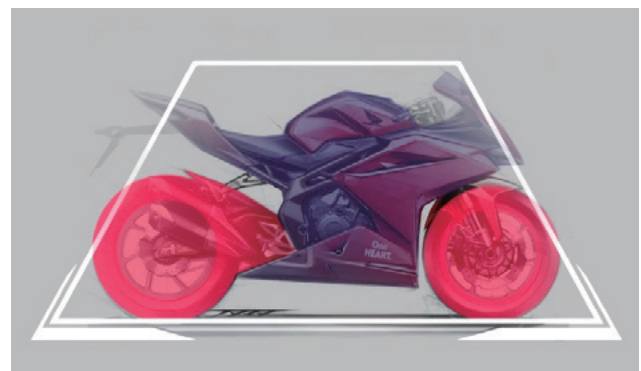


Fig. 18 Sketch showing trapezoidal design form

(Fig. 19), which further emphasizes the image of mass centralization from the peripheral to the center of the motorcycle. Thus enabled is the expression of potential that brings about a speedy image without sacrificing powerfulness while emphasizing the wheels.

These considerations have enabled impressing of the trapezoidal form and expressing of such an image that strongly kicks the earth.

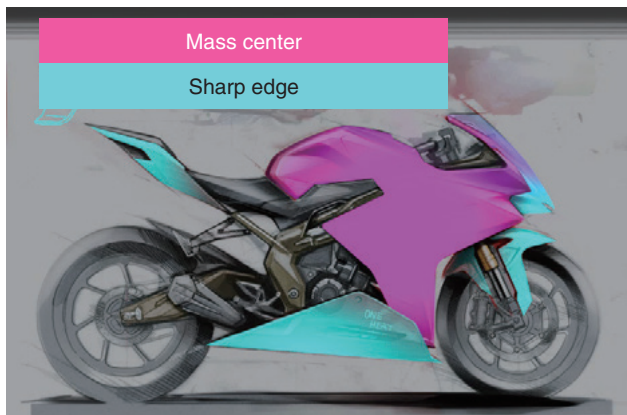


Fig. 19 Different design expression techniques depending on distances from center of mass

6. Verification of Presence in Design Options by Comparison of Virtual Models

After determination of the direction of styling by the sketch, studies of 3D model started using a 1/2 size scale model (Fig. 20). The reason why studies are conducted using a 1/2 size model is such that in addition to the possibility to produce the model in a short period of time, changes of the proportion is easy. Taking advantages of these characteristics, various studies of the 3D model



Fig. 20 Half size clay model

were conducted, the shape appearing fast even when standing still, which was required by the styling key word “Speed Shape,” was determined, and the direction of full-scale clay model was determined. As the following step, measurements were taken from the 1/2 size scale model using the optical measuring instrument, and converted to a virtual model, by which comparison was made with various models including competitive products, and various adjustments were conducted using the live size image on the large monitor screen. Also, the use of this data permitted verification of motorcycle body component layout and CFD analysis, which contributed to an early finalization of specifications (Fig. 21).

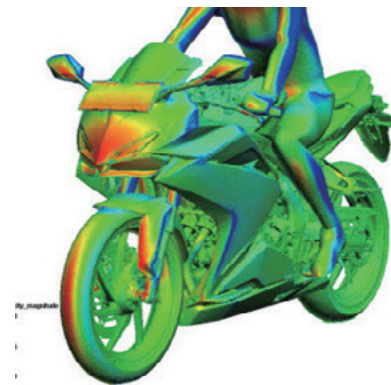


Fig. 21 Analysis of pressure distribution on cowl by CFD

7. Clay Model Production and General Design Decision

On the basis of the measurements taken from the 1/2 scale model, the full scale clay model was produced using the NC milling machine (Fig. 22). Though the data was compiled upon various studies, the impression of the milled clay model was different from the image previewed on the display. Although the data was the same, the “aura” was totally different. The powerfulness from the mass-resembling block or the edginess from the contour was unnoticeable. Also, the “high” feeling that the rider senses when sitting in the seat and grabbing the handlebar or the sense of integrity with the motorcycle when the rider sits astride was inadequate (Fig. 23). We consider such differences are inevitable from the size of model that does not permit sitting astride and the difference of eye line from the scale model. It was therefore decided to create crouching style proportion again and rework to attain edginess.

7.1. Proportion – Release of Explosive Force –

Employing the low front nose and the high-rise rear section as the basic proportion, studies were conducted on the running form and the movement of muscles of the

sprinter just after the start to express the almost ready to start crouching style.

To simulate this posture in that the athlete keeps his head down and maintains even lower posture to produce a force in the horizontal direction, the well-trained muscles, the driving force to kick the ground, and the expression of sense of speed are indispensable. Accordingly, the fuel tank is given the principal role to express the powerfulness, and from there gradual changes are made to express thinness and sharpness. While expressing flexibility, the powerfulness to kick the ground to produce a driving force is expressed by the series of flow from the middle cowl to the frame and the swingarm. The lower cowl is extended as far to the rear of the motorcycle as possible to express



Fig. 22 Production of full scale clay model by numerically controlled clay trimmer



Fig. 23 Lack of sense of unity between rider and vehicle caused by loose distances to components around rider

speediness by the long straight line tilting downward. Thus realized is the proportion that represents the moment the explosive energy contained inside is released (Fig. 24).

7.2. Fuel Tank – Overwhelming Powerfulness –

Among the cubic components, the highest level of powerfulness is expressed by the fuel tank. Assuming the top rear surface of the fuel tank as athlete's trapezius muscle and latissimus dorsi muscle, the overwhelming powerfulness is expressed by the incorporation of edgy surfaces that look as if a hard, massive block is carved with a primitive instrument (Fig. 25). Also, the knee grip area is narrowed to a minimum to express tightness. This shape contributes to easy planting of rider's foot on the ground as well as ensuring optimum holding of rider body in a sporty riding. The fuel tank shape composing of complex and stepped surfaces has been realized by the design considerations such as providing a fuel tank cover on both sides.

7.3. Front Cowl – Gazing Eyes –

The impression like a Kabuki makeup is provided by the character lines and the cut lines deeply engraved in the



Fig. 24 Implementation of crouching style concept



Fig. 25 Shape formation of back portion of tank expressing powerfulness (4-piece tank coverings configuration)

front cowl. Moreover, the shape that looks like intimidating, glaring at the other party has been realized by the reverse-slanted shape of the headlight laid beneath the lowly positioned front nose (Fig. 26).

7.4. Middle Cowl – Edginess and Presence –

The middle cowl has the largest surface area of all body panels. Because the surface area is large, it can end up with “heaviness” if the pursuit of powerfulness is excessive (Fig. 27). To deal with it, the middle cowl is shaped in such a manner that the entire surface is narrowed significantly from the outermost part (a) of the silhouette when viewed from the front toward the lower cowl, which makes most surfaces of the middle cowl facing downward, creating deep shades and shadows.

The air outlets are shaped as if deeply carved with a sharp object to show “awesomeness.”

The deeply overlapped layer structure in the connection



Fig. 26 Headlights that are gazing up from low position

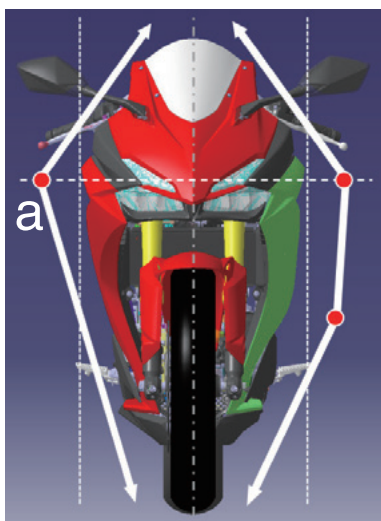


Fig. 27 Difference in impression of weighted object sense evoked by turning point(s) of outer line (ex. two points on the right side in the figure)

with the lower cowl controls flow of air in the cowl, contributing to the improved rider comfort and engine heat management. Also, the thickness of the winged shape of the layered part is reduced to the minimum to show “edginess.” Overall, by the hard-looking surface contours and the large angle given at a surface turning point, the sharp edginess and the contrast of shades and shadows are emphasized. Thus achieved is the style having the presence and powerfulness comparable to a large motorcycle.

7.5. Rear Cowl – Uplifting Image –

The uplifting image is further enhanced by incorporating a turning point in the line facing upward from the seat rail toward the rear in the side view of the rear cowl (Fig. 28). The rear cowl shape is composed of the extensively stretched, upward-facing surface in that the tension is controlled and the downward-facing surface having a stretch to receive rider’s weight. The “stretched out” shape enhances contrast with the narrowed-down seat area, thus implying “massiveness” beyond the class. The air ducts through from the front to the rear contribute to both the massiveness and the sharp swiftness of the rear cowl.

7.6. Completion of Clay Model

The concept to express the crouching style such as the well-trained muscles, the driving force to kick forward from the ground, the speediness was materialized in the form of a full-scale clay model, by which the shape expressing the styling key word “Speed Shape” was produced. The fillet in each part looks even sharper by the clear shifting of surfaces, thus expressing “sharpness like ripping the air.” Also, the shape of fuel tank, which comes into rider’s view when sitting astride, expresses overwhelming powerfulness and has an impact that makes the owner forget about the engine displacement and its class. All these considerations on shaping resulted in the “attractive style.”



Fig. 28 Enhancement of expressions by clay model for further providing uplifting feeling

8. Design Details

Described hereafter are the examples of design details for realization of the concept “attractive style.”

8.1. Headlight – Sharp Look –

The headlight and peripheral parts are designed with an aim at a “sharp look” image to signify “Speed Shape.” The overall light body is composed of four individual lights; two head lights and two position lights to express personality and presence. The position light is of such a shape that is narrow and raised toward the side symbolizing the eyes of an animal trying to catch a game. That further enhances the sharp-looking design of the headlight (Fig. 29). To express the sharp eyes, the plane emission light with a light guide is employed so that the light reaches to the ends.

The RR logo is etched into the headlight reflector (Fig. 30). Like that, the playful mind is maintained even in such a detail that is usually out of sight.

8.2. Tail Section – Expression of Innovative Spirit and Speed –

Considering a matching with the front end design, the

upper and lower, two-tier lens design is incorporated in the tail light unit. The upper tier tail light expresses innovative spirit by the plane emission using the light guide, which is usually employed in large motorcycles. Using a reflector-type stop light in the lower tier, the contrast is emphasized from the upper tail light in the appearance and when lit. With the different lighting characteristics given between the upper and lower lights, the two-tier tail light design becomes even more impressive (Fig. 31).

Incorporating the air ducts in the tail cowl, the appearance lets the viewer imagine air flow management as well as symbolizing speed (Figs. 32 and 33).

8.3. Layered Wing – Detailed Styling Design to Make the Viewer Perceive Speed –

As a way to express the speed for completion of “Speed Shape,” the design having wings is applied to the middle cowl. That design is inspired by the shape of canard, which is seen in fast vehicles such as the super car, F1 machine, MotoGP machine. The vehicle having such a wing makes the viewer imagine air management even when not running and perceive superb running performance at high speeds. This winged shape is an important element that impresses



Fig. 29 Sharp face demonstrated by headlights design



Fig. 30 RR logo on outer upside of extension of headlight reflector



Fig. 31 Two tiered arrangement of upper and lower LED taillights

the style that “looks fast even when standing still.” The unique construction having the end of middle cowl stretched out as a wing from the side of lower cowl also serves as an engine cooling air intake (Fig. 34).

Note that the design incorporating the winged shape is also applied to the front and rear ends.

8.4. Twin Muffler – Presence Symbolizing High Performance –

The twin silencer symbolizing high performance contributes both for the noise suppression and the high power output. The high volume silencer to achieve the target performance is slimmed down by employing the twin silencer construction. The narrow muffler helps to maintain a large banking angle, which contributes to the cornering performance necessary for a super sport model. Appearance-wise, the uniquely shaped cross section of each silencer is also a remarkable feature (Fig. 35). This twin muffler design expresses performance that symbolizes



Fig. 34 Layered cowl and rear cowl expressing speed by wing shape



Fig. 32 Air guiding intake openings on rear cowl



Fig. 33 Air outlets on rear cowl



Fig. 35 Twin mufflers with variant cross sections

a high power output, and realizes the powerful image comparable to a large motorcycle.

8.5. Large Fully Digital Meter – Visualization of Performance and High Tech Image –

The engine performance featuring the highest power output of the class is visually represented by this meter. We want the instrument make the rider envision speed the moment he turns the ignition key. The large fully digital meter having the largest size in the class and designed with the aforementioned intension is of such a graphic design in that the tachometer is deliberately laid in the center of the meter unit (Fig. 36).

The initial display appears as per the following sequence. Firstly, as the ignition key is turned, the tachometer turns up to the maximum revolutions. Then, all the LCD segments glow, and just after that, each segment goes off in a random order. Lastly only the “CBR” logo remains to make the rider excited. In sport riding such as on a race track, it is necessary for the rider to read the meter quickly by a glance. Accordingly, a large, fully digital meter is employed in liter-class sport models with an LED shift-up indicator provided on top of the tachometer. With these display considerations, the rider can recognize the information on the meter in a part of his vision even when taking a fully tacked position. The large fully digital meter employed in this model also has the similar function. Taking into account the recent trends, such a type of LCD, which is the core of the meter, having a narrow frame is employed for a high tech image. Also, the control buttons, which are usually made of rubber, are made of plastic having the same tone as the meter panel to realize the appearance that lives up to user expectations.

8.6. Wheel and Suspension – Envisage Performance beyond the Class –

The upside-down front fork and the aluminum swingarm employed to realize performance beyond the class are also aimed at realization of the “attractive design.” As mentioned



Fig. 36 Large-sized fully digitized gauge unit

in the preceding chapter, such a design is employed in that the upper line of the swingarm is aligned with the line of the main frame to make the viewer feel powerfulness that kicks the ground even when standing still or imagine agility and lightness. This design significantly contributes to the representation of “crouching style” as well as maintaining a sense of integration with the motorcycle (Fig. 37). With the 7-spoke design employed in the wheels, the image of the thing that runs fast like the MotoGP machine RC213V is incorporated to emphasize speed.

8.7. Frame Body – Attractive Structural Body –

As mentioned earlier, it was necessary for the styling designers and the frame/engine designers to collaborate at such a level in that each party stepped into the other’s territory to achieve the “Speed Shape” of this model. Upon such a mutual understanding that “something functional is beautiful, something beautiful is functional,” discussions were repeated to realize a design achieving both style and function.

Firstly, as a basic principle, the design should be such that shows the frame body as a structural body. Accordingly, the pipe frame of a truss structure having an attractive appearance is employed while minimizing use of gusset, etc. which conceals the truss structure. Moreover, such a pipe layout that has a narrow part in the middle of frame body is employed to realize a distinctive body shape.

Also, considerations such as laying the pillion foot peg bracket retainer behind the frame are given to avoid spoiling of the appearance of the frame pipe. That allows to cleanly show the seat rail line that connects the pivot plate to the rear cowl, contributing to demonstration of the “Speed Shape.”

The targeted “attractive style” is also realized in such design details, which successfully make the personality of CBR250RR outstanding.

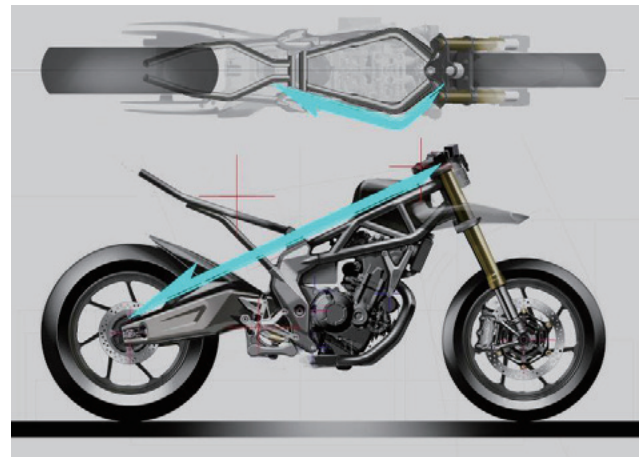


Fig. 37 Expressing unity of vehicle body by aligning main frame and upper edge of swing arm

9. Coloring

The coloring is an important element to convey the model concept to the customer by the first impression.

It is essential to adhere to the basic principles on the appearance to properly convey the model concept “attractive style,” “attractive features” and “attractive performance” to the customers who see this motorcycle for the first time.

The studies of coloring often start after the shape is finalized. In this model, however, the styling designers and the coloring designers mutually exchanged comments across their specialties to realize the solid design.

An important design element of this model is “show off.” Accordingly in the coloring design, the “attractive” coloring is realized to satisfy users’ desire to “look cool.” With respect to the element that realizes “appeal” in terms of coloring, we defined it should be in agreement with each customer’s “sense of value that connects to coolness” in addition to being trendy and innovative. In many cases, the coloring is finalized taking into account the unique requirements of the local market. The target users of this model, however, are those who share global trend and/or sense of value regardless of the subject country. Accordingly in the coloring for those people, we aimed at such coloring that would be globally recognized and accepted rather than being conscious of region-oriented coloring.

When it comes to the “sense of value that connects to coolness,” how to interpret it differs from a person to another. For example, while some may see it cool if he can ride the motorcycle in a stylish manner in the metropolis, others may consider only the racing motorcycle is the symbol of coolness. Rather, there are some who think the only coolness is being eye catching in a group. To respond to those various senses of value, the color scheme comes in 3 themes, 5 types. The color line up is provided to cater for users’ wide variety of demands.

1. Street sport color (2 types)
2. Racing sport color (2 types)
3. Special graphic color KABUKI

The theme and the background of each color are described hereafter.

9.1. Street Sport Color

To create a stylish riding image in the metropolis, the monotone color is selected as the main color of the street sport model, and positioned as the standard color. As the monotone color is easy to make a good match with the cloths and looks nice in any situation, it helps to bring up rider’s image. While employing the monotone color having a quiet image as well and using the color trend of super cars and others, we worked out a way to “appeal” in the daily use situation. Accordingly employed was the method that effectively laid high chroma colors in the monotone color.

9.1.1. Matte black

The matte painting has microscopically uneven surface that diffuses light, it prevents reflection of nearby objects, and is used in military equipment such as the stealth airplane. Especially the matte black has such a visionary effect that hides the object from enemy’s eyes at night. Due to the history of use in military equipment and the hiding effects, the color makes the viewer feel fear, awesomeness, and force. The concept model (Fig. 38) of this motorcycle was intended to display at the motor show as a mystery model. Accordingly, the matte black was selected because it was effective to create a mysterious image and express force and awesomeness of the styling design. Being the good reputation at the show one of the reasons, the color was employed in the mass production model (Fig. 39). With an aim at enhancement of the shape of functional parts such as the air intake, the high-chroma red is applied to the recessed surfaces (Fig. 40). Having such backgrounds that the black with red insets is a popular color of Honda motorcycles, the matte black is positioned as the theme color, and used in the catalogues and photo books.



Fig. 38 Concept Model of “LIGHT WEIGHT SUPER SPORTS CONCEPT”



Fig. 39 Matte black color applied to mass production model

9.1.2. Dark metallic silver

Recently in Indonesia, which is one of the main target markets, such information as “silver is popular in European automobiles” is spread among the rich class having global sense of value. Basically the silver has a strong image of a color for public vehicles such as the taxi, its value for personal car has been low. Due to the above-mentioned information, however, the value is increasing, and some users owning a silver automobile of European brand are appearing.

Although such a trend is seen, the black is still the popular color of motorcycles and cars, and supported by many due to its sharp and strong image. Moreover in the motorcycle market, especially in the sport motorcycle category, there is virtually no variation of silver. Because the market is composed of a wider variety of customer base than that of automobiles and sensitive to the trend, the color line up tends to be composed only of popular colors such as the primary color like black, red and the racer replica color.

Although it was fairly a challenge to propose silver in this model under such circumstances, we worked out a way that allowed representation of innovative image without departing from user preference and recent color trends. Taking into account the color trend, the dark tone silver was selected. Even darker gray metallic was chosen for the lower cowl to relatively emphasize the form of the upper body while achieving a tight overall image. The yellow stripes applied as an accent to the specific areas such as the overlapping or turning of cowl surfaces depict the contour of the motorcycle (Fig. 41). The high chroma yellow is employed as the color that can create an active and innovative image because it matches well on silver although

silver is usually difficult to make a good match with a primary color.

Using the said methods, the coloring that is innovative yet agreeable to user preference has been realized (Fig. 42).

9.2. Racing Sport Color

The two types designated as the racing sport color are for customers having a high interest in the motor sport. The motor sports have a large number of followers in the world, and especially popular in Indonesian where it is growing big, and even those who don't ride a motorcycle enjoy viewing it as a sport spectator. The racing sport color symbolizes the team the fan supports, and owning a motorcycle of such a color boosts enthusiasm of the fan.

9.2.1. Repsol color

Honda has been participating in the MotoGP World Championship, which is the pinnacle of motorcycle road races, also in the year 2017, and maintaining good results. In that MotoGP class, Repsol in Spain has been the main sponsor of Honda Racing since 1995. The works machines



Fig. 41 Stripes arranged along contour of vehicle body



Fig. 40 Red color inserted on recessed sections of cowl



Fig. 42 Color of dark metallic silver applied to mass production vehicles

and the mass production models wearing the same color are usually called the Repsol Color, and widely recognized by race fans.

In the racer replica color, it is crucial to reproduce the color of the racing machine on the motorcycle having a different shape from the actual racing machine while maintaining an image close to the original. The Repsol works machines use flash orange as the main color for easy identification when on the race track (Fig. 43). In the mass-production replica models, the color scheme is materialized using stickers. To reproduce the atmosphere of Repsol color scheme, it was necessary to use large stickers. The larger the sticker, the higher the application skills required. With the cooperation from the skilled, experienced associates of Astra Honda Motor (the manufacturer of CBR250RR in Indonesia), the mass production has become a reality (Fig. 44).

The MotoGP champion racer Marc Marquez plays the role of main character in the catalogue, poster, etc. using the color scheme. He actually rode the machine at an event held



Fig. 43 REPSOL Honda Works Machine, the RC213V



Fig. 44 Replicated coloring reproducing that of original works machine

in Indonesia, and remarkably boosted the enthusiasm of the race fans.

9.2.2. New Astra Honda Racing color

Astra Honda Racing Team is participating in the Asia Road Race Championship (hereafter ARRC). The new Astra Honda Racing color is the replica color of the works racing machine since 2016.

The works machine of Astra Honda Racing Team used to use the red and white two-tone color, which was the team color, as the basis. In the new Astra Honda Racing color, the black and gray graphics are boldly added to the traditional red and white to tighten up the overall image. The graphics running fore and aft on the fairing further emphasize the forward leaning posture and the sharply lifted rear section. Using the large stickers, this color scheme makes the lower half of the motorcycle appear as if painted white to achieve an agile image. With these methods applied, the speediness, which is the aim of the replica color, has been expressed (Fig. 45).

Astra Honda Motor is participating in the 2017 ARRC AP250 cc class by the CBR250RR wearing this color scheme. Being an owner of the motorcycle wearing the replica color of the winning works machine is a big joy and pride for the race-fan user.

9.3. Special Graphic Color KABUKI

The “special graphic color KABUKI” is provided exclusively for the Indonesian market.

In the Indonesian motorcycle market, custom coloring is popular using stickers and wrapping films. Having such trends on the backgrounds, this color scheme is based on such a concept that the manufacturer provides customized version of this model. Before starting the initial coloring design, we worked out a design theme referring to the results of market survey. In the process of seeking various design directions, it has become clear that the animation culture of Japan, the graphics using “Kana” (Japanese



Fig. 45 Coloring of Astra Honda Racing for mass production model

characters), etc. are recognized also in Indonesia as one of the globally accepted expressions (Fig. 46). Moreover, the word “cool Japan” has penetrated worldwide as a key word of subculture trends. On the basis of these findings, design studies were conducted having “Japan” as a principal theme (Fig. 47). Kabuki is used as a motif of the bold graphics drawn on the entire body panels. The title of the Kabuki performance giving the motif is “Shibaraku,” which is a standard of classic Kabuki performances. There are scenarios having a man playing the key role and another having a woman playing the same. Taking the main character of the performance as the motif, the woman is drawn on the right side and the man on the left side, which results in a unique asymmetric design (Fig. 48). The lines



Fig. 46 Graphics with Japanese motifs seen in Indonesian market



Fig. 47 Conceptual sketches on coloring developed from “Japan” as design motif



Fig. 48 Coloring for mass production model with asymmetrically designed left and right graphics based on motif of Kabuki

as if drawn with a stroke of brush are connected to a line of the hair or the outline of the character when combined (Fig. 49). By pasting split stickers in proper combinations, we aimed such an expression that looks like a graphic that fully wraps the entire fairing when viewed from a distance. With the black and white used as the main graphic color and the front and rear wheels colored differently in black or white, the graphic design is finished in such a manner that the first impression is high contrast and eye catching. In the meantime when viewed from near, the viewer can recognize the graphics having “Hanafuda” (Japanese card for game) as a motif scattered around at a low contrast (Fig. 50).

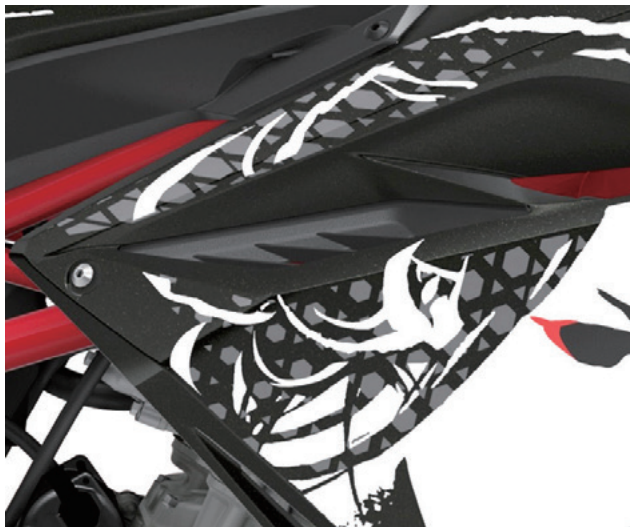


Fig. 49 Representation of contours of face and hairs with brush stroke touch

Though they may appear commonly known Hanafuda at a glance, various parts of this motorcycle are illustrated on each card, which would be a surprise hidden in the details when found. Using such methods, the color scheme like a customized motorcycle, which is a challenge in a mass-production model, has been achieved.

10. Conclusion

In the styling design of CBR250RR, we always aimed at “attractive style.” For styling, we set the key word “Speed Shape,” which means that the motorcycle looks fast even when standing still. To materialize the key word, multi-faceted approaches were made from the perspectives of basic frame structure, overall proportion, details of functional components, and coloring.

Maintaining communication with the engine and frame design teams, the basic frame structure was determined keeping in mind realization of the design key word “Speed Shape,” and achieved the wedge shape that should stand out when compared to other motorcycles. Moreover, using various methods to make the motorcycle look fast such as the crouching style in various areas of styling design such as the sketch, clay modeling, up to the designing of functional parts, the “Speed Shape” has been realized.

In terms of coloring, the personality of this model is appealed even more strongly by the globally-attractive graphic design.

This model was launched in Indonesia in October 2016, and gained remarkable popularity from a large number of customers. It was also launched in Japan in May 2017, and received a large number of orders as soon as introduced.

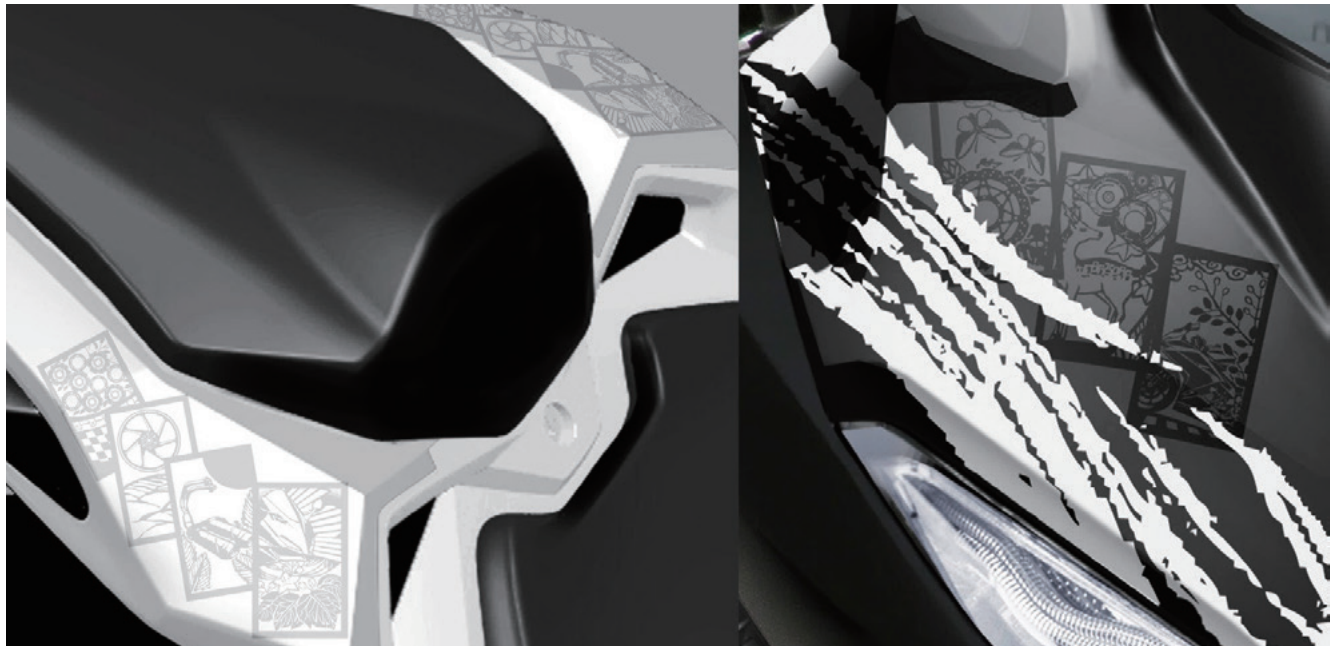


Fig. 50 Graphics featuring Hanafuda (Japanese floral playing cards) as motif

From the reputation from the users and the media, we trust the original goal of the styling design has been achieved.

We hope this styling design will become a new benchmark for the future super sport models in the 250 cc class.

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Development of New 3.5 L V6 Turbocharged Gasoline Engine for New NSX

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ABSTRACT

The concept for Honda's new NSX was to balance power performance achieving a high level of dynamic performance with a level of environmental performance meeting the demands of the times. A 3.5 L V6 turbocharged gasoline engine with a new frame was developed to realize this concept. In order to balance high power and high thermal efficiency, combustion was optimized through the use of in-cylinder direct injection and high-tumble ports, and the engine applies a twin turbocharger system featuring independent turbochargers positioned on the left and right banks and a fuel supply system combining in-cylinder direct injection and port injection. The powertrain was reduced in size and weight and given a low center of gravity in order to enhance vehicle dynamic performance. In addition, in response to the higher power of the engine, Fe spray-coated cylinder bores, a dry sump lubrication system, a three-piece water jacket, a swing arm valve train, and reduction chain drive were applied in order to help ensure cooling performance and frame reliability suited to the demands of sports driving.

As a result, the new engine achieves a maximum power of 373 kW (500 HP) and a maximum torque of 550 Nm across a wide range from 2000 rpm to 6000 rpm, in addition to complying with the European Euro6b and US ULEV125 regulations.

1. Introduction

Honda commenced mass production of the new model NSX in North America in 2016. The new NSX is a super sports model that inherits the concept of high dynamic performance balanced with high steering stability embodied in the first-generation NSX, which appeared in 1990.

The lightweight body of the new NSX is realized using innovative compound materials. The vehicle is provided with a 3.5 L V6 turbocharged gasoline engine positioned midship in a longitudinal layout behind the cockpit, and a three-motor hybrid system.

The 3.5 L V6 turbocharged gasoline engine for the new NSX, which will be discussed in this paper, is part of a direct-injection turbocharged gasoline engine series developed by Honda to balance environmental performance and the fun of driving (Fig. 1), but stands

out as having been developed with a particular focus on the fun of driving.

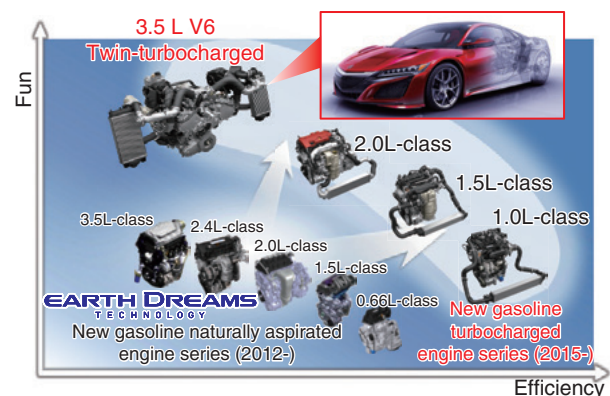


Fig. 1 Honda's series of direct injection turbocharged engines

* Automobile R&D Center

2. Development Aims

The concept for the new NSX was to balance power performance achieving a high level of dynamic performance with a level of environmental performance meeting the demands of the times (fuel efficiency, reduction of CO₂ emissions, compliance with exhaust gas regulations). In order to achieve a high level of steering stability, a compact engine frame able to be fitted longitudinally in a low-center-of-gravity position in the center of the vehicle would also be necessary. At the same time, it would be necessary to attempt to ensure the reliability of the engine under the high-load and high-acceleration conditions of sports driving. A 3.5 L V6 turbocharged gasoline engine was newly developed in order to satisfy these demands. The main development aims were as follows:

- (1) To balance the achievement of a maximum power of 373 kW (500 HP) and a maximum torque of 550 Nm with compliance with exhaust gas regulations in each country in which the vehicle would be sold (EU: Euro6b; US: ULEV125); and
- (2) To achieve a lightweight and compact frame suited to the rigors of sports driving.

3. Main Engine Specifications

Table 1 compares the specifications of the 3.5 L V6 turbocharged gasoline engine for the new NSX and a Honda mass production 3.5 L V6 naturally aspirated engine. The frame of the turbocharged gasoline engine applied in the new NSX has been modified against the naturally aspirated engine. In addition, turbochargers have been fitted in the left and right banks in order to increase power and efficiency. The combustion system incorporates high-tumble ports, a DI+PI fuel supply system that combines in-cylinder direct injection (DI) with port injection (PI), and hydraulic VTC (Dual-VTC) in the intake and exhaust valve train systems.

Figure 2 shows the exterior of the engine, and Fig. 3 shows the layout for mounting in the vehicle. By applying a dry-sump lubrication system and setting the V-bank angle at 75°, it has been possible to realize a low center of gravity and packaging that reduces the necessary space for the engine, both important factors in enhancing driving performance.

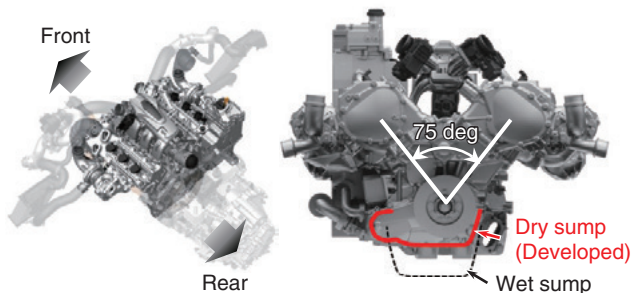


Fig. 2 Overall view of engine

Table 1 Engine specifications

Engine type	Developed JNC1	Previous JNB1
Cylinder configuration	V6-cylinder	V6-cylinder
Bore × Stroke (mm)	91.0 × 89.5	89.0 × 93.0
Displacement (cm ³)	3493	3471
Intake system	Turbocharged	Naturally aspirated
Bank angle (deg)	75	60
Lubrication system	Dry sump	Wet sump
Crank journal diameter (mm)	72	72
Compression ratio	10.0	11.5
Valve train	DOHC Hydraulic VTC (Intake/Exhaust)	SOHC VTEC/VCM
Number of valves	4 per cylinder	4 per cylinder
Fuel injection type	DI+PI	DI
Maximum power (kW/rpm)	373/6500-7500	231/6500
Maximum torque (Nm/rpm)	550/2000-6000	371/4700

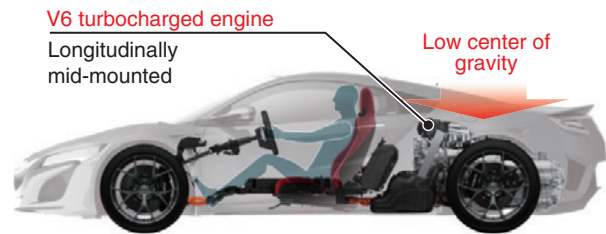


Fig. 3 Vehicle mounting layout

4. Engine Frame Technologies

In order to increase dynamic performance, the development sought to make the engine unit lighter and more compact. This section will introduce the main engine frame technologies applied in the new engine in order to also balance cooling performance, in response to the increased generation of heat resulting from the engine's increased power, with the realization of an engine frame that would be reliable under sports driving conditions.

4.1. Fe Spray-coated Cylinder Bores

A cylinder bore surface treatment using an Fe spray coating has been applied in the new engine in order to balance cooling performance in response to the engine's increased power with a lightweight and compact engine unit (Fig. 4).

In order to enhance cooling performance, cooling water channels have been positioned between the cylinder bores. Because it was necessary to realize a wall thickness on both sides that satisfies casting conditions when forming the cooling water channels, their use would increase the bore pitch, increasing the total length of the engine and

creating issues in terms of engine layout. The use of conventional iron cylinder sleeves (with a wall thickness of approximately 2.5 mm) would make the increase in bore pitch unavoidable. The use of Fe spray coating substituted the section corresponding to the sleeve with a thin 0.2 mm film that made it possible to control the bore pitch to 11 mm and position the cooling water channels in bore bridges. In addition, reducing the wall thickness of the iron increased thermal conductivity by 52% [Fig. 5(a)] and a weight reduction by 11% [Fig. 5(b)] against a conventional iron sleeve, making it possible to realize a lightweight and compact cylinder block.

In applying Fe spray coating, it is necessary to ensure the bond strength of the spray coating film. Broadly classifying the bond force of Fe and Al in the spray coating film, the forces at work can be categorized as follows. It is important to manage the area and the roughness of the spray-coated surface in relation to these forces:

- (1) Residual compressive stress in the spray coating Fe;
- (2) Mechanical bond force due to the base roughness of the sprayed surface (anchor effect); and
- (3) Intramolecular bond force at the boundary with the spray coating film.

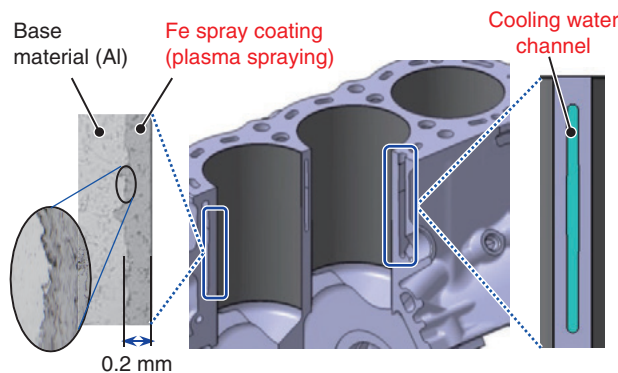


Fig. 4 Fe spray coating film and cooling water channels

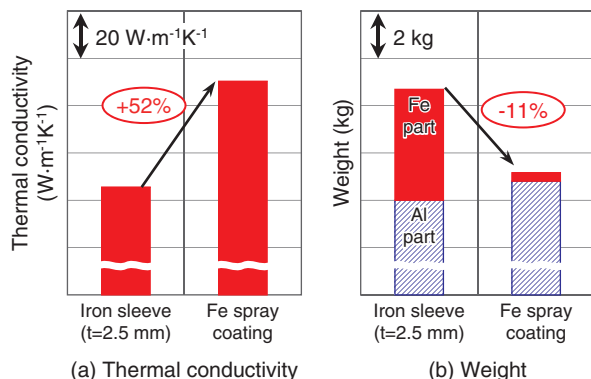


Fig. 5 Performance of Fe spray coating

Shot-blasting is utilized for base surface activation in the new engine. The base surface roughness was adjusted by changing the blast media size, and surface activation conditions that realized the desired bond strength were selected.

It was possible to realize the target bond strength by specifying the size of the blast media used in shot-blasting and managing surface roughness to within the range shown in Fig. 6.

As a result, the Fe spray coating displayed no peeling in durability tests using an engine dynamometer, achieving cylinder bores that displayed good cooling performance and contributed to the reduction of weight and size and the reliability of the engine frame.

4.2. Dry Sump Lubrication System

A dry sump lubrication system has been applied in the new engine in order to enhance dynamic performance and help ensure engine lubrication performance in severe driving environments.

Figure 7 shows an image of the entire dry sump lubrication system. In conventional wet sump lubrication, an oil pan and oil pump are positioned at the bottom of the

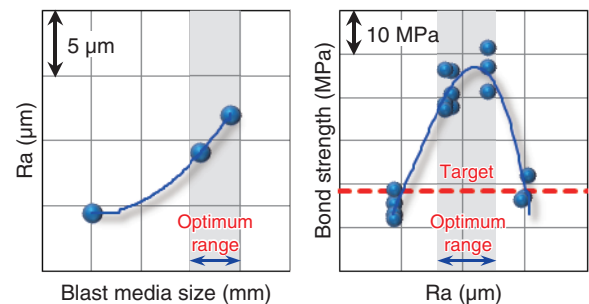


Fig. 6 Bond strength results

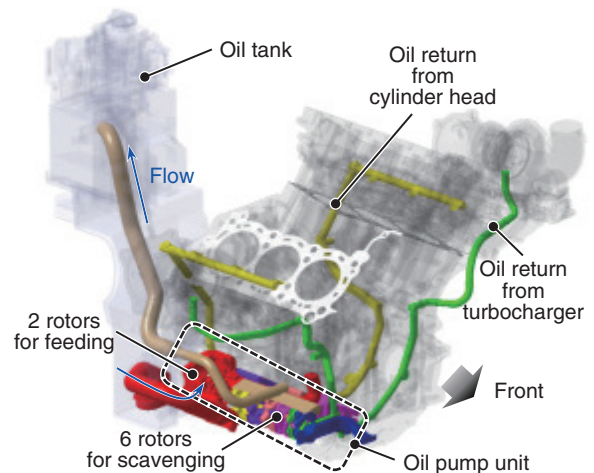


Fig. 7 Layout of dry sump lubrication system

engine. However, dry sump systems position an oil pump and oil tank separate to the engine, making it possible to reduce the mounting height of the engine by approximately 60 mm, thereby enhancing dynamic performance through the realization of a low center of gravity.

The use of an integrated structure in which the oil pump unit is positioned at the lower right of the engine and a feed pump and scavenge pump are positioned on the same shaft, in addition to increasing the speed of pump rotation and reducing the rotor diameter, has enabled a more compact lubrication system. Furthermore, offsetting the phase of each rotor (Fig. 8) has controlled pressure pulsations when oil is being discharged and reduced pump drive torque.

In a dry sump lubrication system, oil and blow-by gas are collected simultaneously from the crank chamber and the cam chamber by a scavenge pump, causing a high aeration rate in the oil returned to the oil tank. Because the supply of oil with a high aeration rate produces lubrication issues, it is important to control aeration. For the new engine, the gas separation performance inside the oil tank was increased, while the flow ratio of the feed pump and the scavenge pump was also optimized⁽¹⁾.

A cylinder known as a swirl pot is used for gas separation inside the oil tank. Oil sent from the scavenge pump is introduced to the swirl pot, where it is rotated, following the walls. The effect of centrifugal force promotes gas separation, while also controlling the trapping of air when the oil enters the surface of the liquid by reducing flow speed (Fig. 9). Because factors including the internal diameter of the swirl pot, the area of its opening, and the angle of introduction of the oil affect gas separation performance, analyses were conducted using CFD, and a swirl pot shape able to control aeration at the oil inlet was selected.

The longitudinal configuration shown in Fig. 10 was applied for the oil tank, and the oil amount was set between 4 L and 5 L. Under body acceleration conditions projected for sports driving around a circuit (cornering: 17.7 m/s^2 ;

accelerating: 9.8 m/s^2 ; decelerating: 11.8 m/s^2) and with 1.0 L of oil in the oil tank, the oil inlet shown as Area (a) in Fig. 10 is not exposed, and stable supply is ensured. In addition, under the same conditions, even with an oil amount of 5.0 L, oil does not reach the breather chamber positioned at the top of the oil tank, indicated by Area (b) in Fig. 10.

As a result, good lubrication performance has been achieved, with no issues such as declines in oil pressure due to oil intake issues or oil consumption due to oil infiltration into the breather chamber or the intake side, even during sports driving on a circuit.

4.3. Cooling System

Because increased power also increases heat rejection by the engine, it is important to reduce temperature, particularly that of the walls of the combustion chamber and of the

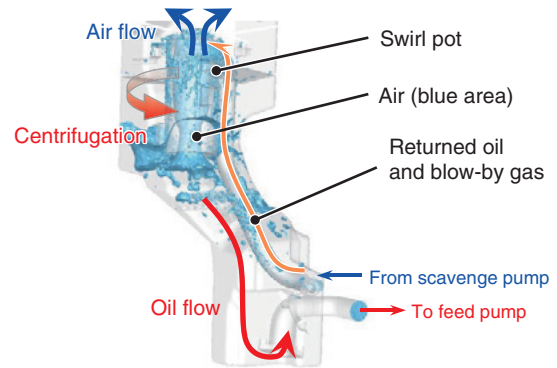


Fig. 9 Visualization of air separation in oil tank

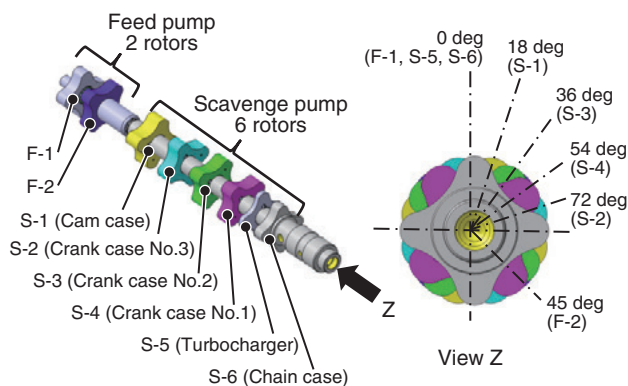


Fig. 8 Oil pump rotors

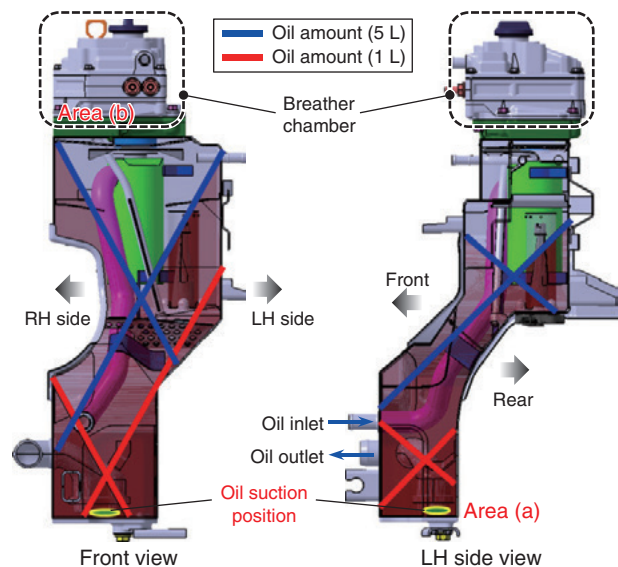


Fig. 10 Oil tank shape and oil level

exhaust gas. A three-piece water jacket configuration⁽²⁾ (Fig. 11) in the new engine increases reliability and controls knocking. This configuration actively cools the combustion chamber and the area around the exhaust ports.

CFD was utilized in studying the cooling water channels in order to analyze the distribution of cooling water flow speed and the temperature of each area of the cylinder heads and allow optimization of the shape of the water jacket. Figure 12 shows the results of study of the flow speed distribution of the cooling water. The use of a shape for the cooling water channels that controls peeling and stagnation of the flow and actively sends cooling water to the combustion chamber and the area around the exhaust ports, which have a high thermal load, has realized efficient cooling.

The use of a three-piece water jacket has expanded the area for heat conduction and optimized water flow, increasing heat rejection by approximately 14% against a conventional naturally aspirated 3.5 L V6 engine. In addition, the reduction of the temperature of the cylinder

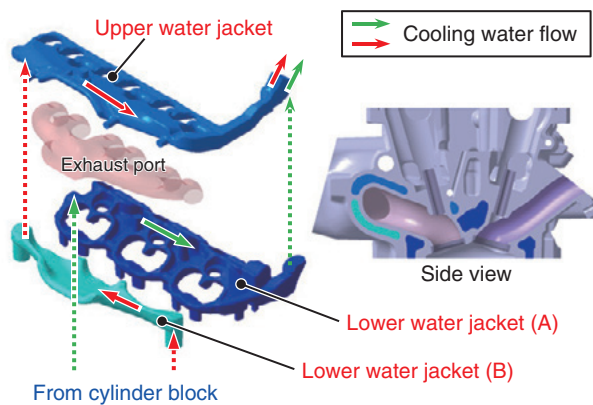


Fig. 11 3-piece water jacket

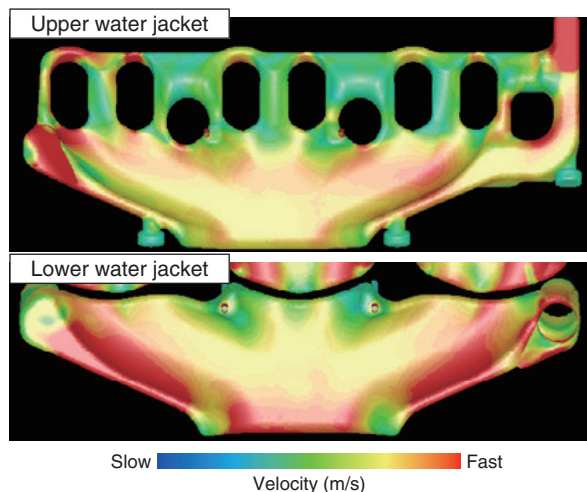


Fig. 12 Visualization of cooling water flow

heads has reduced the incidence of heat stress, contributing to the reduction of the size and weight of the engine.

4.4. Valve Train

A swing-arm valve train was adopted in order to reduce the size and weight of the engine unit (Fig. 13). This made it possible to realize compact cylinder heads, reducing the cross-sectional ratio of the cylinder heads by approximately 17% against a Honda mass-production 2.0 L in-line 4-cylinder turbocharged gasoline engine (DOHC), and realizing the same cylinder head size as a 3.5 L V6 naturally aspirated engine (SOHC). This also contributed to increasing the ability to fit the cylinder heads within the vehicle layout, making it possible to increase the angle of the V-bank to 75° within the limited space available and to position turbochargers on both sides of the engine.

4.5. Valve Timing Drive Method

Chain drive was adopted as the valve timing drive method in order to increase reliability in relation to the loads produced and to make the engine more compact. Figure 14 shows the chain drive system, in which three chains drive the cams on both banks via a reduction chain.

CAE was used in studying the drive layout, and the load

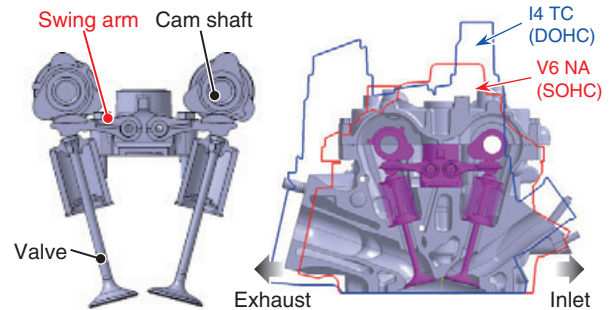


Fig. 13 Cylinder head layout

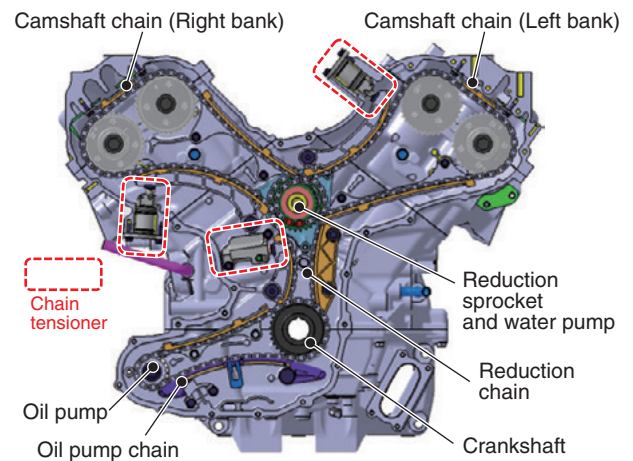


Fig. 14 Layout of reduction chain drive system

characteristic on the chains was compared for configurations using different numbers of chains (Fig. 15). It was observed that at some point, the load increases due to resonance with any number of chains. However, the three-chain system showed the desirable outcomes as it generated the least load by synthesizing the left and right bank cam drive torque via a reduction sprocket (an intermediate shaft), reducing the amplitude of torque transmitted to the reduction chain.

In addition, because the reduction chain is greatly affected by fluctuations in the angular velocity of the crankshaft, the chain tensioner relief pressure was optimized. The loads on the chain and tensioner displacement are in a trade-off relationship with relief pressure. Given this, relief pressure was set to enable control of tensioner displacement within an acceptable range of chain load (Fig. 16).

The positioning of the water pump on the same shaft as the reduction sprocket also increased the compactness of the layout of the auxiliary components.

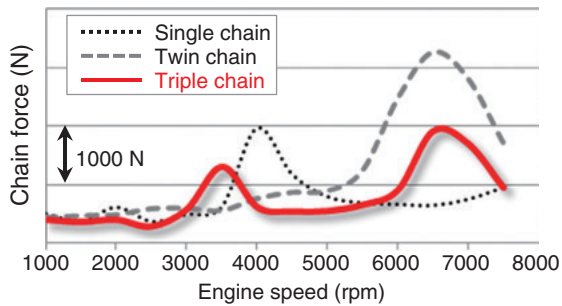


Fig. 15 Results of analysis of chain force

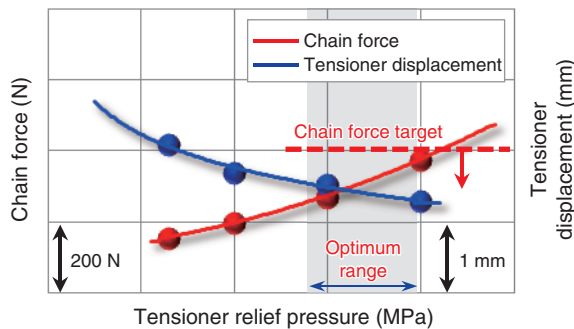


Fig. 16 Results of study of chain tensioner

5. Combustion Technologies

In order to balance high power and high thermal efficiency with low emissions, the combustion system of the new engine applies technologies to realize rapid and stable combustion: DI using multi-hole injectors and high-

tumble intake ports^{(2), (3)}. These technologies have enhanced both combustion and emissions performance. In addition, in order to increase power, the engine uses a twin turbocharger system (independent turbochargers on the right and left banks) and a DI+PI fuel injection system. This section will introduce these technologies.

5.1. High-tumble Intake Port

The use of high-tumble intake ports promotes the mixture of fuel and air and increases turbulent kinetic energy around the top dead center in the compression stroke, enabling rapid and stable combustion.

Figure 17 shows the shape of the intake ports in the new engine, while Fig. 18 shows the results of actual measurements of the tumble ratio. The intake ports produce a high-tumble flow displaying a tumble ratio two times or more that of a conventional 3.5 L V6 naturally aspirated engine across the entire range of valve lift, contributing to the realization of increased combustion stability.

5.2. Turbocharging Technologies

The new engine employs monoscroll turbochargers with electronic wastegates in order to increase power and enhance responsiveness. The use of a twin turbocharger system that positions turbochargers on each of the banks has enabled both an efficient longitudinal layout of the midship V engine, as well as exhaust interference control through the three-cylinder-per-side configuration. In the process of turbocharger selection, one-dimensional simulations were

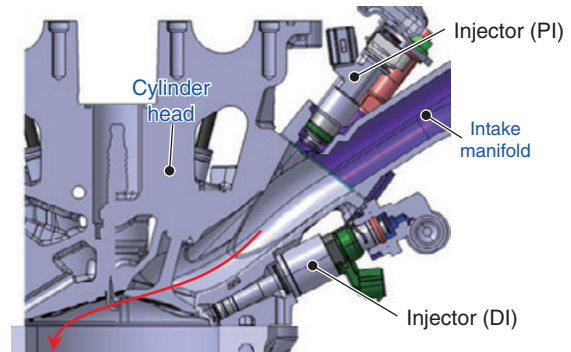


Fig. 17 Intake port layout

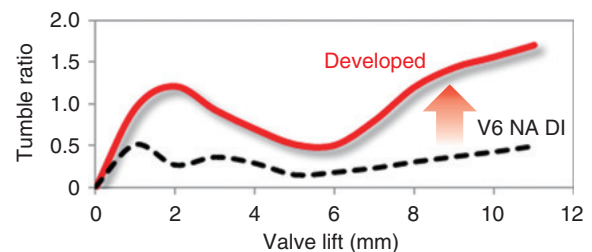


Fig. 18 Results of measurements of tumble ratio

used to study performance during operation at wide-open throttle. Turbocharger size results in a trade-off between low-speed torque and maximum power performance. For the new engine, small turbochargers able to achieve the target power were selected, and a balance was achieved between high power and high torque (Fig. 19). The turbochargers are directly mounted on the cylinder heads, thereby reducing the length of the pipes from the exhaust ports to the turbine and enhancing turbo response.

A high-efficiency air-cooling intercooler is positioned on the intake side, directly beside the engine (Fig. 20). Reducing the length of the turbocharger pipes from the compressor to the throttle reduces intake pressure loss, enhancing turbo response.

5.3. DI+PI Fuel Supply System

A DI+PI fuel supply system has been adopted in the new engine in order to provide a fuel supply system able to cope with the increased volume of fuel flow with higher engine power.

Increasing the size of a DI injector in order to increase the fuel supply presents an issue in adequately controlling the injection amount when the required amount of fuel is very small, for example when the vehicle is idling at high altitudes where the air density is low or in high-temperature

environments. In the new engine, the fuel flow range of the DI injector is the same as that in a conventional naturally aspirated engine. The DI injector satisfies the demands of fuel flow rate control on the low-flow-rate side, and is supplemented by PI during high-load driving, realizing a wide range of fuel flow rates.

The operation of DI and PI was comprehensively judged from the perspectives of combustion stability, brake specific fuel consumption (BSFC), and emissions, and was set as shown in Fig. 21.

(1) Low engine speed/high-load area

In this area, the turbocharger scavenges using Dual-VTC. DI is used in this area in order to help prevent fuel being blown to the exhaust system.

(2) High engine speed/high-load area

DI is supplemented by PI in this area in order to realize the demanded fuel flow.

(3) Partial area

To establish the partial area, the effect of the injection ratio between DI and PI was determined based on engine dynamometer testing with the results shown in Fig. 22. In a DI engine, it can occur that the vaporization and mixture of the fuel does not proceed in the low engine speed, low-load range in which the tumble flow is weak, and combustion stability declines. Combustion design for the new engine was conducted with DI as the basis, and port shapes were selected to generate a strong tumble flow even at low loads.

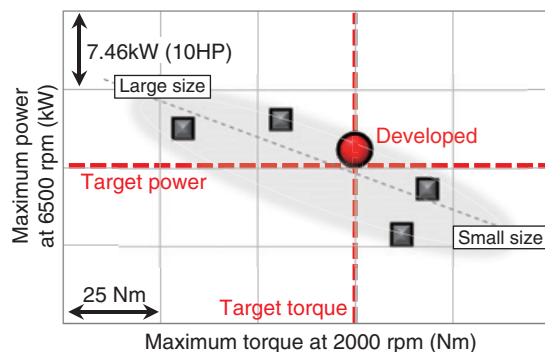


Fig. 19 Relationship between low-speed torque and maximum power

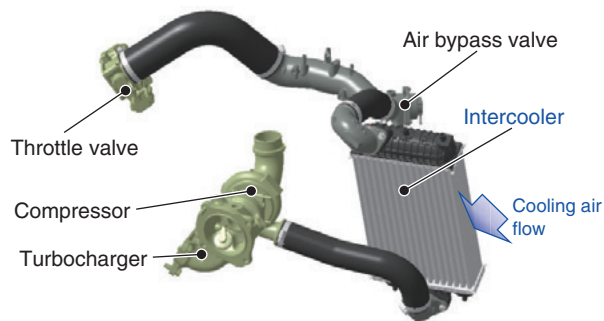


Fig. 20 Layout of turbocharger and cooling system

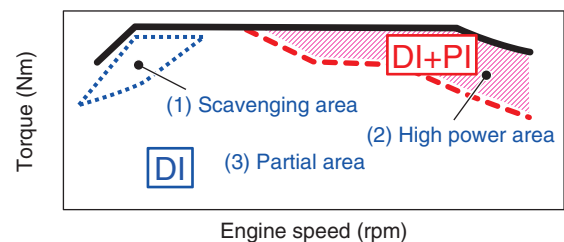


Fig. 21 DI+PI fuel injection system operation

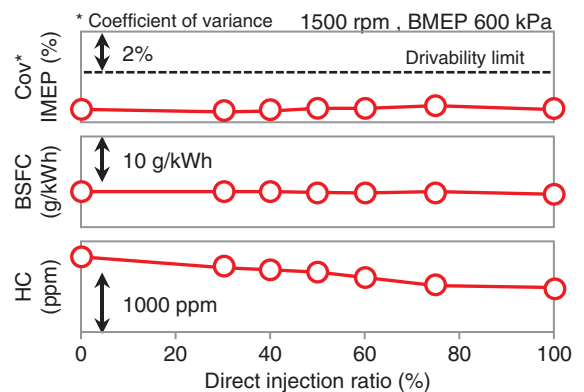


Fig. 22 Combustion characteristics by direct injection ratio

Because of this, combustion stability and BSFC do not change in response to the injection ratio between DI and PI, and rapid and stable combustion is ensured by a strong tumble flow, allowing the engine to achieve good combustion under all conditions. The PI spray has been set pointing downwards in order to control the adhesion of fuel sprayed by the PI system to the sleeve due to strong tumble motion at high loads. Because of this, a higher volume of fuel adheres to the undersides of the ports during PI at low loads. As a result, DI is superior from the perspective of hydrocarbons (HC) in the exhaust gas. Based on this result, DI only is used in the partial area.

This mode of operation has created a system that realizes optimal fuel supply throughout the entire driving range.

6. Achieved Engine Performance

6.1. Power Performance

Figure 23 shows the power and torque characteristics of the new engine.

The engine's maximum power of 373 kW (500 HP) is produced from 6500 rpm to 7500 rpm in the red zone. Maximum torque of 550 Nm is produced from 2000 rpm to 6000 rpm.

Using automotive performance design technologies, the engine power target was determined with consideration given to the power provided from the 3-motor hybrid system in order to achieve the overall vehicle dynamic performance target. In addition, the achievement of flat torque in the medium engine speed range offers a smooth acceleration characteristic with no feeling of inconsistency as engine speed increases.

The system overall achieves a maximum power of 427 kW (573 HP) and a maximum torque of 646 Nm, a level of power performance suited to the new NSX.

6.2. Fuel Efficiency Performance

The fuel efficiency of the new engine has been increased by rapid and stable combustion enabled through DI and high-tumble ports, and internal EGR achieved through Dual-VTC. In addition, knocking has been controlled by enhancing cooling performance in the area around the combustion chamber via the use of Fe spray-coated cylinder bores, pistons provided with cooling channels, and efficiently cooled cylinder heads, enabling a compression ratio of 10.0. As a result, the engine achieved a good BSFC characteristic across a wide driving range, and a maximum thermal efficiency of 36.3% (Fig. 24).

As a vehicle, the new NSX achieves a fuel consumption of 21.1 mpg in North American fuel consumption mode and 12.4 km/L in Japanese JC08 mode.

6.3. Emissions Performance

Reducing the volume of exhaust gas when the catalyst

is cold and speeding up the activation of the catalyst are particularly important factors in reducing emissions. In addition, because regulations on soot emissions are becoming more stringent, it is also necessary to reduce the amount of fuel adhesion in the cylinders, which is a factor in the production of soot.

In previous stratified combustion using a wall guide (a cavity), fuel adhesion to the top surfaces of the pistons cannot be prevented. By combining strong tumble motion and double injection by the DI system in the new engine, it has been possible to reduce the amount of fuel adhering to the pistons and to realize weak stratified combustion close to the spark plugs (Fig. 25)⁽²⁾.

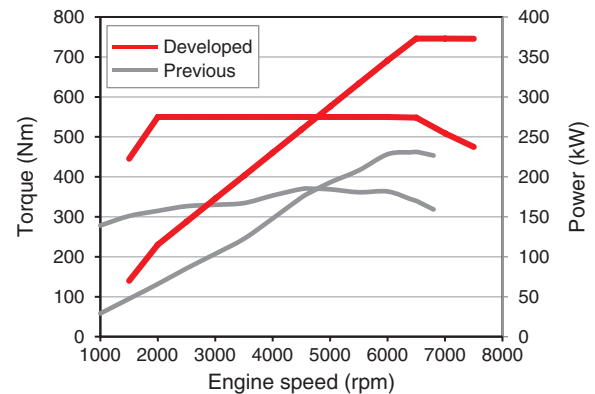


Fig. 23 Engine performance

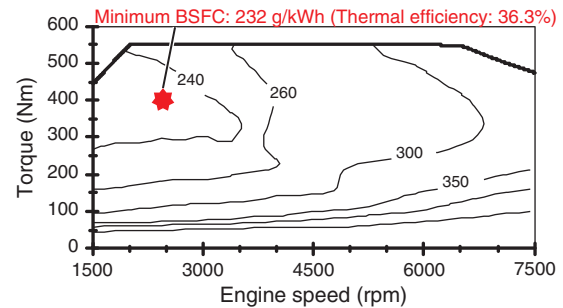


Fig. 24 Engine BSFC map

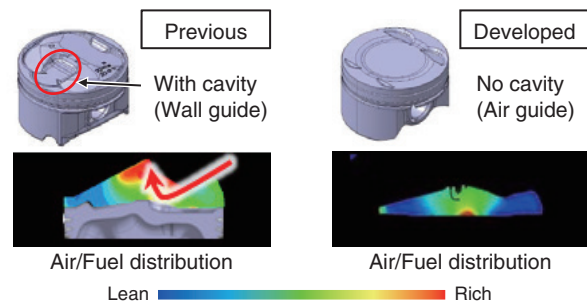


Fig. 25 Stratified combustion concept

Injecting during the intake and compression strokes and optimizing the injection amount and injection timing has achieved an A/F close to the spark plugs that promotes stable combustion, and reduced the amount of fuel adhesion to the pistons to one-half or less that of a conventional engine.

The realization of increased combustion stability has made it possible to retard ignition timing to approximately 20 deg before top dead center. The use of turbochargers has increased heat capacity, which could have reduced the warm-up performance of the catalyst, however the catalyst reaches 300°C or more within 20 sec following engine start (Fig. 26). As a result, mode emissions comply with the European Euro6b and the US ULEV125 regulations.

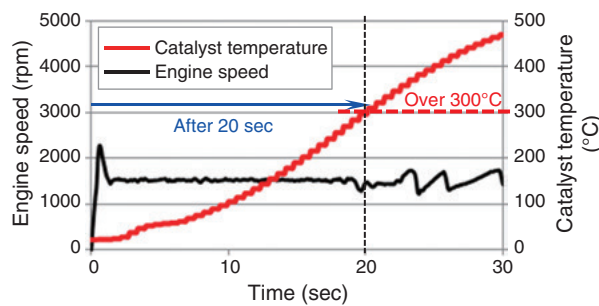


Fig. 26 Catalyst warm-up performance

7. Conclusion

A 3.5 L V6 turbocharged gasoline engine has been developed for the new NSX. As targets, the development of this engine set a high level of power performance and environmental performance, a compact engine layout with a low center of gravity suited to vehicle demands, and a level of engine reliability adequate to sports driving. The development process produced the following results:

- (1) The use of turbochargers and the combustion technologies in-cylinder direct injection and high-tumble ports, and the application of a DI+PI fuel supply system, have made it possible to balance high power characteristics (maximum power of 373 kW (500 HP) and maximum torque of 550 Nm) with emissions performance complying with the European Euro6b and US ULEV125 regulations.
- (2) The use of Fe spray-coated cylinder bores, a dry sump lubrication system, efficiently cooled cylinder heads, a swing arm-type valve train, and reduction chain drive have achieved a lightweight, compact, and low-center-of-gravity engine frame that also achieves a level of reliability, with increased engine power, suited to sports driving.

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New CVT for 2018 Model Year N-BOX

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ABSTRACT

A new CVT was developed based on the basic structure of the K-car CVT that started mass production in 2011, mainly with the goal of increasing efficiency. This new CVT was equipped on the 2018 model year N-BOX.

The new CVT reduces oil pump workload with the dual-rotor oil pump system, new CVT fluid, and enlarged pulley piston diameters, and enhances transmission efficiency with reduced friction in various areas, including reduced stirring resistance due to decreased oil levels. With these technologies, transmission efficiency was enhanced by 2% over the 2012 model year N-BOX CVT.

In addition, powertrain cooperative control has been adopted for better traction, together with the new shift control logic, G-design Shift logic. These changes provide quick response to driver demands and maintain high acceleration to achieve an exhilarating driving experience.

1. Introduction

With environmental issues such as global warming drawing increasing focus in recent years, the demands for reduction of automotive CO₂ emissions are growing even more. The transmission plays a large role in fuel economy improvements, and transmission performance also greatly contributes to drivability: what makes driving enjoyable to the driver.

Starting with the 1996 model year CIVIC⁽¹⁾, Honda has expanded its use of CVTs, which combine both fuel economy performance and driving excitement. Honda currently uses CVTs in a wide assortment of its compact⁽²⁾ and mid-size⁽³⁾ gasoline models, including its overseas models.

For the Japanese K-class, Honda has developed a lightweight, compact CVT characterized by primary reduction mechanisms with parallel shaft⁽⁴⁾. Since applying this CVT to the 2012 model year N-BOX, it has sequentially rolled out the CVT to other models, improving the overall fuel efficiency of K-cars.

For this full model change of the N-BOX, a new CVT was developed based on the basic structure of the previous K-car CVT, with more driving excitement, while realizing further weight reductions and enhanced transmission efficiency. This paper introduces the basic construction and key technologies of this new CVT.

2. Development Goals

The following items were the goals in developing the new CVT for K-cars:

- (1) Enhance transmission efficiency by reducing the oil pump workload through reduced oil pressure and other measures, and by reducing friction in various areas; and
- (2) Enhance drivability by developing powertrain cooperative control and CVT shifting control.

3. Key Specifications and Basic Construction

Table 1 compares the key specifications between the 2018 model year N-BOX CVT (hereinafter, “new CVT”) and the 2012 model year N-BOX CVT (hereinafter, “previous CVT”). Also, Fig. 1 depicts an exterior drawing of the new CVT, and Fig. 2 gives the main section view. The distance between pulley shafts and pulley ratio are set to be the same as those in the previous CVT, while the final reduction ratio was decreased from the previous CVT given the weight reductions to the vehicle body.

The four-shaft layout of the previous CVT was retained, situating a parallel shaft primary reduction mechanism upstream of the continuously variable transmission mechanism and eliminating the secondary reduction mechanism. While the case structure follows suit with a simple configuration, comprising just the transmission case

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Table 1 Specifications (NA model)

			2012 model year N-BOX	2018 model year N-BOX
Ratio	Primary reduction	Forward	1.605	1.605
		Reverse	1.187	1.290
	Pulley (low – overdrive)		2.293 - 0.420	2.293 - 0.420
	Final gear		5.176	4.318
Dimension	Overall length [mm]		344.5	344.5
	Pulley axis distance [mm]		147	147
Weight (Wet) [kg]			59.6	56.9

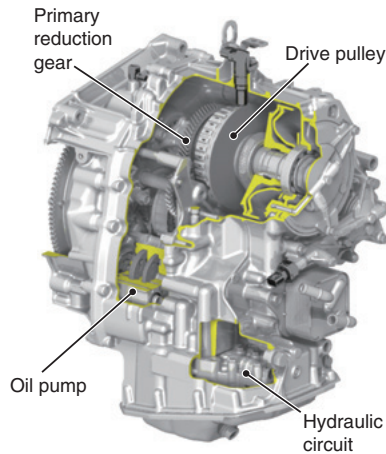


Fig. 1 Appearance of new CVT

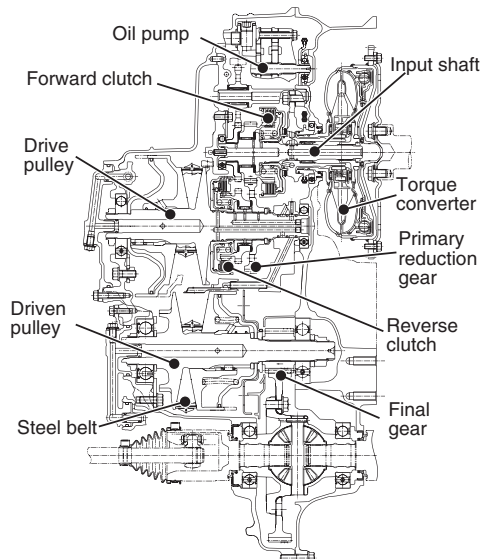


Fig. 2 Main section of new CVT

and torque converter case, changes were made to adapt to the new oil pressure control system and enlarged pulley diameters.

The new CVT will be mated to two engine types: naturally aspirated (NA) and turbocharged (TC). The differences are adjusted for with different torque converters, forward primary reduction ratios, and final reduction ratios.

4. Transmission Efficiency Enhancements

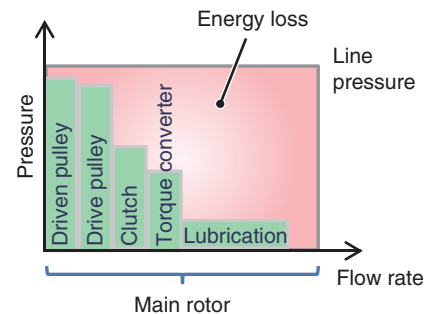
Three main factors are known to degrade transmission efficiency in CVTs: metal belt friction, loss in driving the oil pump, and stirring resistance. In the new CVT, oil pump drive torque was reduced by reducing the pump discharge pressure, in turn achieved by adopting the dual-rotor oil pump system and new CVT fluid, as well as by enlarging pulley piston diameter. Also, stirring resistance was reduced by decreasing the oil level for enhanced transmission efficiency.

4.1. Dual-rotor Oil Pump System

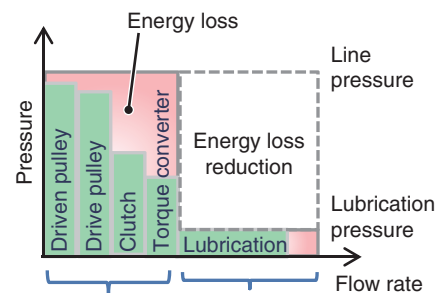
For the new CVT, the dual-rotor oil pump system was adopted, reducing oil pump drive torque. The new pump system comprises an oil pump with two sets of rotors and a hydraulic circuit, which is equipped with a switching valve and switching control solenoid.

4.1.1. Operating principle and hydraulic circuit

A conceptual diagram of energy loss in the oil pump of the previous system is given in Fig. 3(a). The line



(a) Conventional system



(b) Dual-rotor oil pump system

Fig. 3 Concept of energy loss reduction

pressure, or oil pump discharging pressure, is controlled to cover the required hydraulic pressure, as determined by the driving conditions. Loss was high in the previous system, particularly in driving conditions that required higher hydraulic pressures. The entire discharge volume was first brought up to line pressure, then pressure was successively reduced to regulate pressures for the pulleys, clutch, torque converter, and lubrication.

In the new system, discharge is bifurcated, with pressure reduced on the one side to discharge the lubrication pressure directly. This reduces the oil pump workload as given in Fig. 3(b). As shown in detail in the hydraulic circuit of Fig. 4, two sets of oil pump rotors are arranged with independent discharge oil passages, with discharge on the main rotor constantly regulated to the line pressure by the main regulator valve. Meanwhile, the sub-rotor incorporates a switching valve in the discharge oil passage that can select between feeding to the main regulator valve and regulating to line pressure, or feeding to the lubrication regulator valve and regulating to the lubrication pressure. During rapid shift changes and other driving conditions that require heavy flow at high pressure for the pulleys, both rotors can discharge to line pressure to secure sufficient discharge volume. In steady driving and mild acceleration, the sub-rotor discharges at lubrication pressure to reduce loss.

Hereinafter, the state in which sub-rotor discharge is regulated to line pressure by the main regulator valve will be referred to as “high-pressure mode,” and that in which sub-rotor discharge is regulated to lubrication pressure by the lubrication regulator valve will be referred to as “lubrication mode.”

4.1.2. Oil pump construction and specifications

The construction of the oil pump is shown in Fig. 5. The compact construction has two sets of rotors driven by a single shaft, with a single barrier plate positioned within the oil pump between the main rotor and sub-rotor. The pump has a shared suction port but is fitted with independent discharge ports for each rotor.

Theoretical discharge for the main and sub-rotors was

set as described below, aiming to keep total actual discharge equivalent to that of the previous system and to increase fuel efficiency to the utmost.

In combining the theoretical discharge of the main and sub-rotors to equal actual discharge, reducing the main rotor theoretical discharge too much would decrease drive torque for lubrication mode but, due to a balance judgment to be described below, also limit how frequently lubrication mode is used in driving, limiting fuel efficiency savings. Conversely, whereas increasing the main rotor theoretical discharge too much would allow for more driving in lubrication mode and drive torque in lubrication mode would be reduced only slightly, again limiting fuel efficiency savings.

Upon fixing the discharge volume, the workloads needed to drive the oil pump in the decided drive modes were calculated to combine the main and sub-rotor theoretical discharges such that total actual discharge equals that of the previous oil pump. The results are shown in Fig. 6, giving the reduction in workload between the main rotor theoretical discharge and the previous system, as well as the frequency in time that the vehicle is driven in lubrication mode. In the new CVT, the theoretical discharge that minimizes the combined workload was selected to

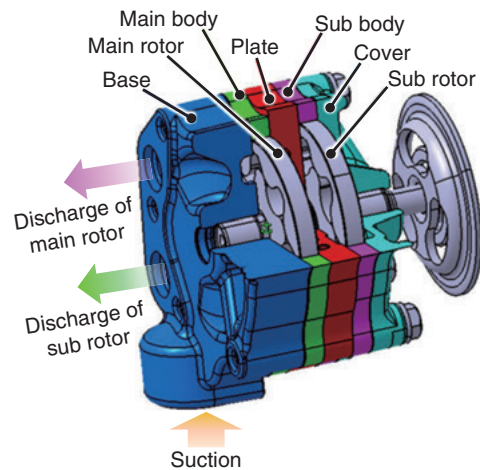


Fig. 5 Construction of dual-rotor oil pump

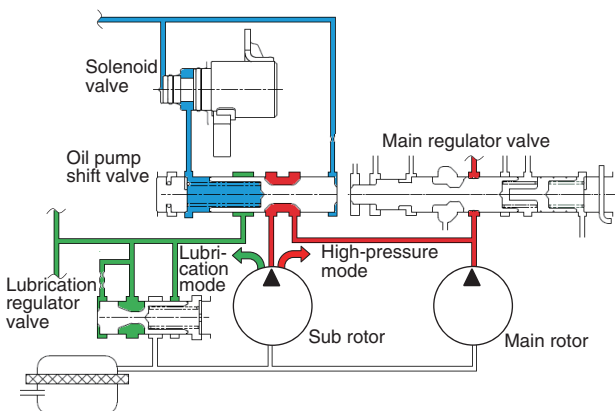


Fig. 4 Hydraulic circuit

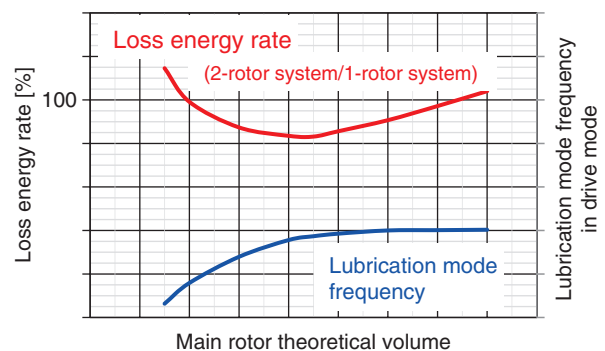


Fig. 6 Setting of oil pump volume

secure the needed discharge volume while improving fuel economy performance.

As an example, Fig. 7 gives the oil pump drive torque when driving with a line pressure of 1 MPa. In lubrication mode, drive torque was reduced by approximately 30% compared to that of the previous system.

4.1.3. Discharge mode switching control

For mode switching, a control system was adopted to continuously calculate the flow rate balance for the driving conditions and switch between high-pressure and lubrication modes based on the calculations.

More specifically, the system switches to lubrication mode when the main pump discharge volume sufficiently exceeds the sum total of pulley side pressure flow needed for rapid change, the flow needed for the torque converter, and leakage of each part; when this volume is insufficient, the system switches to high-pressure mode (see Fig. 8).

4.2. New CVT Fluid

The new CVT will use the new CVT fluid⁽³⁾ as rolled out starting with CVTs for 2013 mid-size models. The higher metal friction coefficient has reduced the belt clamping force needed to transmit torque, reducing line pressure.

4.3. Enlarged Pulley Piston Diameter

The maximum system pressure is set to be either the

drive pulley side pressure or driven pulley side pressure, depending on the driving conditions. In such a system, reduction of the drive pulley side pressure by enlarging the drive pulley piston diameter is effective in reducing line pressure, particularly in steady driving. For the new CVT, the drive pulley outer piston diameter was enlarged from 150 mm to 160 mm, increasing the pressure receiving area by approximately 15%. Reducing clamp force with the aforementioned new CVT fluid and using CAE to effectively reduce stress (see Fig. 9) has enlarged piston diameter while reducing weight.

4.4. Reduced Oil Pump Drive Torque

The reductions to oil pump drive torque under steady driving at 60 km/h are shown in Fig. 10. Oil pump drive torque was reduced approximately 37% for similar

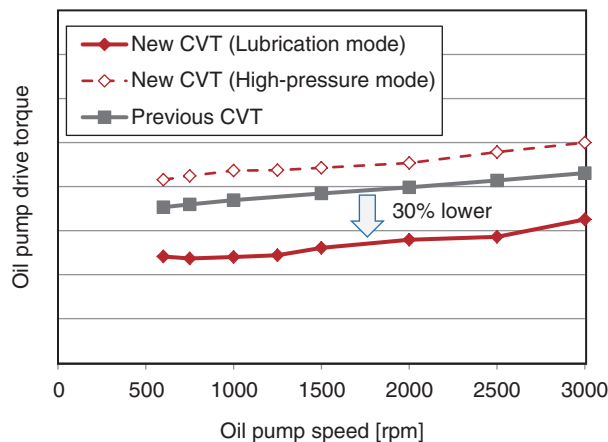


Fig. 7 Oil pump drive torque characteristic

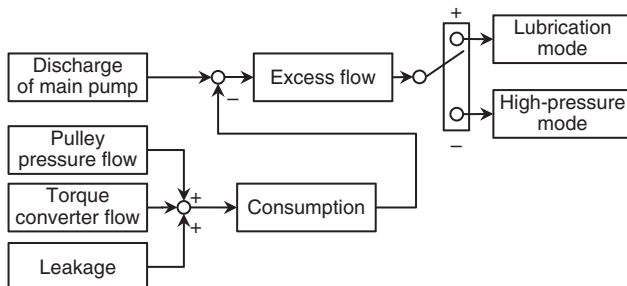
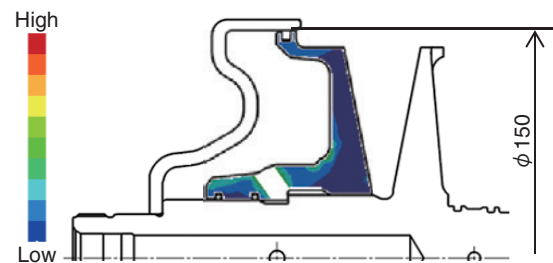


Fig. 8 Judgment of flow balance



(a) Previous CVT



(b) New CVT

Fig. 9 Drive pulley construction and stress contour

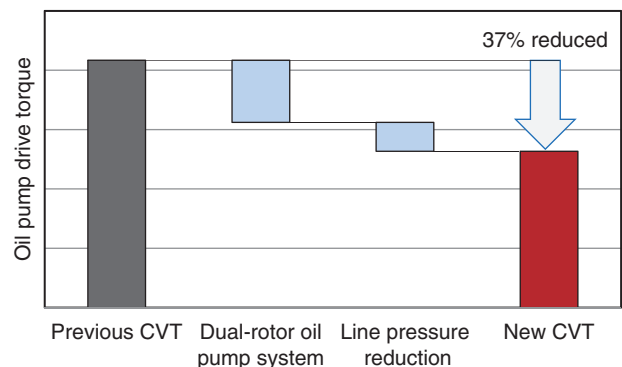


Fig. 10 Reduction of oil pump drive torque

conditions thanks to reductions in loss from adopting the dual-rotor oil pump system, and to reductions in line pressure from adopting new CVT fluid and enlarging the drive pulley piston diameter.

4.5. Friction Reductions

In order to reduce friction for each area, the other sliding and revolving areas, namely the oil seal and seal rings, were replaced with low friction parts, and oil levels were reduced to reduce gear stirring resistance.

While reducing oil levels does reduce stirring resistance, it also adds the concern of reduced oil pressure when oil shifts to one side within the transmission during acceleration, deceleration, or cornering, forcing air intake from the strainer. Sloshing from the gears and inertial forces make it challenging to accurately predict the motion of oil between the gaps in the complex shapes in the transmission. In development for the previous system, the oil level and position of the strainer intake port had to be experimentally confirmed.

In development for this CVT, CVT fluid agitation from the gears and air entrainment was modeled with CFD^{(5), (6)} in the design phase to predict dynamic behavior of the fluid in the transmission. As a result, strainer intake port position and the required fluid amount were effectively rationalized, reducing the fluid level by approximately 5 mm. Results from analysis of oil agitation from the gears and pulleys are given in Fig. 11(a), and those from analysis of fluid shifted by inertial force during deceleration in Fig. 11(b).

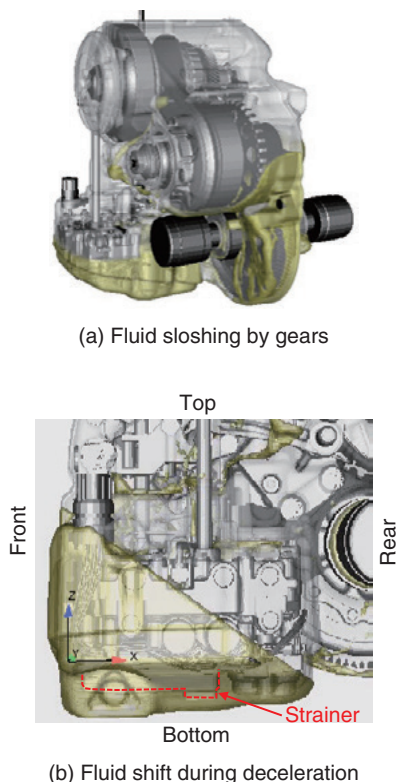


Fig. 11 Simulated trajectory of new CVT fluid

Transmission efficiency for the new and previous CVT by vehicle speed for steady driving conditions is given in Fig. 12. Transmission efficiency in steady driving was increased 2% with the technologies described in the previous sections. In addition, CVT weight was reduced by approximately 2.7 kg by reducing pulley shaft weight, lowering oil volume, and making other adjustments.

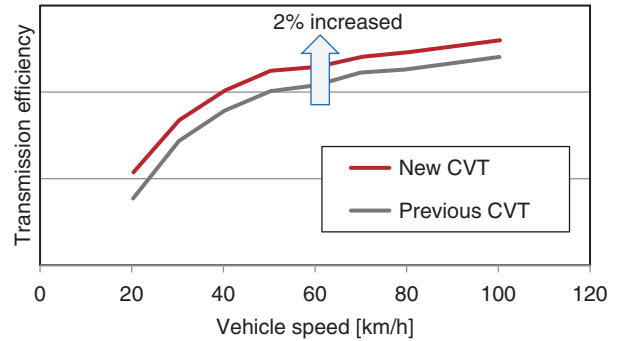


Fig. 12 Increased transmission efficiency

5. Drivability Enhancements

A new shift control logic, G-design Shift logic, was adopted to enhance drive feel in the new CVT. G-design Shift logic offers powertrain cooperative control with drive force target values and responds quickly to driver demands to maintain a high, sustained acceleration feel. By designing these controls to optimally fit driver feel, the system achieved an exhilarating, sporty drive feel.

5.1. Powertrain Cooperative Control

Figure 13 diagrams the control structure for both the previous drive-by-wire cooperative control and the newly adopted powertrain cooperative control with drive force target values. In the previous control system, the throttle is opened according to the accelerator pedal position. When engine speed is increased by changing the CVT ratio, engine load has a tendency to decrease, in turn reducing torque and resulting in acceleration that gradually tapers off.

In the new CVT, powertrain cooperative control is adopted with drive force target values. Engine torque output is determined according to the change in CVT ratio, thus allowing the system to restrict decreases in engine torque as engine speeds increase.

5.2. G-design Shift Logic

The G-design Shift logic offers shift schedules for quick response and sustained high acceleration. If the system clearly senses an intention to accelerate from driver input in terms of accelerator pedal position and pressing speed, it switches over to a dedicated shift schedule.

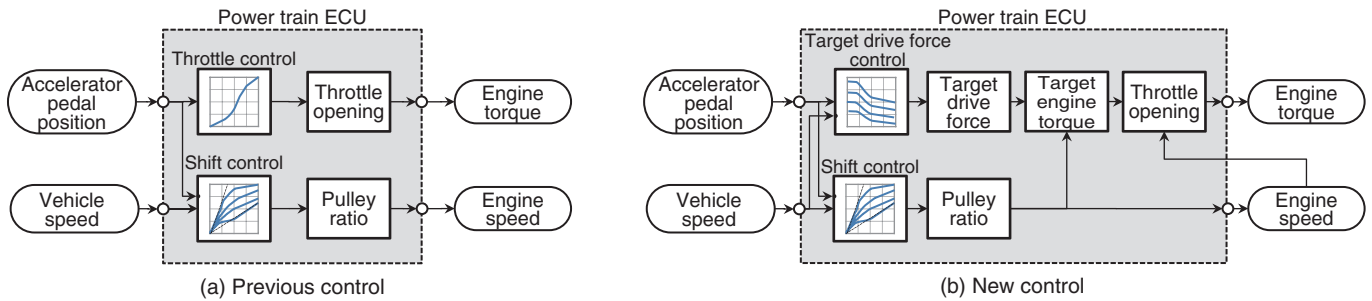


Fig. 13 Schematic diagram of cooperative control

5.3. Acceleration Feeling at Launch

When launching from a stop or from the low-speed range, if the system judges that the driver intends to accelerate, the dedicated launching shift schedule is selected to keep engine speed elevated, producing acceleration launch performance with sustained high acceleration (see Fig. 14).

5.4. Direct Feel during Kick-down Acceleration

The shift schedule after step shifting by kick down was revised for the new CVT. Images of the new and old shift schedules are given in Fig. 15. Whereas in the previous system, the shift characteristics were controlled to converge to the normal shift schedule even after kick down, the new CVT has a dedicated setting of the shift schedule after step shifting by kick down that increases vehicle speed with engine speed synchronously.

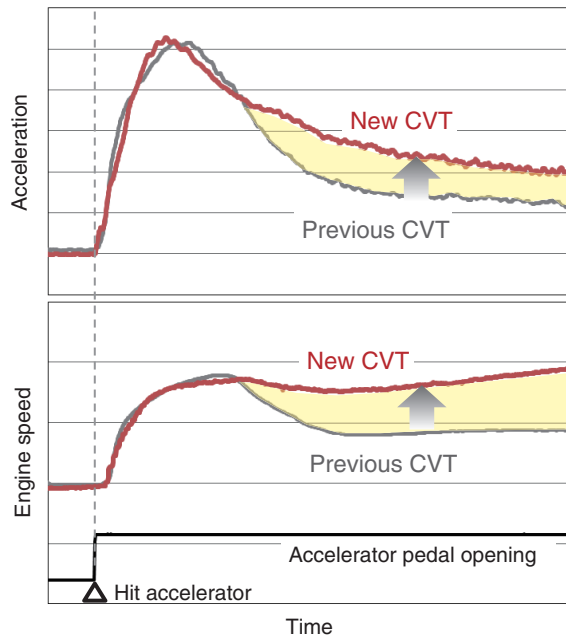
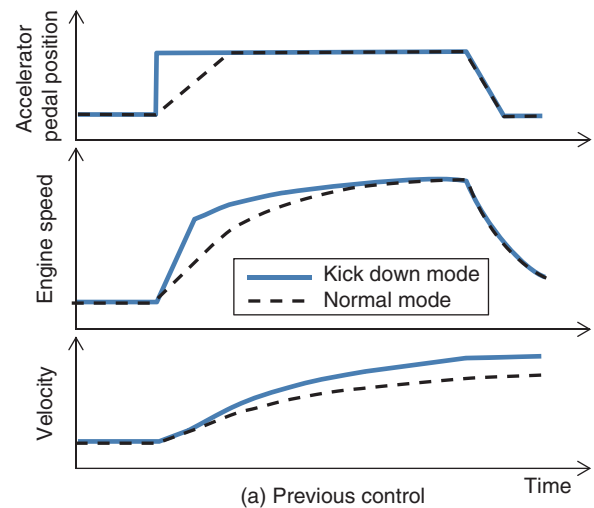
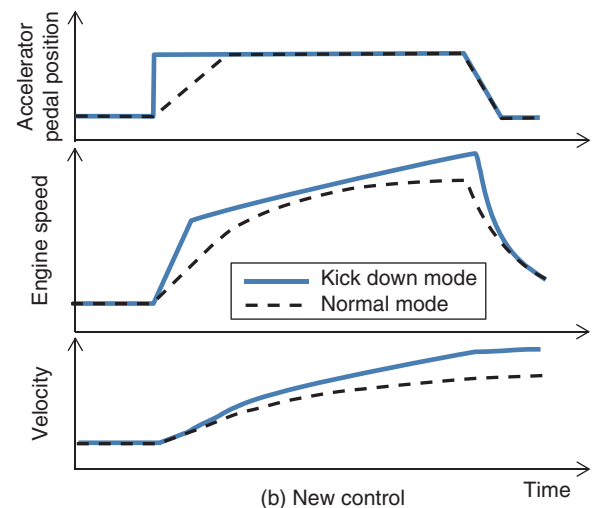


Fig. 14 Launch acceleration characteristics

The shift schedule after step shifting is designed to optimally increase engine speed according to accelerator pedal position, achieving acceleration performance that feels linearly linked to engine speed and maintains high acceleration (see Fig. 16).



(a) Previous control



(b) New control

Fig. 15 Kick down shift control

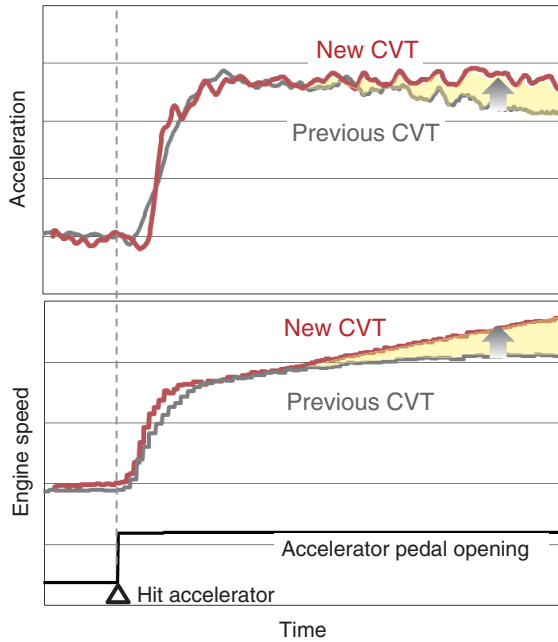


Fig. 16 Kick down characteristics

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6. Conclusion

A K-car CVT was developed with the following results:

- (1) Transmission efficiency was enhanced by 2% with technologies including a dual-rotor oil pump.
- (2) Acceleration characteristic matching driver feel was achieved with powertrain cooperative control and new shift control logic.

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Hideo NIRASAWA



Toshikazu UNEYAMA

Design of Safety Factor for Slip of Half-toroidal Variator by Dynamic Behavior Analysis

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ABSTRACT

In order to determine the power transmission characteristics of half-toroidal variators, a dynamic behavior analysis technique was developed to predict the traction coefficient. The approach uses the finite element method so that the elastic deformation of the parts in actual operation can be reproduced in variator modeling. As the technique reflects the shear characteristics of the traction fluid on the traction surface, frictional force was identified based on a four-roller test and used for the contact surface in the behavior analysis model. To control ratios, feedback control was applied based on the shifting mechanism of the toroidal variator. Using this technique to quantitatively predict the change in slip rate for the traction coefficient of the half-toroidal variator allows for the corresponding safety factor to be established.

1. Introduction

Demands continue to increase in recent years for response to environmental issues such as global warming. With these demands, fuel consumption of automobiles is decreasing, thanks to factors such as enhanced efficiency of engines and application of electrified powertrains. For transmissions, extension of the ratio coverage is demanded in order to achieve both better fuel economy when cruising and the required acceleration force for launching. For example, the nine-speed AT covers the ratio spread of 9.823⁽¹⁾. In metal pushing V-belt-type CVTs as well, transmissions with a ratio coverage of 8.7⁽²⁾ have seen practical applications incorporating an auxiliary gearbox.

The infinitely variable transmission (IVT)⁽³⁾ presents possibilities as a transmission for allowing even wider ratio coverages. In the IVT, the ratio of transmission output rotation speed to input rotation speed can be set to zero. This ratio is called the geared neutral (GN) point. At near this ratio, a lower speed ratio can be achieved for takeoffs. This renders the torque converter and start clutch unnecessary and is expected to reduce both slip loss and number of parts.

The authors have developed an IVT utilizing a half-toroidal variator in the shift mechanism. In order to shift the variator speed ratio from the maximum speed side to the minimum side, the pulley on a metal pushing V-belt-

type CVT requires a stroke of approximately 20 mm. Meanwhile, the power roller on a toroidal-type CVT only needs to be offset by approximately 1 mm, offering the advantage of faster shifting. This characteristic can enhance response levels during kick down and reduce time lags during acceleration. Further, reports show that transmitting efficiency is high during usage in the high-speed range⁽⁴⁾.

The power transmission of the toroidal variator is through traction drive, a mechanism by which power is transmitted through the shear force of the traction fluid interposed between two bodies. Pressing the two surfaces together at high pressure causes the traction fluid to undergo a glass transition into a solid phase⁽⁵⁾. Determining the traction coefficient, or ratio of shear force to contact force, and setting appropriate its values for use when operating will enhance transmitting efficiency and reliability against slipping. However, whereas operation with a high traction coefficient will enhance transmitting efficiency, a state of gross slip will result if the limit value is exceeded, and no power will be transmitted.

To date, the traction coefficient has been predicted⁽⁶⁾ and measured⁽⁷⁾. These studies, however, focus on the maximum value and do not go into detail on the relationship with the slip rate. In this paper, therefore, a dynamic behavior analysis technique was developed for half-toroidal variators to predict the traction coefficient in actual operation. This allows for quantitative prediction of the relationship

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between the transmitting efficiency and slip rate for the traction coefficient used. This paper will report methods for establishing the safety factor.

2. Transversely Installed Half-toroidal IVTs

2.1. IVT Configuration

Figure 1 depicts a cross-section of the prototyped IVT for a front-wheel-drive vehicle, and Fig. 2 gives the relationship between the speed increasing ratios of the IVT

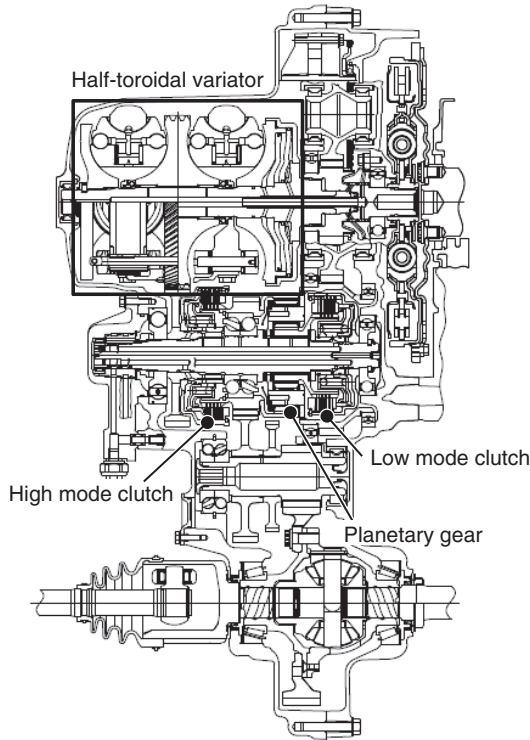


Fig. 1 Cross section of half-toroidal IVT

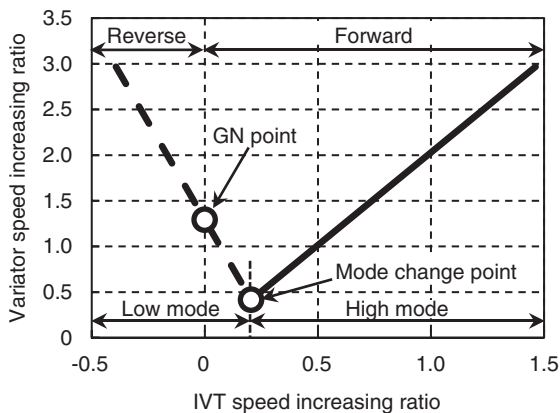


Fig. 2 Relationship between variator and IVT speed increasing ratio

and variator. A double-cavity half-toroidal variator was positioned on the input shaft, and the planetary gears for splitting power and the low- and high-mode clutches for shifting modes were positioned on the countershaft. Here, low mode is used mainly during takeoffs and reversing, and is thus set to a ratio width including the GN point. High mode, also called the CVT mode, includes cruising conditions.

2.2. Mechanism of Power Transmission for Half-toroidal Variator

Figure 3 shows an external view of the double-cavity half-toroidal variator, and Fig. 4 shows its cross-section. In order to allow for transverse installation on the vehicle, total length is shortened compared to longitudinal installation⁽⁸⁾ with changes including integration of the front and rear cavity output disks and the output gear⁽⁹⁾, and involute splines to fit the input shaft and input disk. The power rollers are supported by trunnions via thrust bearings. The power rollers are driven by axial force from the hydraulic loading piston to rotate between the input and output disks, and driving power is transmitted by the torque flow. This



Fig. 3 Double-cavity half-toroidal variator

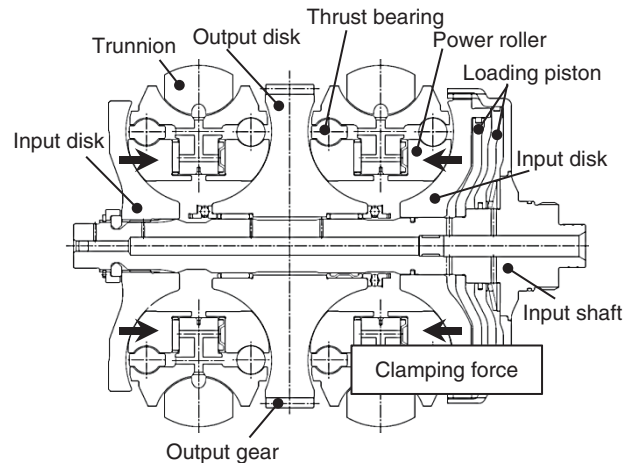


Fig. 4 Cross section of double-cavity half-toroidal variator

process is depicted in Fig. 5.

Tilting the power rollers to alter the ratio of r_1 and r_2 will in turn alter the toroidal variator ratio (see Fig. 6). Here, r_1 and r_2 are the radii of the respective points of contact on the power roller for the input and output disks.

2.3. Shifting Mechanism

Figure 7 depicts the shifting mechanism for the toroidal variator. Here, V_{id} , V_{od} , and V_{pr} are the circumferential

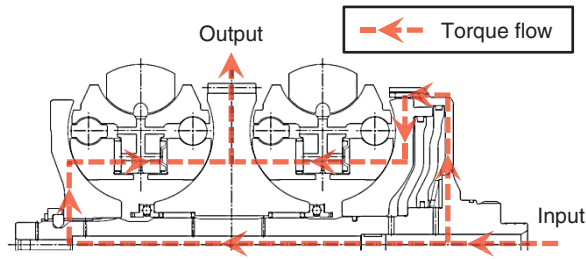


Fig. 5 Torque flow of double-cavity half-toroidal variator

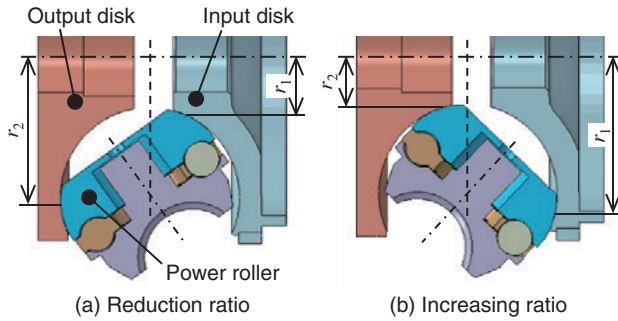


Fig. 6 Relationship between ratio and contact radius

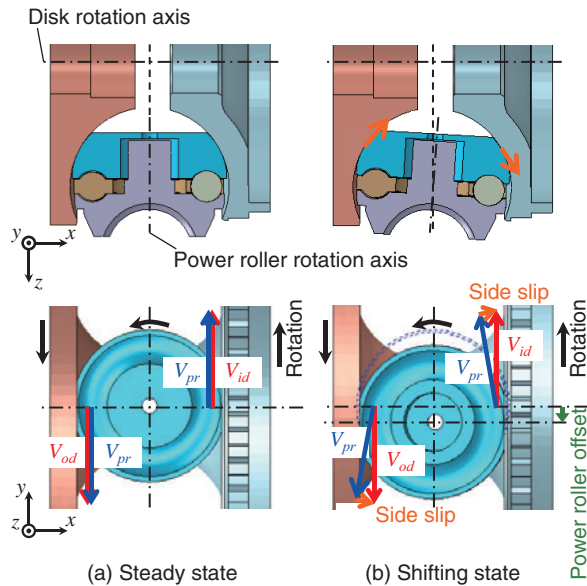


Fig. 7 Shifting mechanism

velocity at the respective points of contact for the input disk, output disk, and power roller. As depicted in Fig. 7 (a), when the rotation axis of the power roller is on plane zx including the input and output disk rotation axes, the directions of V_{id} and V_{pr} are aligned and the power roller does not tilt. This puts the ratio in a steady state. Meanwhile, as depicted in Fig. 7 (b), offsetting the power roller slightly in axial direction y will produce a difference in orientation between V_{id} and V_{pr} . The frictional force in the tilted direction produced by this difference will set the power roller into a tilting motion, transitioning it to a shifting state. When the power roller is returned from its offset, the tilting motion will stop and the power roller returns to the steady-state ratio. When looking to shift in the reverse direction, the power roller is offset in the opposite direction.

Each of the power rollers is offset by the hydraulic shifting piston mounted on the lower part of the trunnion (see Fig. 8). Hydraulic pressures P_{high} and P_{low} are exerted on the upper and lower parts of the pistons, respectively. A pressure difference is created by increasing P_{high} when shifting to the speed increasing side or P_{low} when shifting to the reduction side, moving the trunnion up or down.

2.4. Power Transmission Characteristics

Figure 9 depicts a concept drawing of the power transmission characteristics for the half-toroidal variator

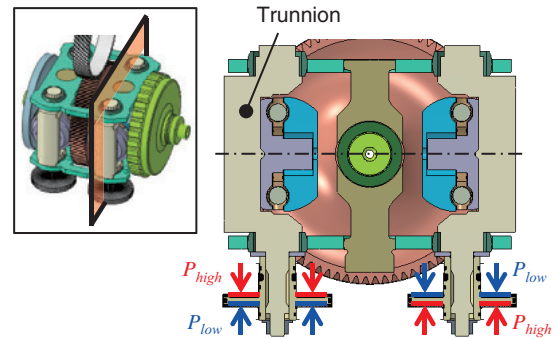


Fig. 8 Shifting piston

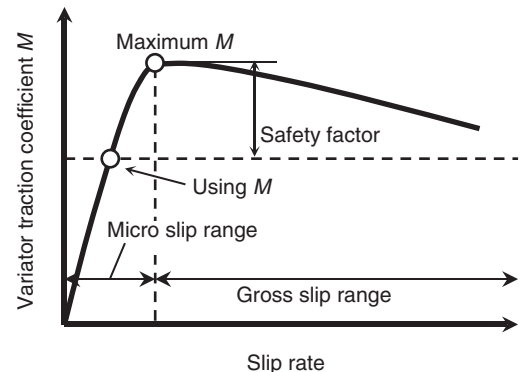


Fig. 9 Traction characteristic of variator

(M -Slip characteristics). Traction coefficient M of the half-toroidal variator is defined as given in Eq. (1):

$$M = \frac{T_{cav}}{n \cdot r_1 \cdot F_c} \quad (1)$$

Here, T_{cav} is the transmission torque per cavity, n is the number of power rollers per cavity, and F_c is the contact force between power roller and input disk. Given their relationship in Eq. (1), the greater the contact force is relative to transmission torque, the smaller M will be. This contact force F_c is reduced by the axial force from the hydraulic loading described in Section 2.2. If axial force is insufficient for the transmission torque, the variator will enter a gross slip and no torque will be transmitted. Conversely, it is known that applying axial force in excess reduces transmitting efficiency⁽¹⁰⁾. In order to establish traction drive and avoid reducing transmitting efficiency, the axial force created should be in step with the operation state in just proportion. Thus, the appropriate safety factor should be required upon pre-determining the limit value of M to operate the variator.

3. Goals and Targets

In order to predict the power transmission characteristics of the half-toroidal variator and use simulations to set the safety factor for gross slip, development proceeded with the following targets:

(1) Create a dynamic behavior analysis technique for

variators that reflects the shear characteristics of the traction fluid

(2) Quantify the relationship between traction coefficient M and transmitting efficiency

(3) Visualize the spin state of the traction surface

4. Dynamic Behavior Analysis Technique for Half-toroidal Variators

4.1. Identification of Traction Fluid Characteristics

The shear characteristics of the traction fluid were identified based on the actual measurement values to be reflected in the simulations. Figure 10 shows a sample relationship⁽¹¹⁾ between traction fluid limiting shear strength τ_L [MPa] and pressure p [GPa]. As shown, the shear strength of the traction fluid is characteristically known to quickly increase under high surface pressure. Also, the shear characteristics change depending on the fluid temperature and slip speed of the two surfaces the fluid flows between. Accordingly, shear force of the traction fluid to be used was measured with surface pressure, temperature, and slip speed as the parameters.

Traction fluid characteristics were measured using the four-roller machine⁽¹²⁾ shown in Fig. 11. Relative slip speed can be controlled by forcing a difference in rotational speed between the three outer rollers, which revolve at the same speed, and the center roller. However, as the rotation axes of the rollers on the four-roller machine parallel one another, no spin as seen in the toroidal variator is produced on the test apparatus traction surface.

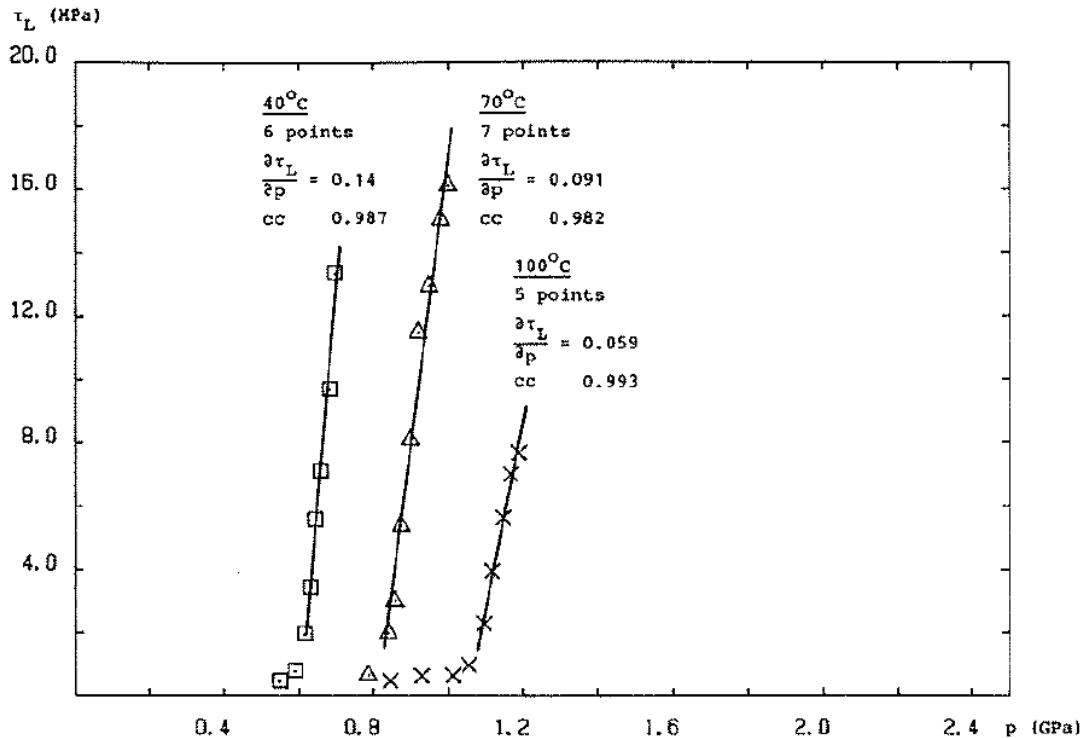


Fig. 10 Limiting shear strength for lubricant No. 9, traction fluid, as a function of pressure and temperature

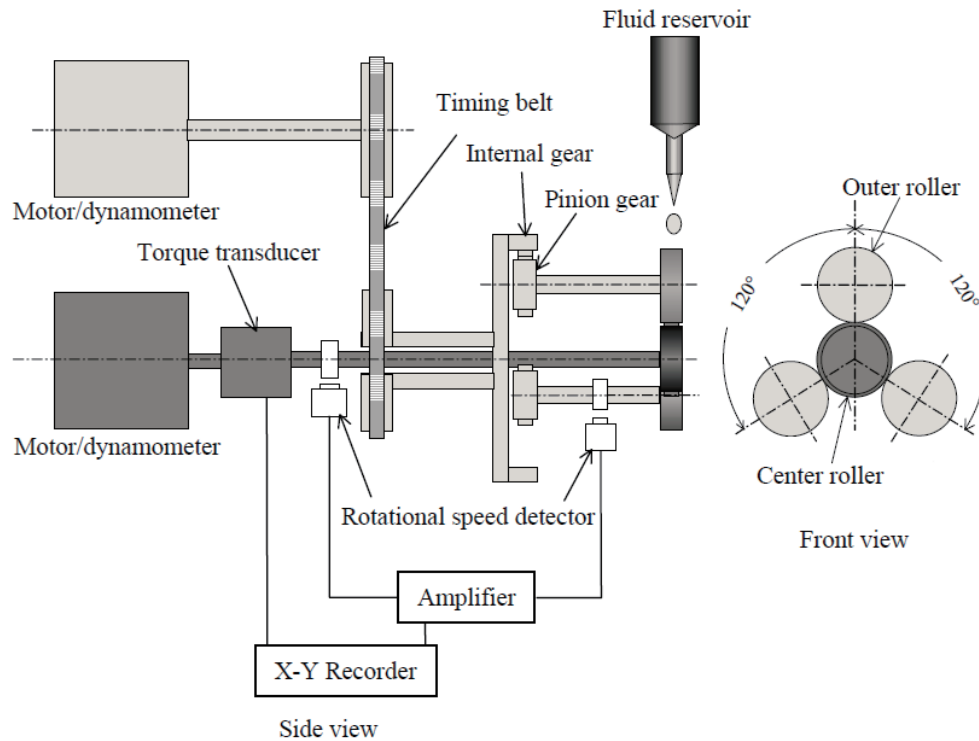


Fig. 11 Structure of the four-roller machine

As traction drive is treated as the model for friction transmission in the behavior analysis model, the shear force of the traction fluid should be replaced with the frictional force of the contact surface. A behavior analysis model was therefore created for the four-roller machine (see Fig. 12) to identify the frictional characteristics for achieving the same torque response as the measured results from Fig. 13. The created model was taken as the flexible body, and the mesh size was taken as the expressible size at which the rollers rolled smoothly.

As a sample friction coefficient identified by the four-roller test model, Fig. 14 gives the coefficient values for each contact pressure at 100°C. While measured traction coefficients are normally given as averaged for the entire contact surface, the friction coefficients given here are values for each nodal point measured on the contact surface.

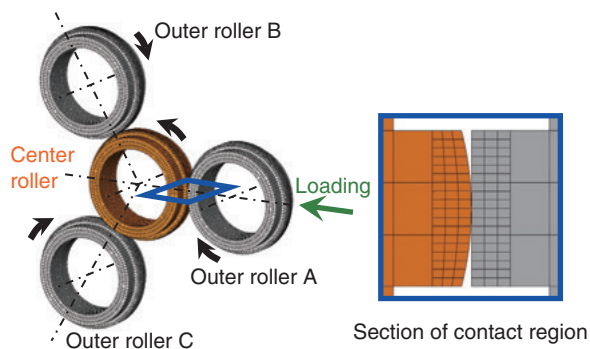


Fig. 12 Simulation model of four-roller machine

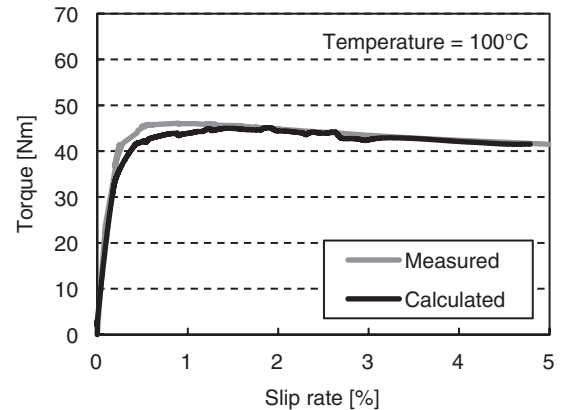


Fig. 13 Comparison between measured and calculated torque

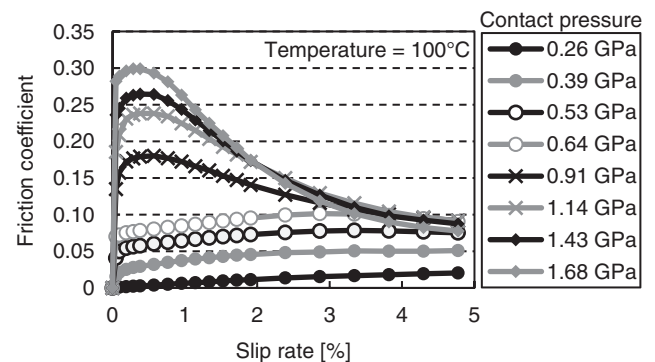


Fig. 14 Friction coefficient of traction surface for simulation model

The identified friction coefficients are high at high contact pressures, perceived to be characteristic of the traction fluid.

4.2. FEM Model for Half-toroidal Variator

Figure 15 shows a half-toroidal variator model using behavior analysis. The contact pressure required to establish traction drive reaches approximately 4 GPa at maximum. Therefore, in actual operation of the half-toroidal variator, the contacted surfaces and other parts operate in a state of elastic deformation. To account for this elastic deformation, FEM was used to model the parts. In order to utilize the traction fluid shear characteristics identified with the four-roller test model, the mesh size for the traction surface was made the same as that for the roller surfaces in the four-roller test model. A predetermined clamping force was applied to the power roller by hydraulically pressurizing the loading pistons. The shift force required for ratio control is generated by directly applying an axial force to the lower part of the trunnion in place of the shifting piston hydraulics. The shift force is controlled for feedback based on the operating state.

A block diagram using variator ratio control is given in

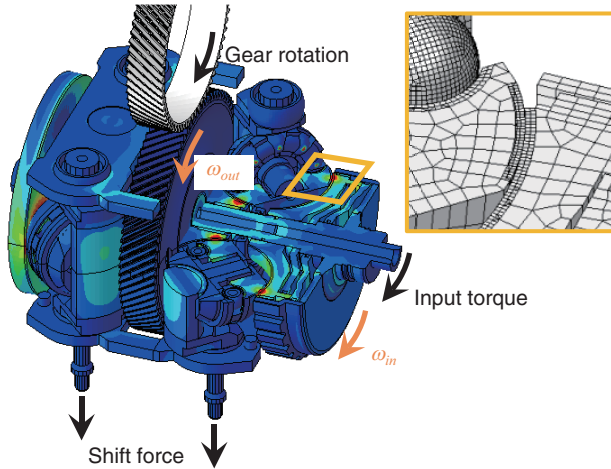


Fig. 15 Simulation model of half-toroidal variator

Table 1 Operating conditions

Input speed	1000 rpm
Input torque	300 Nm
Variator speed ratio i_V	0.430

Fig. 16. The feedback comprises that from ratio deviation and from offset deviation. Speed ratio i_V , representing the ratio of input disk rotation speed ω_{in} and output disk rotation speed ω_{out} , is expressed with the following equation:

$$i_V = \frac{\omega_{in}}{\omega_{out}} \quad (2)$$

For offset deviation, observational estimates were used with no sensors.

The M -Slip characteristics for the variator were predicted by simulation under the operating conditions in Table 1. As illustrated in Fig. 17, values for M were changed by decreasing loading piston pressure at a constant input torque. As shown in Fig. 18, test values generally reproduced the M values predicted in the simulations.

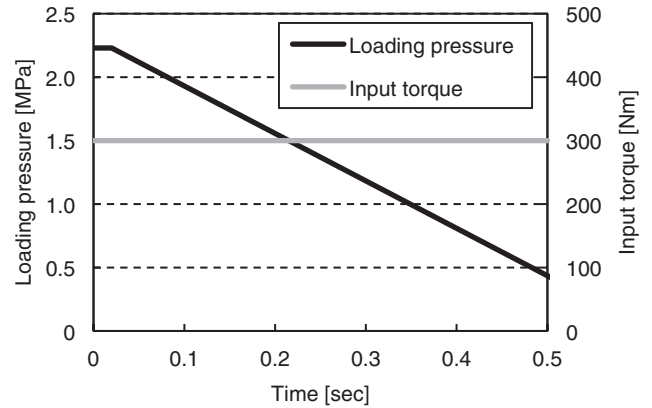


Fig. 17 Operation of loading pressure

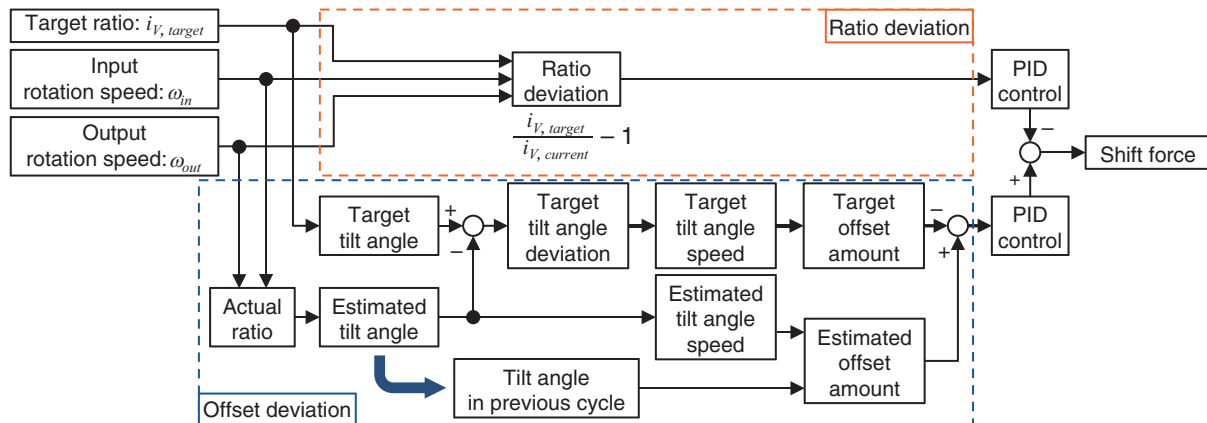
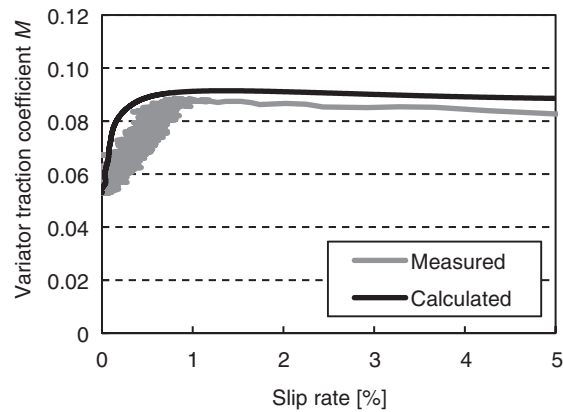


Fig. 16 Speed ratio controller

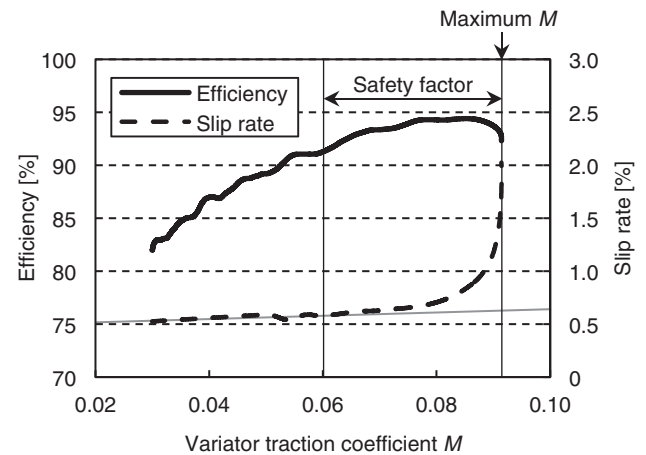
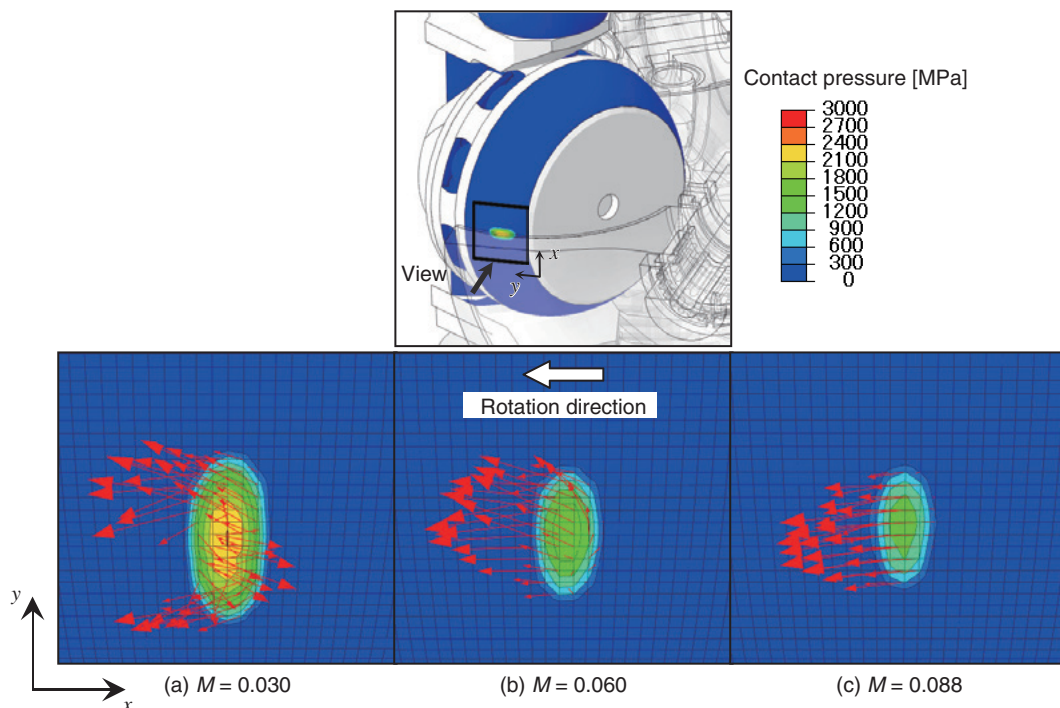
Fig. 18 M -Slip characteristics of variator

5. Safety Factor and Power Transmitting Efficiency

Figure 19 shows the relationship of transmitting efficiency and slip rate for M as obtained in the simulations. From Fig. 9, in the micro slip range, the safety factor for gross slip increases as M decreases. However, as seen in Fig. 19, transmitting efficiency for the variator is low when M is smaller. This is perceived to show that transmitting efficiency decreases the more excessive contact force is applied to the transmitted torque. One possible factor in this is increased spin on the traction surface. The distribution of frictional force on the power roller traction surfaces (see

Fig. 20) shows that spin increases as M decreases. In this way, spin on the traction surface will change according to the contact force, even at a constant torque and ratio. Also, when M is larger, transmitting efficiency is lower in Fig. 19 regardless of how small the traction surface spin. This may be due to the slip rate increasing sharply and more loss due to slippage near maximum M at the right edge of the graph.

The curve for slip rate change is linear at M values of near 0.06 and below and non-linear at M values greater than 0.06. The slip rate will sharply increase, with a tendency to reach gross slip, as M increases due to sudden changes in running resistance of the vehicle when M is larger.

Fig. 19 Relationship of efficiency and slip rate for M Fig. 20 Comparison of friction force vector of traction surface on power roller for difference of M

Thus, operating the variator at M values of approximately 0.06 — the point at which the slip rate curve is linear and transmitting efficiency is high — will retain a safety factor for gross slip with limited decrease in efficiency.

6. Conclusion

Simulations allowed for setting of the safety factor for gross slip of the half-toroidal variator by achieving the following:

- (1) In order to express traction drive with behavior analysis, frictional characteristics for the traction fluid were identified using a four-roller test model. The dynamic behavior, accounting for elastic deformation of the parts, was handled by using an FEM model of the variator on the identified frictional characteristics.
- (2) The power transmission characteristics for the half-toroidal variator (M -Slip characteristics) were predicted using dynamic behavior analysis. This allowed for quantification of the relationship between traction coefficient M and the transmitting efficiency.
- (3) Frictional force vectors for the traction surface at each operating condition were quantified, allowing visual representation of spin during actual operation.

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Development of All-in-one Smart Hydrogen Station

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Jun TAKEUCHI*

Yuji ASANO*

ABSTRACT

An all-in-one smart hydrogen station has been developed, using Honda's original high differential pressure water electrolysis technology. The key components are packaged to be the size of a ten-foot container, reducing footprint and simplifying installation work. In addition, an interface was created to be easily understandable for those having no hydrogen refueling experience. In terms of performance, the pure water production method was revised to reduce water consumption to less than one tenth of the previous method. In addition, high-pressure water discharge technology was developed to increase the durability of the hydrogen production system. Furthermore, in order to expand the installable area to include semi-cold regions, heater functionality was added, preventing function loss from freezing. With these changes, smart hydrogen stations are being introduced by municipalities and private parties around Japan as an effective approach for achieving a hydrogen society and for promoting popularization of fuel cell vehicles.

1. Introduction

In order to reduce carbon dioxide (CO₂) emissions and reduce dependence on fossil fuels, Honda has been developing fuel cell vehicles (FCVs), which use hydrogen as their energy source and discharge only water while driving.

If the compressed hydrogen can be conveniently and efficiently made from renewable energy, it would both stimulate the popularization of FCVs and help to resolve environmental issues. Given these points, Honda is researching methods of hydrogen production concurrently with vehicle development.

To date, Honda installed a small hydrogen station assembled with commercially-available equipment at the Honda R&D Los Angeles Center in Los Angeles, CA, USA in 2001. In 2003, Honda then developed and introduced a normal pressure water electrolysis stack, which was subjected to verification testing for more than 4 years⁽¹⁾. In 2010, Honda developed a high differential pressure water electrolysis stack, which integrated Honda's original water electrolysis and hydrogen pressurization functions, updating the electrolytic method from normal pressure water electrolysis to high differential pressure water electrolysis^{(2), (3)}. These changes made the station more compact and space saving compared to other stations using standard mechanical compressors.

In March 2012, a high differential pressure water electrolysis station conforming to Japanese regulations was

installed on Saitama Prefectural Office grounds and used for 3 years as the filling station for an official vehicle, an FCX CLARITY^{(4), (5)}. Given that this was the first high differential pressure water electrolysis facility in Japan, and, even globally, without precedent as a facility on public grounds, regulatory compliance and safety verifications with risk assessment by third party officials were implemented.

However, with support from the Japanese national government, development of large-sized commercial hydrogen stations is underway. The current locations of commercial hydrogen station installations are shown in Fig. 1⁽⁶⁾. While the development started centers around the four biggest Japanese metropolitan areas, hydrogen filling systems will need to be installed in regions where the infrastructure is undeveloped in order for FCV use to spread further.

Thus, striving for simpler installations requiring less footprint than the commercial hydrogen stations, we developed the smart hydrogen station (SHS), in which key structural components are stored in a single enclosure. Furthermore, in order to increase the installable area of SHS, we added a winter support function to help prevent water from freezing and expand the installable area to include semi-cold regions.

This paper will give an overview of the SHS with further system development from the verification test station at the Saitama Prefectural Office that have accumulated experience.

* R&D Center X

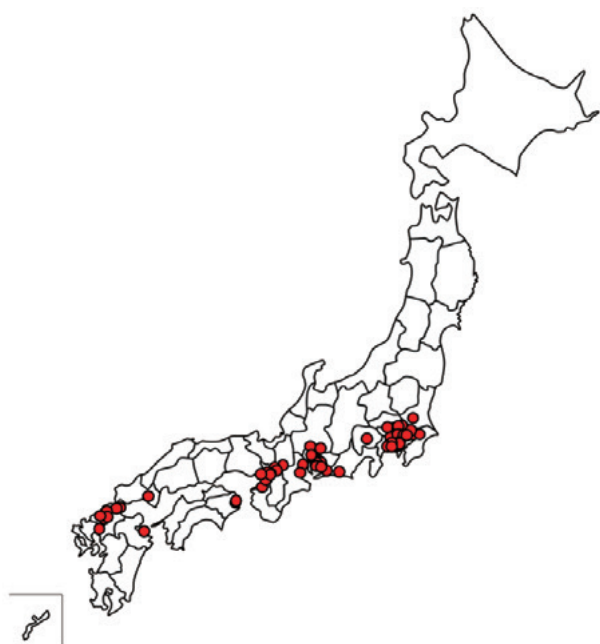


Fig. 1 Locations of commercial hydrogen stations, as of Jan. 2017

2. System Overview

An overview of the SHS is given in Fig. 2. The SHS is a compact hydrogen station, combining a high differential pressure water electrolysis system (Power Creator), developed by Honda, and storage tanks and a dispenser from Iwatani Corporation, all stored in a single

enclosure. Power Creator is capable of pressurizing hydrogen at the same time as water electrolysis, producing compressed hydrogen which meets the standards for FCV fuel⁽⁷⁾. This electrochemical method of pressurizing hydrogen generates no friction loss or motor loss, making efficiency higher than that of pressurization methods using mechanical compressors. If also combined with a renewable energy-derived power source, CO₂ emissions can also be reduced during the steps of hydrogen production and FCV fueling.

The major specifications for the SHS are given in Table 1. Hydrogen production capacity is 1.5 kg per day, allowing for a maximum annual hydrogen supply of approximately 550 kg. As FCVs can generally drive for approximately 100 km on 1 kg of hydrogen, assuming a per vehicle annual driving distance of 10,000 km, the hydrogen supplied by the SHS alone can fill approximately five vehicles. Additionally, the SHS was designed with a hydrogen storage capacity of approximately 19 kg, to allow the station to supply sufficient hydrogen for driving, even when filling multiple vehicles in succession.

In order to accelerate our progress toward a hydrogen society, in which hydrogen is widely used as a common energy source, and to proliferate FCVs across a wider range, the following items were developed from the verification test station:

- (1) A packaged unit for simplified installation
- (2) Easy user operation, which is understandable for those with no hydrogen refueling experience
- (3) Reduced water consumption and enhanced durability for the high-pressure water removal system
- (4) Installation area expanded to semi-cold regions

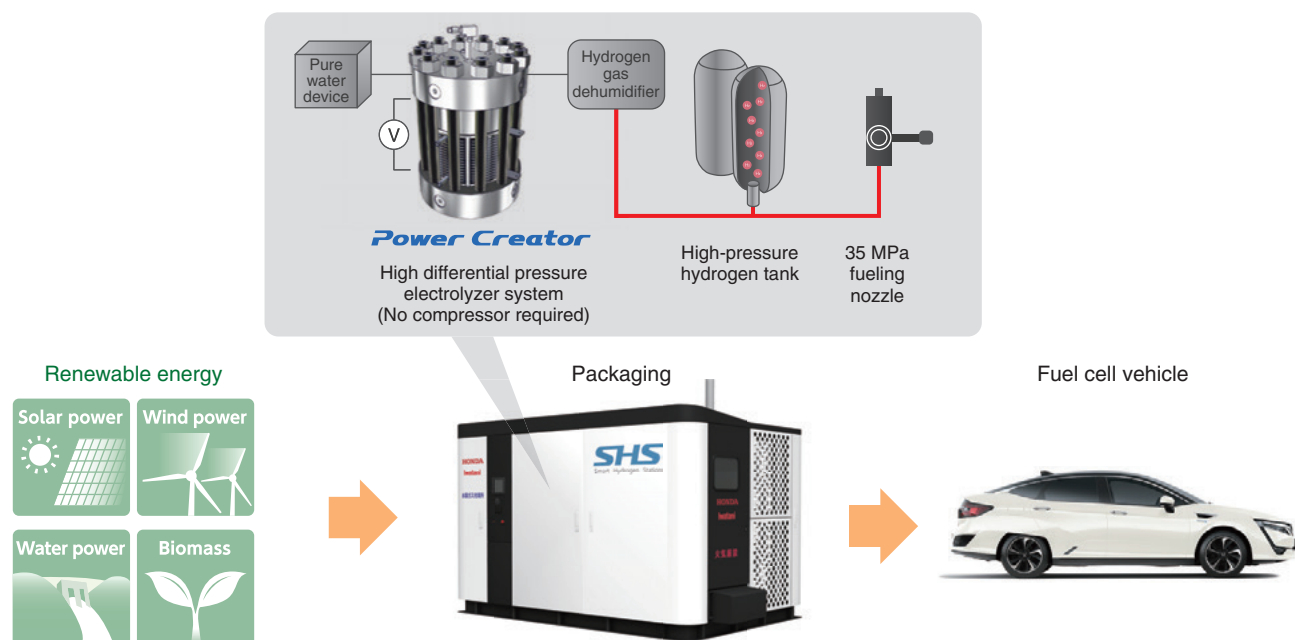


Fig. 2 Concept of SHS

Table 1 Specifications of SHS

Hydrogen production	Max capacity	1.5 kg/day (0.7 Nm ³ /h)
	Production pressure (dispensing pressure)	40 MPa (35 MPa)
	Storage capacity	Approx. 19 kg at 15°C
	Purity	>99.99%
Components	System size	W3280xD2140x H2100 (mm) Footprint: Approx. 7 m ² (10-ft container size)
	Electrolysis unit	High differential pressure electrolysis system
	Dispensing method	Double-bank cascading
	Utilities	200 V AC/tap water

3. Evolution from Verification Test Station

3.1. A Packaged Unit for Simplified Installation

To date, the verification test station used the same approach to installation as other standard commercial hydrogen stations, with the hydrogen production part, storage tanks, and a dispenser each installed as separate units. However, this dispersed approach to installation meant that the station would take up a large area (Fig. 3). Furthermore, this approach also took long time to install as pit work was required to run the piping and wiring to connect the dispersed units. Thus, seeking to help promote popularization by resolving these issues, an all-in-one SHS design was targeted. In studying the package shape, transport containers were referenced to account for easy transport by truck after factory shipment. For size, a target was set to fit the package within a ten-foot container, the smallest transport class container size.

The inner configuration of the SHS is given in Fig. 4. The user-operated dispenser is positioned on the front surface, and controls including a touch panel display for operation were positioned in the adjoining compartment to minimize the footprint. The Power Creator, which houses the high-pressure hydrogen piping, and the valve unit for cascade refueling operation are stored in the same compartment. The valve unit is positioned on the right

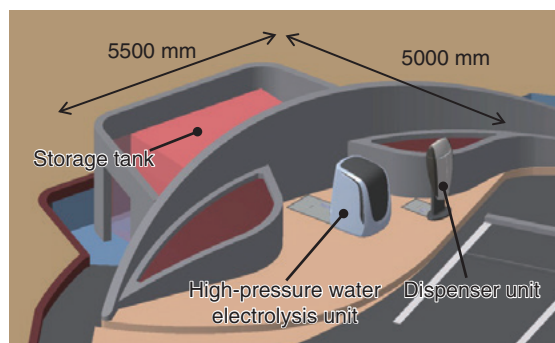


Fig. 3 External view of previous model

of the unit face, oriented in step with the storage tank connection port to minimize high-pressure hydrogen piping for the system overall.

This configuration has reduced footprint of the SHS by roughly 25% compared to the verification test station⁽⁴⁾, which had almost the same hydrogen production capacity and storage capacity.

Next, the status of SHS installation work is given in Fig. 5. As packages ship from the factory fully completed,

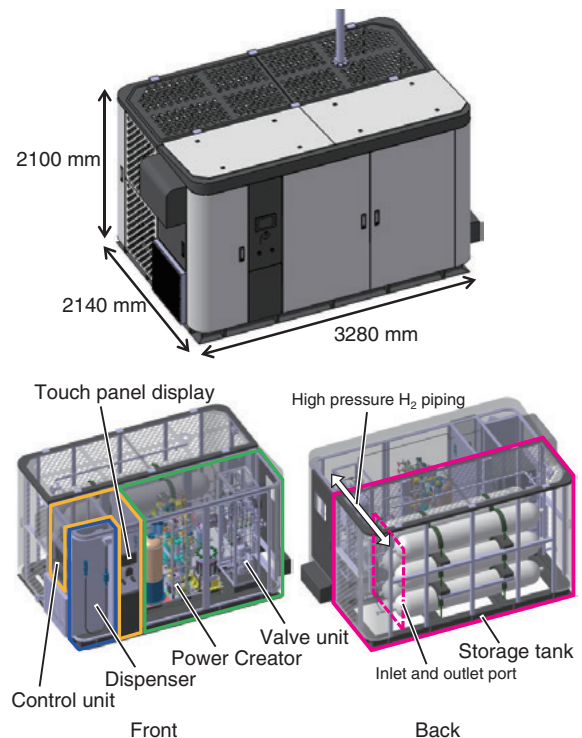


Fig. 4 Inner configuration of SHS



Fig. 5 Installation of SHS

installation is completed by simply connecting the water and electricity at the installation site. Thus, excluding any days needed for foundation work and application to the prefecture of jurisdiction for high-pressure gas equipment at the installation site, the SHS can produce hydrogen the next day after installation.

3.2. Simplified User Operation

In refueling the vehicle with hydrogen, the user operates two parts: the touch panel display and the fueling nozzle (Fig. 6).

The touch panel display is positioned directly next to the fueling nozzle holder to make filling operation easier for the user. It is positioned at a height allowing operation by smaller users.

The flow of touch panel operation is given in Fig. 7. As hydrogen refueling of vehicles is still not a widely understood process, the display visually represents each specific operational step with illustrations to make it easy for the user to understand operation. To set the user at ease, the display also shows as a guide of the time remaining until filling is complete as calculated from the fueling nozzle hydrogen pressure, storage tank pressure, pressurization rate, temperature, and other factors.

To refuel the vehicle, the user follows the instructions on the display, first opening the dispenser door, then taking out the fueling nozzle and connecting it to the vehicle. The fueling hose is 3 m long — the same length as hoses at the standard gas station. This is long enough that the user can fill up without thinking about where the vehicle is stopped, yet short enough that the hose can be folded for storage inside the dispenser door. Also, the fueling nozzle holder is positioned at the same height as the touch panel display so that the user can comfortably transition from touch panel to nozzle operation.

3.3. Reduced Water Consumption and Enhanced Durability

The SHS is designed to operate for 8 years, which

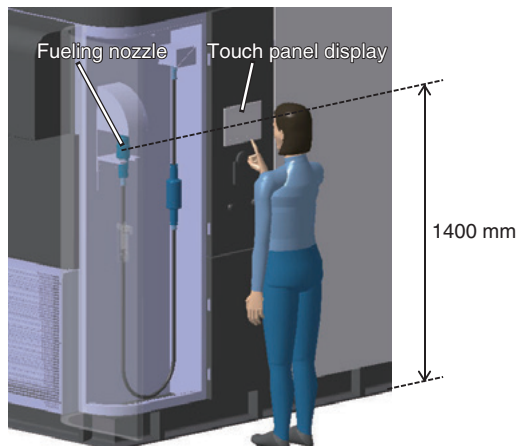


Fig. 6 User interface

is longer than the existing verification's test period. Accordingly, efforts were made to reduce water consumption and enhance durability in order to reduce running costs.

An overview of the system for supplying the water for electrolysis to the high-pressure water electrolysis stack is given in Fig. 8. Due to its chlorine and mineral content,



Fig. 7 Operation screen

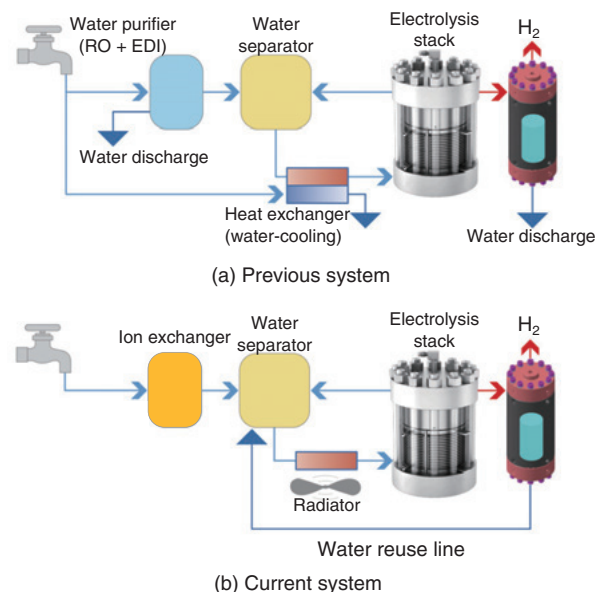


Fig. 8 Comparison of water supply systems

supplying tap water directly to the high-pressure water electrolysis stack has been found to degrade electrolysis efficiency. Therefore, a pure water production system is required to convert tap water into pure water to supply water for electrolysis. In the previous verification test station, a reverse osmosis membrane (RO) and electrodeionization system (EDI) were adopted as the pure water production system, eliminating ion concentrated water during pure water production [Fig. 8(a)]. As high-pressure water was also eliminated when moving to the high-pressure hydrogen side in the electrolysis, this system eliminated roughly two thirds of the tap water used as water for electrolysis.

Therefore, as a result of revising and checking the water quality levels required to maintain electrolysis efficiency, the approach was changed to an ion exchange resin system, allowing for pure water production without eliminating the ion concentrated water [Fig. 8(b)]. Also, the system can now reuse high-pressure water as water for electrolysis. Furthermore, cooling for the heat generated from the electrolysis stack was switched from water cooling to air cooling, reducing water usage to less than one tenth the volume used in the verification test station.

Next up to enhance durability of the hydrogen production system, efforts were made to enhance the high-pressure water discharge method as it was damaging the flow paths. The structure of the high-pressure water lines for the high-pressure water electrolysis system is given in Fig. 9. High-pressure hydrogen gas and liquid water coexist in the high-pressure hydrogen delivery lines of the high-pressure water electrolysis stack. As there are regulations⁽⁷⁾ on the allowable impurity concentrations for hydrogen for fueling FCVs, moisture should be separated and removed as

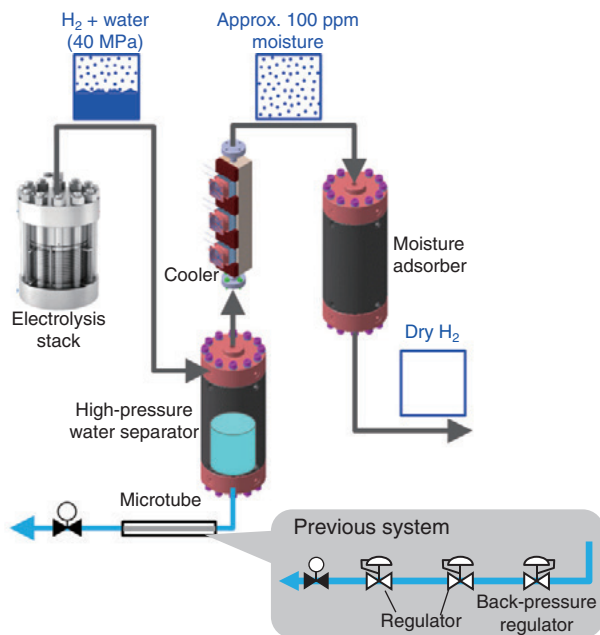


Fig. 9 Construction of water removal system in high pressure hydrogen line

well. As the first step in moisture removal, a high-pressure hydrogen separator is in place, using gravity to separate the liquid water. In the previous verification test station to date, the approach was to discharge the continuously pooled high-pressure water in the separator to an ambient pressure environment while maintaining the hydrogen pressure. This was implemented by installing multiple pressure regulators in series to step down the pressure incrementally. However, with the water passing through extremely narrow, short flow path gaps in the pressure regulators during the pressure drop process, the hydrogen dissolved in with the water would suddenly generate bubbles. This bubble generation phenomenon damaged the surface of the flow paths, resulting in loss of function (Fig. 10).

A new approach was taken as a remedy to suppress this phenomenon: pressure was stepped down gradually while discharging the water slowly through long, small bore metal microtubes instead of the narrow, short gaps in the pressure regulators. With this approach, the produced hydrogen was confirmed to maintain pressure at 40 MPa without using the pressure regulators, and high-pressure water could be discharged at a constant flow rate of approximately 40 cm³/min. Change in rate of discharge with the microtubes is shown in Fig. 11. The flow paths were confirmed to be

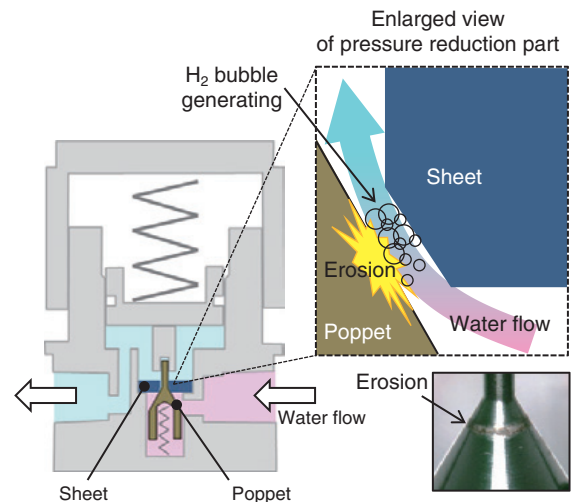


Fig. 10 Erosion mechanism of microchannel (inside of pressure regulator)

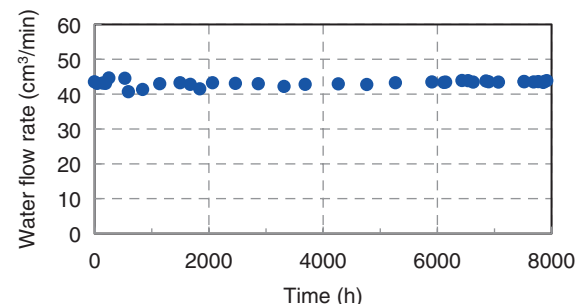


Fig. 11 Discharging water flow rate by using microtube

undamaged after 8000 hours with the microtubes, resulting in a prospective service life of 8 years.

3.4. Installation Area Expanded to Semi-cold Regions

Water runs through the water feed section, the separated water residual in the high-pressure hydrogen lines, and several other parts of the SHS system. Thus, verification test has to date been conducted in warm regions with no risk of water freezing in winter. Measures to prevent water from freezing will be needed to install the SHS over a wider region and promote hydrogen energy use. As the first step, the minimum installation environment temperature was set to -10°C with the goal of installing in semi-cold regions⁽⁸⁾.

An overview of the measures for sub-freezing temperatures is given in Fig. 12. First, as the enclosure is ventilated at all times, a heater was installed to keep water from freezing in the systems when temperatures fall below the freezing point. Next, a hose-type water heating device was added to the water feed line to help prevent freezing in the radiator, which comes in direct contact with ambient air.

Operational data in sub-freezing temperatures is given in Fig. 13. Both water temperature and enclosure internal

temperature were kept above 0°C , confirming that operation is possible in environments of -10°C . With these changes, the first hydrogen station in the Tohoku region was opened in March 2016 in Sendai, Miyagi Prefecture, bringing us one step closer to the popularization of FCVs.

4. Installation Progress

Public appeals and installation of the SHS are being promoted as a means of achieving the low-carbon hydrogen society promoted by the Ministry of the Environment subsidy program and of promoting popularization of FCVs. As of June 2017, 13 station installations have been completed (Fig. 14) and are operating as filling stations for official vehicles and other FCVs. Hopes are to further expand installations to other regions with demand and contribute to the popularization of FCVs.

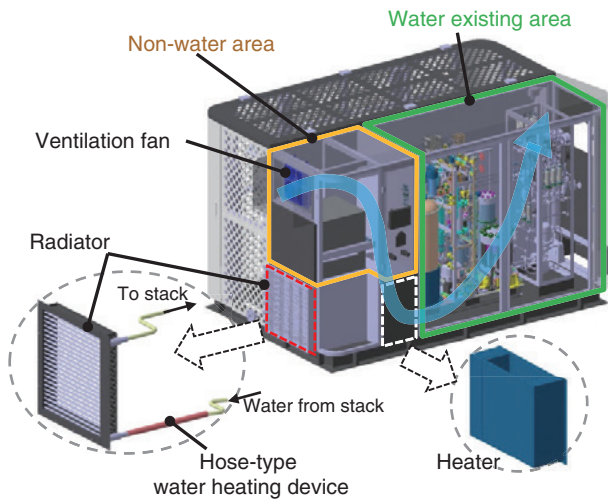


Fig. 12 Adding heating devices for semi-cold region



Fig. 14 Locations of SHS installations, as of June 2017

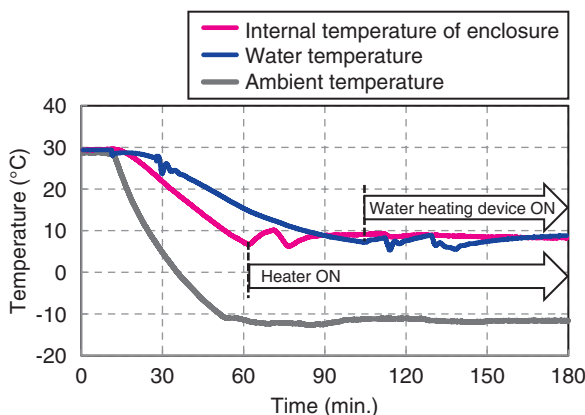


Fig. 13 Effect of heating devices

5. Conclusion

An all-in-one smart hydrogen station was developed, attaining the following results:

- (1) Footprint was reduced and installation work was simplified by containing the key components in an all-in-one package, sized to fit within a ten-foot container.
- (2) An interface allowing for simple operation was created in the interest of making operation easier for the user.
- (3) Water consumption was reduced to less than one tenth of the previous model. The high-pressure water discharge method was modified, enhancing durability.
- (4) Functionality for preventing water from freezing was added, expanding the installable area to include semi-cold regions.

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Development of New FC Separator for CLARITY FUEL CELL

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ABSTRACT

A compact and highly impact-resistant fuel cell separator was developed to enable the CLARITY FUEL CELL fuel cell stack to be mounted under the front hood.

By changing the seal cross-section of the separator from the previous trapezoidal shape with a broad foot section to a rectangular shape for downsizing, the seal width was reduced and stack volume was decreased by approximately 3 L. Also, covering the separator in resin and rubber to help ensure insulation obviated the need for the waterproofing and insulating structures commonly known as enclosure boxes, resulting in a structure that does not require sealing parts in the enclosure. Furthermore, the number of parts was reduced and processes were simplified by forming a flow path structure using the same rubber as the seal materials during seal molding. Impact resistance was also enhanced by providing indented sections made of resin at the four sides of the separator to suppress misalignment of the separator during a collision.

By integrating the production processes of press-forming, resin molding, and rubber molding for making a separator having these structures into a single process, a low-cost manufacturing method that can be applied to mass production was developed.

1. Introduction

Fuel cells (FC) are anticipated as a recycling type of clean powertrain that discharge zero CO₂ and toxic substance emissions.

In 1999, Honda mounted the in-house developed FC stack in a fuel cell test vehicle, and in 2003 announced the Honda FC stack capable of being started in cold regions⁽¹⁾. In 2006, the even more compact and lighter weight V Flow FC stack was introduced⁽²⁾. Moreover, in development of the CLARITY FUEL CELL, the aim was to make the FC stack even more compact and lighter to enable it to be mounted under the front hood⁽³⁾, so the cell was downsized and the impact resistance of the stack was enhanced. In this way, in 2016, a new FC stack that has a stack volume approximately 18 L smaller than that of the V Flow FC stack was unveiled. Figures 1(a)

and (b) respectively show the appearance of the V Flow FC stack and new FC stack. This paper introduces the separator incorporated in the new FC stack (separator for new FC stack).

2. What is a “Separator”?

As shown in Fig. 2⁽⁴⁾, the solid polymer-type FC uses a polymer electrolyte membrane to directly convert chemical energy to electrical energy by the electrochemical reaction between hydrogen and oxygen in air.

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

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

The polymer electrolyte membrane through which hydrogen ions are conducted is sandwiched between two catalyst layers and gas diffusion layers, a hydrogen electrode and an oxygen electrode (air electrode) form a membrane electrode assembly (MEA)⁽⁵⁾, and this MEA is sandwiched between two separators from both sides to form a cell. Since a voltage of only approximately 1 V can be obtained by one cell even in an open circuit, cells are laminated so that a high voltage is generated.

A separator is a sheet-like part that is sandwiched between each of the cells to perform the role of cutting off hydrogen and air. In addition to functioning to seal the gas and coolant of each cell, it comprises flow paths through

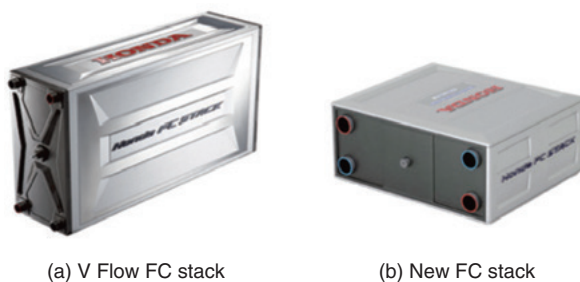


Fig. 1 Appearance of FC stack

* Automobile R&D Center

which gas flows and assumes the function of feeding in hydrogen and air. Of all the FC stack components, the separator occupies the largest volume, and this part should be downsized so that the FC stack can be mounted on various types of vehicles. Also, misalignment of the separator should be suppressed so that the FC stack can be mounted at locations under the front hood that are subjected to large impact force during a collision.

Because several hundred separators are used per vehicle, a major issue in the manufacture of separators is how to shorten the production cycle time to reduce costs. Consequently, the molding of separators by using molds is currently being studied. Honda has so far focused on reducing cycle time by downsizing and metallic molding, and has adopted a method of injection molding of liquid rubber to help ensure insulation at press-formed separator metal parts.

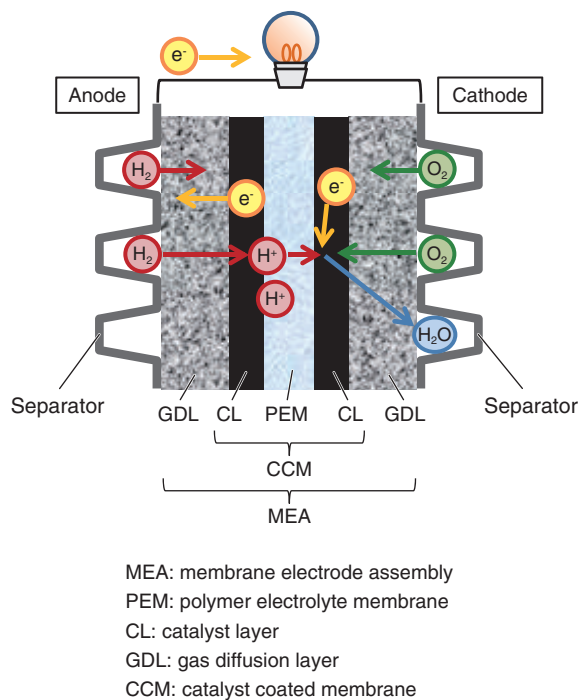


Fig. 2 Mechanism of electricity generation in FC stack

3. Development Goals

A separator was developed with the following structures to resolve the issues described above:

- (1) Seal structure for downsizing the FC stack;
- (2) Insulation coating structure for decreasing the number of parts;
- (3) Flow path structure that uses rubber for simplification of processes; and
- (4) Misalignment suppressing structure for enhanced impact resistance.

4. Features of the New FC Separator

4.1. Basic Structure of the New FC Separator

First, the basic structure of the newly developed FC separator will be explained. As shown in Fig. 3, the authors have continued to use the cell structure used in previous stacks in which two MEAs are held by three separators and that allows coolant to flow to the outer surface. The three fluids – hydrogen, air, and coolant – required for electricity generation are supplied to the electricity generating section of each cell via continuous holes set up at the separator outer periphery.

Next, the overview of development goals (1) to (4) described above will be explained. As shown in Fig. 4, these three structures – (a) gas and coolant seal structure, (b) coating structure that insulates the separator outer periphery, and (c) flow path structure that supplies gas and coolant to the electricity generating section – are molded in rubber. The seal structure should have a thick wall shape since fluids are sealed by counterforce at rubber compression. On the other hand, the insulation coating section should be of a thickness that satisfies electrical insulation requirements and that allows downsizing without rubber compression of that seal being hindered. Also, to increase the electricity

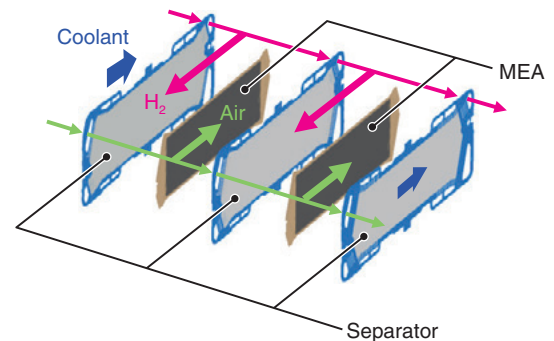


Fig. 3 One cooling layer per two cells

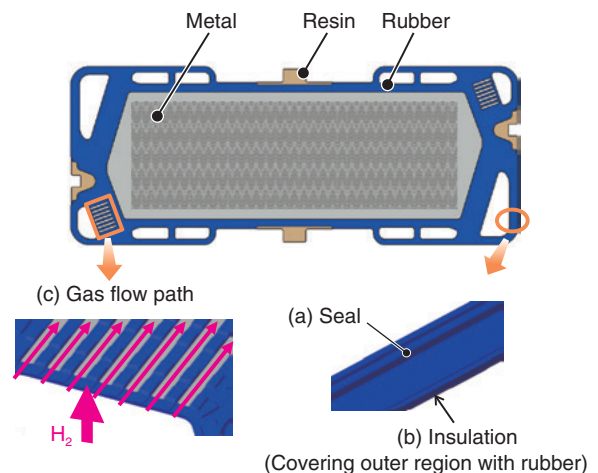


Fig. 4 New separator

generation efficiency, although all reactant gas should flow through fluid paths, some of the reactant gas flows between parts and not via fluid paths, namely, via shortcuts. This needs to be suppressed and reactant gas should be supplied uniformly to fluid paths. Normally, when press-formed separator metal parts are set in a mold for rubber molding and rubber is molded, solid rubber material, for example, is used for molding the rubber by compression [Fig. 5(a)]. However, during rubber molding, high pressure is applied to the metal parts, resulting in the issue of thin metal parts becoming deformed. Also, as it is not easy to make microshapes by compression molding, a manufacturing method of injection molding low-viscosity liquid rubber was adopted [Fig. 5(b)]. This method made it possible to mold rubber on both sides of metal parts without deformation of metal parts by reducing the compacting pressure, as well as to mold a variety of shapes having thicknesses that vary depending on their location. The misalignment suppression structure also uses high-strength resin to absorb the impact force during a collision, comprising a structure integrated with separator metal parts.

4.2. Seal Structure for Downsizing the FC Stack

Before considering downsizing, lengthening the life of seals to ensure a service life equal to that of gasoline engine vehicles was studied. Generally, compressive permanent sets of seals can be reduced and seals can be made to last longer by compressing them at a lower compression ratio. In order to obtain a high seal load even at a low compression ratio, a shape that would be less likely to spread in the lateral direction at compression was targeted, and the cross-section from the previous trapezoidal shape with a broad foot section was changed to a new rectangular shape. Figure 6 shows the results of using finite element structural analysis to compare stress in rubber under an equivalent seal load. It can be seen that, with this new

shape, an equivalent seal load is obtained at a compression ratio lower than that with the previous shape. By changing the shape of the cross-section, the required seal load at a lower compression ratio can be obtained (Fig. 7), and as a result, the amount of reduction in the seal load can be reduced and durability can be enhanced as shown in Fig. 8.

Next, the seal width was decreased from that in previous specifications. Seals approximately 1000 m or more in

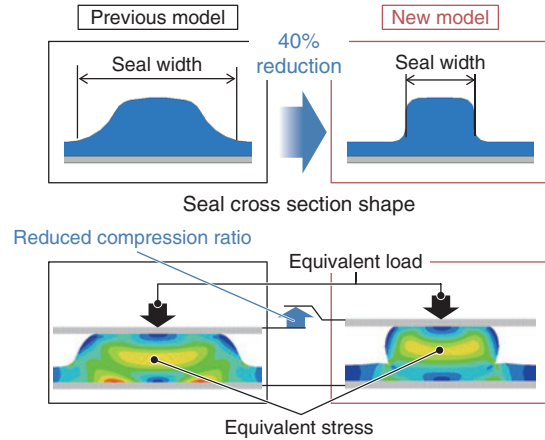


Fig. 6 Stress distribution in seal compressed state

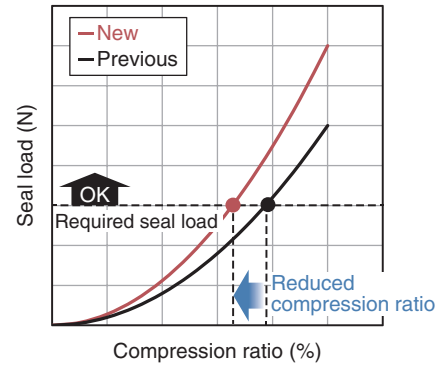


Fig. 7 Comparison of compression ratios

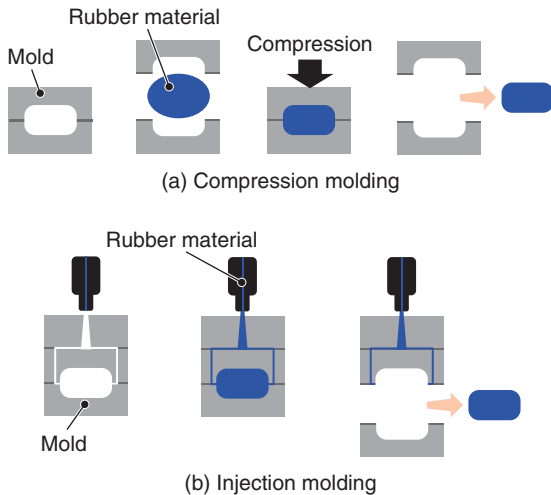


Fig. 5 Comparison of rubber manufacturing methods

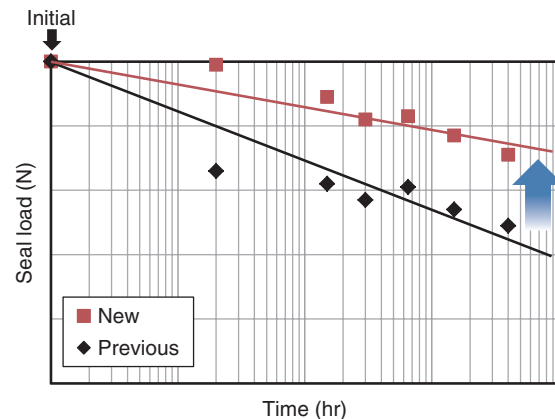


Fig. 8 Comparison of seal load behavior

length are used in each FC stack. For this reason, the stack volume can be reduced if the seal width can be decreased. However, ensuring sealing performance with misaligned parts as shown in Fig. 9 becomes a challenge if the seal width is reduced too much on a stack in which thin metal sheets and seals are repeatedly laminated.

For this reason, flat sections were provided at the seal upper surface, producing a shape that is difficult for a drop in seal load to arise even with parts in a misaligned state. Moreover, the distribution of the seal load was predicted by finite element structural analysis. Although a region in which two seals do not overlap is formed when parts become misaligned and out of position, it can be seen that the rigidity of the metal sheets in between generates a seal load in that region, as well (Fig. 9). Because part of the region in which the seals do not overlap is regarded as seal width, the actual seal width becomes larger than the width in which the seals are overlapping. The width was further reduced by the amount of increase in seal width due to this effect.

The width in which the required seal load could be ensured was ascertained, and the seal width was reduced by approximately 40% and the stack volume was decreased by approximately 3 L from the previous specification.

4.3. Insulation Coating Structure for Decreasing Number of Parts

Separator metal parts using high voltage should be electrically insulated from the outside. In one generally known method, rather than providing individual separators with an insulating structure, separators are stored in an enclosure box with waterproofing and insulation functions⁽⁶⁾. In this development, however, a structure that gives separators an insulating coating was achieved by seal rubber molding as described above, and at the same time, by covering the outer periphery of separator metal parts in rubber. Giving separators an insulating coating obviates the need for the waterproofing and insulating structure of enclosure boxes, enabling a structure that does not require sealing parts in the enclosure.

Figure 10 shows the outer circumference insulating structure of the separator. Resin is outsert molded on metal parts and rubber is formed to cover that resin. Metal is insulated from the outside by adhering the boundary

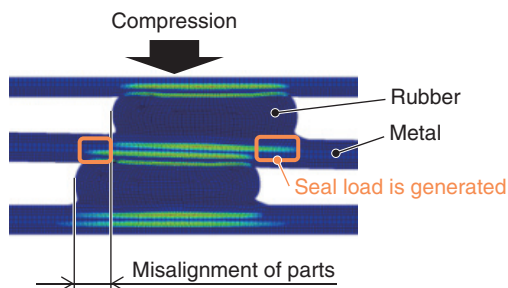


Fig. 9 Cross section of seal

between the resin and rubber during molding. The adoption of this structure improved insulation.

4.4. Flow Path Structure Using Rubber to Simplify Processes

Although a separator needs both inlet and outlet to supply fluids to the electricity-generating section, a structure for affixing variously shaped metal or resin parts to the separator is commonly used. However, securing and fastening the variously shaped metal or resin parts required in this case increases costs.

In this development, sealing rubber molded by the manufacturing method described above was applied and, at the same time, rubber was used in forming the fluid inlet and outlet. The fluid inlet and outlet should intersect with the seal of a different layer isolating each of the fluids. This was achieved by the bridge pier structure as shown in Fig. 11. Since this is an integrated structure formed by

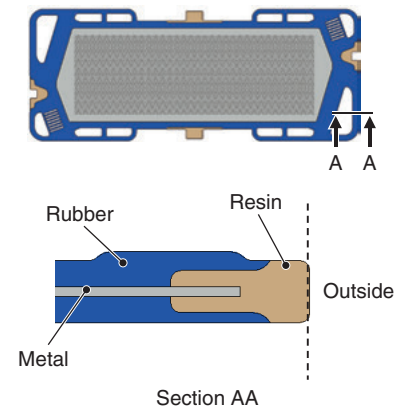


Fig. 10 Electrical insulation structure

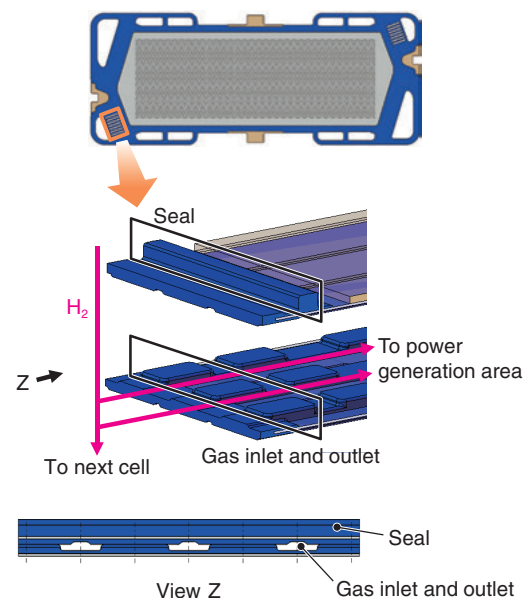


Fig. 11 Fluid inlet and outlet structure

a mold, dimensional accuracy is high, which also makes it effective for the stable supply of fluids.

Next, this section explains the structure that uses rubber to suppress shortcuts that allow some of the reactant gas to avoid the fluid paths and flow to gaps between parts. As shown in Fig. 12(a), when molding rubber on press-formed metal, the mold should be pressed against the metal, requiring a mold press fixture to prevent outflow of rubber. Because metal is in close contact with the mold in that section, rubber cannot be molded in the forming of a space. Electricity generation efficiency drops because gas that cannot contribute to electricity generation flows to that space. In response to this issue, ribs such as that shown in Fig. 12(b) are formed in rubber and the space that has been formed until now is filled in with rubber. As a result, gas making a shortcut while the mold press fixture is secured can be reduced. This gas shortcut suppression structure using rubber is an effective measure since it has a high degree of shaping freedom and can also be applied to microgaps.

Next, the features of the manufacturing method for the gas shortcut suppression ribs will be explained. Uneven shapes from which molded shapes cannot be removed simply by splitting the mold in two are generally called “undercut,” as illustrated by the slide mold shown in Fig. 13(a) in which the mold is split. However, a slide mold cannot be situated near rib forming since there exist press-formed parts. In this development, the angle of the rib was studied and an easily molded shape was established to enable rubber to be removed by a two-way extraction mold without being damaged and without the use of a slide mold, by a method called “forced extraction” as shown in Fig. 13(b).

4.5. Misalignment Suppressing Structure for Enhanced Impact Resistance

In mounting the FC stack under the front hood, impact resistance should be enhanced since the impact force on the FC stack in the event of a frontal collision increases when compared with previous mounting on the center tunnel.

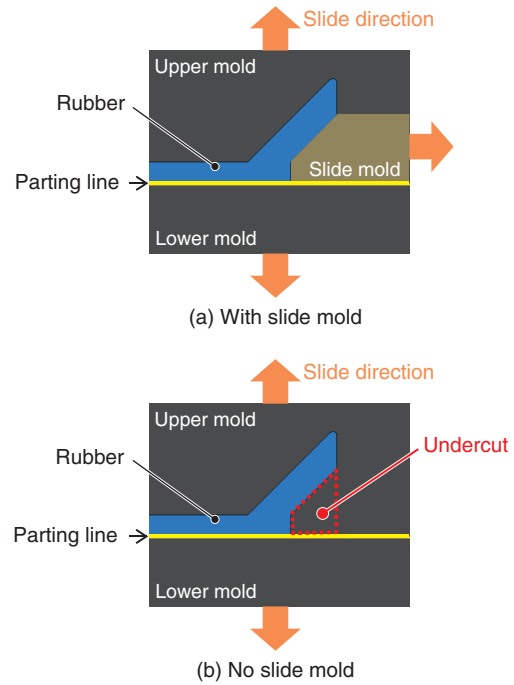


Fig. 13 Rubber undercut shape

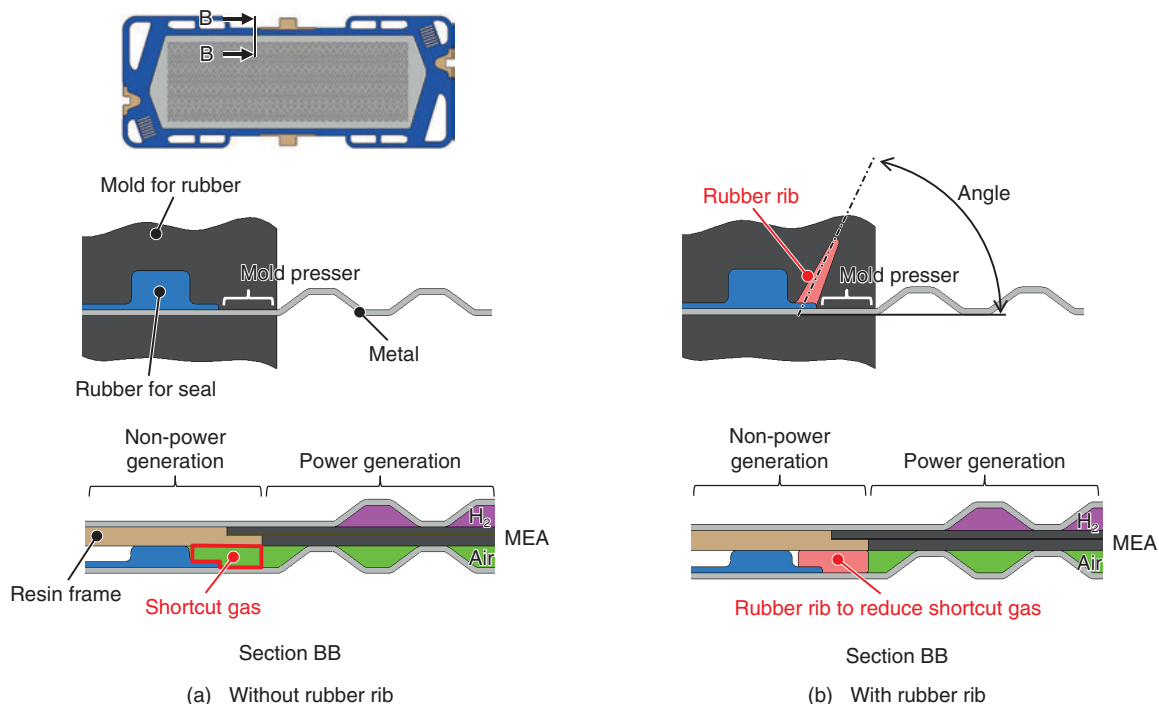


Fig. 12 Rubber rib to reduce shortcut gas

Major impact force applied on the separators of a stack, which is a laminated body, could result in misalignment of parts. For this reason, a bar connection single-box stack structure capable of suppressing cell misalignment was developed. This structure provides indented sections at the four sides of the separator as shown in Fig. 14, and connects the end plates at both ends of the stack by means of bars to hold the indented sections on the separator. Because these indented sections use injection molding of high-strength resin to form an integral structure on the metal separator, insulation between the connection bars and separator, which is a high-voltage area, can be ensured.

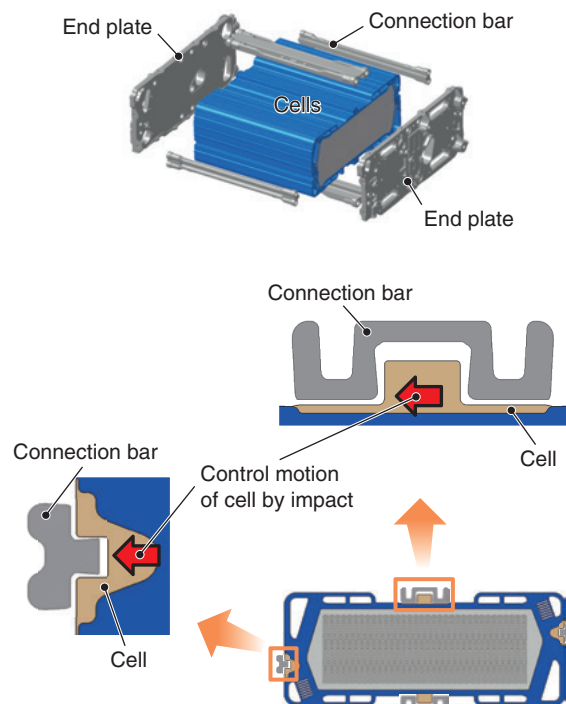


Fig. 14 Separator with high impact resistance

5. Conclusion

Listed below are the benefits of the compact and highly impact-resistant new FC separator that was developed using a manufacturing method that can be applied to mass production:

- (1) Application of finite element structural analysis to optimize the seal cross-section of the separator seal to a rectangular shape decreased the seal width by approximately 40% over previous separators while enhancing durability, also reducing the volume of the stack by approximately 3 L.
- (2) The structure of the separator insulation coating does not require sealing parts in the enclosure.
- (3) Use of rubber at fluid inlets and outlets reduced the

number of parts and simplified processes. In addition, the amount of gas that cannot contribute to electricity generation was reduced by means of gas shortcut suppression ribs made using a forced extraction manufacturing method characteristic of rubber.

- (4) Mounting of the fuel cell stack under the front hood was enabled by providing indented sections made of resin at the four sides of the separator to increase impact resistance.

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Technologies for Low Iron-loss in New SPORT HYBRID i-DCD Motor

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ABSTRACT

The use of generally available materials for the electromagnetic steel sheets in a new motor for a one-motor SPORT HYBRID i-DCD has reduced costs, while the application of heavy rare earth-free magnets has assisted in the avoidance of procurement risk. The thickness of the steel sheets employed in the stator cores was increased from the previous 0.25 mm to 0.35 mm. The increased loss resulting from increased sheet thickness was responded to by modifying the number and position of the caulking dowels used in each stator core in order to reduce eddy current. Iron loss has also been reduced by machining corrugations into the inner circumference of the stator holder in order to reduce the contact area and thus reduce residual stress from press-fitting. In order to help ensure magnet heat resistance with the application of heavy rare earth-free magnets, the configuration of the magnets was changed from a parallel configuration to a V-shaped configuration fitted deep inside the inner circumference of the annulus formed by the rotor cores. In addition to this, the number of divisions of each magnet was changed from four divisions arrayed in the axial direction to two divisions arrayed in the circumferential direction, simplifying the production procedure and helping to realize a level of loss equivalent to that of the previous motor.

1. Introduction

The reduction of CO₂ emissions today, as a result of their environmental effects, is an important issue for the automotive industry, and the development of automotive electrification technologies is proceeding apace. However, given the fact that the cost of the main electrification-related components (motors, inverters, and batteries) remains high, from a global perspective electrification has still not widely spread. In 2013, Honda began to market a one-motor SPORT HYBRID i-DCD as a hybrid system within a set price range, allowing wide-spread use by a larger number of customers. The permanent magnet motor employed in this system (referred to as the “previous motor” below) was independently developed by Honda, and realized a high level of maximum efficiency (96% or higher). The use of 0.25 mm-thin, high-grade materials in the electromagnetic steel sheets employed in the previous motor realized low loss in the electromagnetic sections. However, the cost of thin, high-grade materials is expensive, and the global expansion of their use involves material procurement risks.

The FREED Hybrid that went on the market in 2016 therefore employed a newly developed motor (referred to as the “new motor” below). Employing generally-

available 35A270-grade electromagnetic steel sheets, low-loss technologies were developed in order to realize a high-efficiency motor.

In the previous motor, the heavy rare earths dysprosium and terbium were added to the magnets in order to realize a high level of heat resistance. Heavy rare earths are only mined in specific regions, and therefore represent a materials procurement risk. A heavy rare earth-free technology⁽¹⁾ was accordingly developed and employed in the new motor. This paper will discuss technologies employed to reduce iron loss in the stator and the optimization of the divisions in the heavy rare earth-free magnets.

2. Vehicle System and Motor Specifications

2.1. Vehicle System

The one-motor SPORT HYBRID i-DCD, in which the new motor is employed, features a 7-speed transmission with a built-in motor. The transmission system is compact enough to be fitted in a FIT-class vehicle. Salient pole concentrated windings featuring copper wire wound around split stator cores have been adopted as the winding method for the motor. The development was conducted with a view towards balancing the antagonistic demands of reduced size

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and increased efficiency. Figure 1 shows an external view of the transmission. By disconnecting the engine and the motor in response to driving conditions, the system is able to operate as a hybrid vehicle, driven by the engine and the motor, as an engine-driven vehicle, driven by the engine alone, or as an EV, driven by the motor alone⁽²⁾.

2.2. Motor Specifications

Figure 2 shows the configuration of the motor. Broadly speaking, the motor is made up of a stator and a rotor. The stator is connected to the transmission case, and plays the role of generating a rotating magnetic field by transmitting electricity from the inverter to the three-phase winding coils, continuously generating torque in the rotor.

In the stator component, the stator cores are made up of electromagnetic steel sheets laminated using caulking dowels. The stator cores are sandwiched between insulators in order to maintain insulation, and are wound with magnet wire. Following the formation of an annulus using 18 of the split cores, the unit is press-fitted into a stator holder to fix the stator cores in position (Fig. 3).

By contrast, because the rotor transmits torque to the transmission, it is formed by inserting an annulus, made up of magnets producing magnetic flux, into the interior of an annulus made up of rotor cores formed from electromagnetic steel sheets, which is then press-fitted onto a rotor shaft. The magnets are generally divided into multiple individual magnets in order to reduce loss. 48 magnets are employed in the new motor (Fig. 4).

Table 1 compares the specifications of previous motor and the new motor.

Table 1 Comparison of specifications

		Previous motor	New motor
Type		IPMSM	
Phase		3	
Number of poles		6	
Coil turns		55	
System voltage [V]		173	
Maximum motor power [kW]		22	
Maximum motor torque [Nm]		160	
Volume [L]		2.57	
Stator	Plate thickness [mm]	0.25	0.35
	Number of caulking points	2	1
	Holder	Press fit	Low-contact press fit
Rotor	Magnet layout	Axial: 4	Circumferential: 2
	Heavy rare earth magnet	Applied	Not-applied
	Number of magnets	96	48
	Magnet Br [T]	1.27	1.35
	Magnet H _{ej} [kA/m]	>2294	>1500

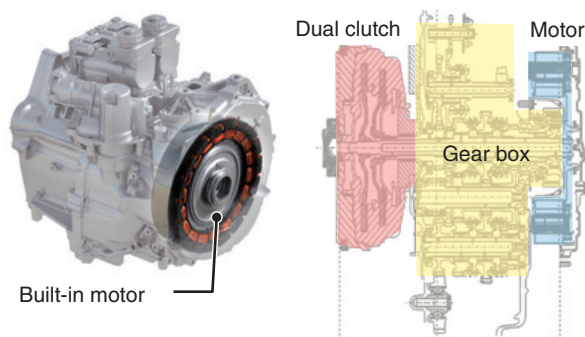


Fig. 1 Layout of 1-motor SPORT HYBRID system

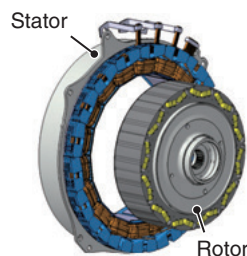


Fig. 2 Motor components

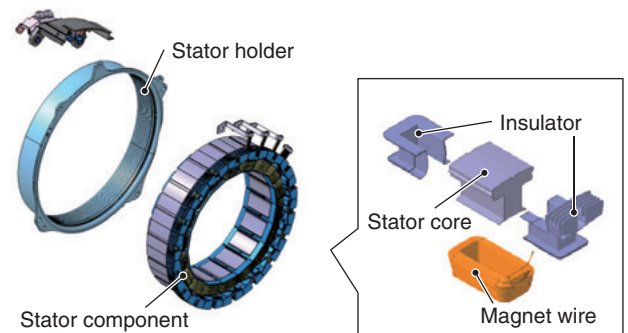


Fig. 3 Stator component parts

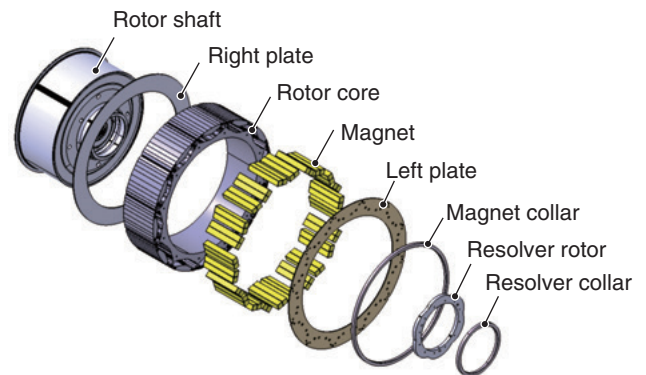


Fig. 4 Rotor component parts

3. Development Aims

In the previous motor, the stator cores were formed from 0.25 mm thick (thinner than 0.35 mm or 0.50 mm) high-grade materials in order to reduce iron loss. If it was possible to form the stator cores from more generally available grades of materials, it would help to ensure global procurability, and a cost reduction effect could be predicted. Looking towards global procurement, 0.35 mm 35A270-grade electromagnetic steel sheets have been employed for the stator cores in the new motor.

Iron loss in the electromagnetic steel sheets employed in the stator cores can be found using Eq. (1). Iron loss is the sum of the first term on the right-hand side of the equation, hysteresis loss, and the second term, eddy current loss, is affected by sheet thickness.

$$W = fB^{1.6} + f^2 B^2 t^2 \quad (1)$$

B : Flux density

f : Frequency

t : Thickness

Magnetic field analysis showed that increasing sheet thickness from 0.25 mm to 0.35 mm would increase iron loss during motor operation by 50% against the previous motor. The effect of this increase would reduce motor efficiency, potentially resulting in a decline in the fuel economy of the vehicle. It was therefore essential to employ technologies to reduce loss.

The employment of heavy rare earth-free magnets made it necessary to apply measures to realize heat resistance in the magnets. The magnet layout was therefore changed from the parallel layout employed in the previous motor to a V-shaped arrangement in which the magnets are fitted deep in the inner circumference of the annulus formed by the rotor cores. Reducing the magnet loss that is a factor in iron loss is possible. However, while loss is generally reduced in proportion to the fineness of the divisions in the magnets, increasing the number of divisions also increases machining costs. It is therefore necessary to balance reduced magnet loss with reduced machining costs.

The following two technological aims were therefore set in order to realize a level of iron loss in the new motor equivalent to that of the previous motor:

- (1) Realization of technologies for the reduction of iron loss in the stator
- (2) Realization of the optimal number of divisions in the heavy rare earth-free magnets

4. Technologies for the Reduction of Stator Iron Loss

4.1 Optimization of Caulking Dowel Shape

The stator cores are formed by the lamination of

electromagnetic steel sheets through which magnetic flux is readily able to pass. When the electromagnetic steel sheets are pressed, they are caulked using caulking dowels, helping to enable them to maintain their shape. As Fig. 5 shows, in the previous motor, two caulking dowels were positioned at a distance in each stator core in order to help control twisting when the cores were laminated.

In addition, the surfaces of the electromagnetic steel sheets were coated with an insulating film in order to help control loss by insulating the eddy current between the sheets. However, when the caulking dowels are pressed into place, the insulating film peels and neighboring sheets come into contact, resulting in eddy current loss occurring in the conducting sections.

As Eq. (1) indicates, eddy current loss is also greatly affected by magnetic flux density. Loss can be considered to further increase in the high-rotation range because frequency is high, and in the high-torque range because magnetic flux density is high. In the new motor, therefore, single caulking dowels have been positioned in the centers of the core teeth, where there is a minimal change in magnetic flux density, as shown in Fig. 6. The issue in employing single caulking dowels was a twisting of the cores when the electromagnetic steel sheets were laminated.

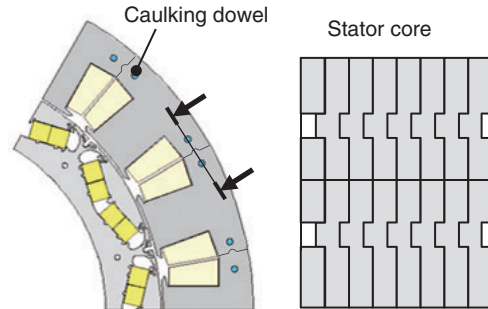


Fig. 5 Caulking dowels in stator cores

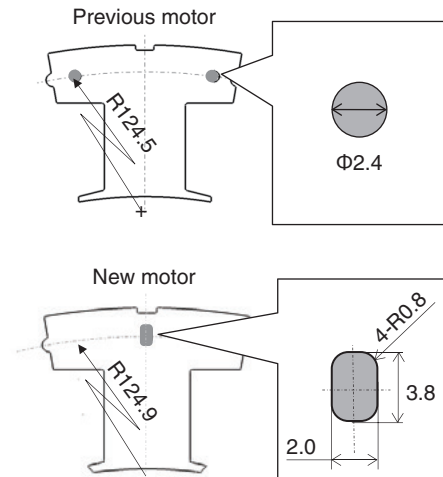


Fig. 6 Caulking shape

The shape of the caulking dowels was therefore changed from a circular to an oval shape. The use of a caulking shape having a width between two faces made it possible to constrain the direction of rotation of the divided stator cores.

Figure 7 shows the results of a magnetic flux density analysis at the points of maximum load frequency in JC08 mode. Positioning caulking dowels at points where magnetic flux density is low controls the fluctuations in

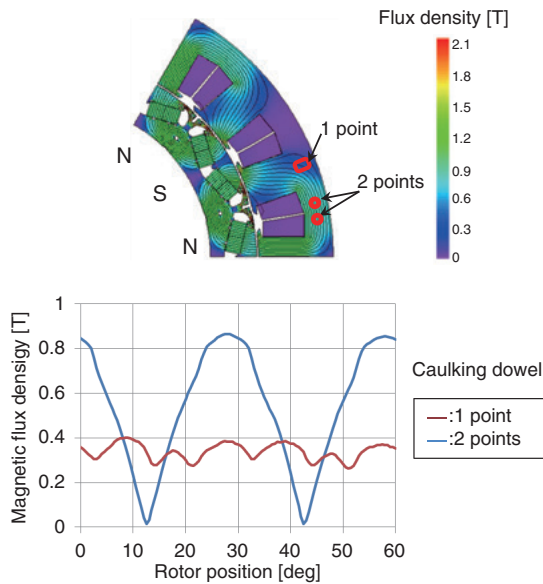


Fig. 7 Number of caulking points and results of analysis

magnetic flux density associated with rotor phase, reducing iron loss.

4.2. Low-contact Press-fitting

The stator employed in the new motor is formed by press-fitting an annulus formed from 18 divided cores into an annular stator holder. It is known that iron loss in electromagnetic steel sheets increases under compressive stress⁽³⁾, and it was therefore considered that reducing the number of sections in contact and thus limiting the number of high-stress areas would control overall loss to a low level.

In the new motor, corrugations have been machined into the press-fitted surface of the stator holder, and the stator core and the stator holder make line contact at the apices of the corrugations.

Figure 8 shows the results of a stress analysis of press-fitting stress in a stator core following low-contact press-fitting. While the contact areas in sections (5) and (6) in Fig. 8 display high compressive stress, compressive stress is low in section (1). A consideration of the overall compressive stress contours suggests that iron loss gradually increased with contact area. In addition, based on the results of calculation of iron loss in the stator cores for each stress distribution, it was estimated that low-contact press-fitting reduced iron loss by an average of 11% in the stator as a whole.

Figure 9 shows a photograph of a section of the internal circumference of an actually machined stator holder. Finishing and machining of the press-fitting surface of the stator holder has simplified the setting of the tightening margin between the stator holder and the stator cores when

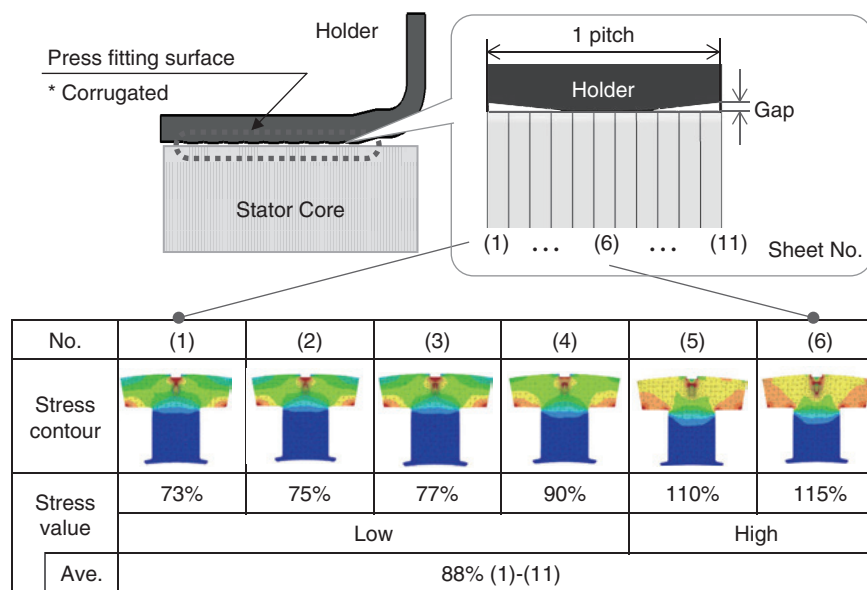


Fig. 8 Low-contact press-fitting characteristic

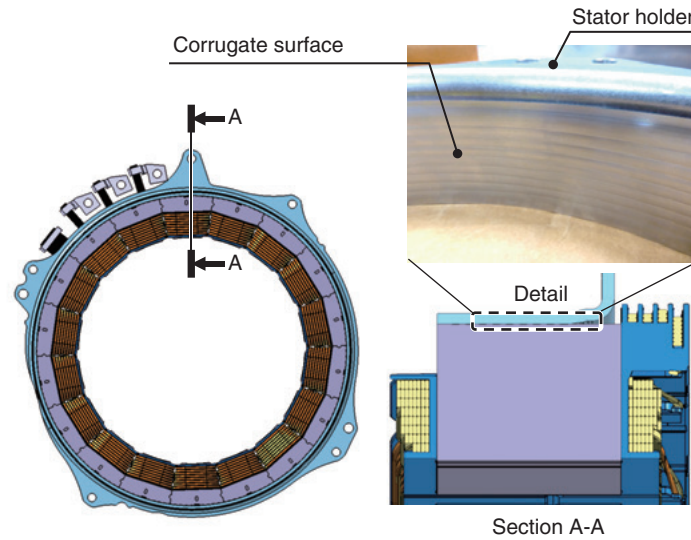


Fig. 9 Corrugated surface of stator holder

press-fitting. This has enabled to manage the tightening margin to the optimal setting for the necessary holding force and for iron loss.

5. Optimization of Divisions in Heavy Rare Earth-free Magnets

AS the use environment for the main traction motors fitted in automobiles features high temperatures and strong demagnetizing fields, a high level of heat resistance, i.e. holding force (H_{cj}), is demanded from the magnets used in the motors. A reduction in heat resistance represented an issue in using heavy rare earth-free magnets. This necessitated responses via the magnetic circuits⁽¹⁾, in addition to a reduction in the opposing magnetic field.

Increasing the number of divisions in a magnet is known to reduce internal eddy current loss in the magnet⁽⁴⁾. In the previous motor, magnets were divided into four and arrayed in the axial direction for each pole in order to control heat generation in the magnets, resulting in a total of 96 magnets. At the same time, because machining costs increase with the number of divisions in the magnet, it is also necessary to minimize the number of divisions.

Figure 10 shows a contour diagram of the eddy current generated in the interior of a magnet when an opposing magnetic field is imparted to it. As this diagram indicates, because the eddy currents generated in the interior of the magnet cancel each other out, there is a difference in the eddy currents in the interior and those at the ends of the magnet. Based on these results, it was considered effective to reduce the area receiving eddy currents generated in the interior of the magnet.

A parameter study using a three-dimensional magnetic field analysis was therefore conducted to help minimize

the number of divisions in the magnets and achieve the same level of iron loss as the previous motor. Based on the results, rather than dividing each magnet into four and arraying the parts in an axial direction, as in the previous motor, in the new motor each magnet was divided into two and arrayed in a circumferential direction, as shown in Fig. 11.

Figure 12 shows the results of magnetic field analyses conducted in order to determine the effect of the presence or absence of divisions in the magnets and differences in the arrangement of the divisions on iron loss in the magnets. The analyses were conducted at 7000 rpm and 30 Nm, conditions under which eddy current loss is at its maximum in the new motor. In addition to indicating that dividing the

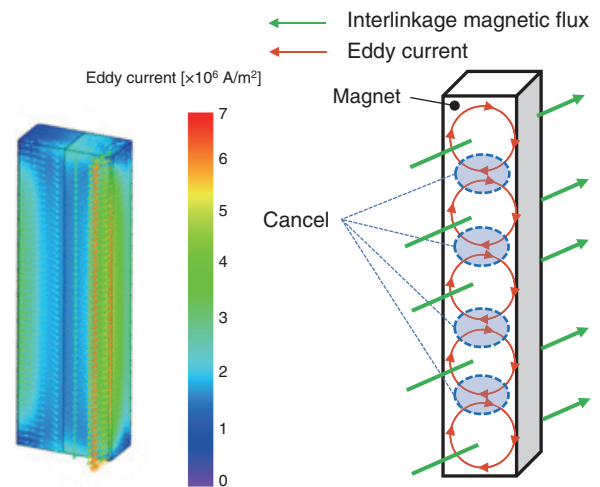


Fig. 10 Analysis of magnet loss

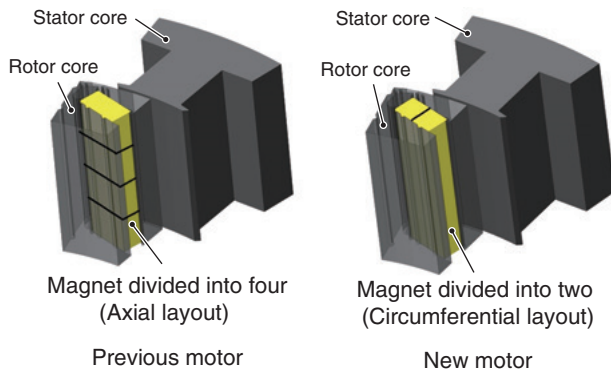


Fig. 11 Magnet division

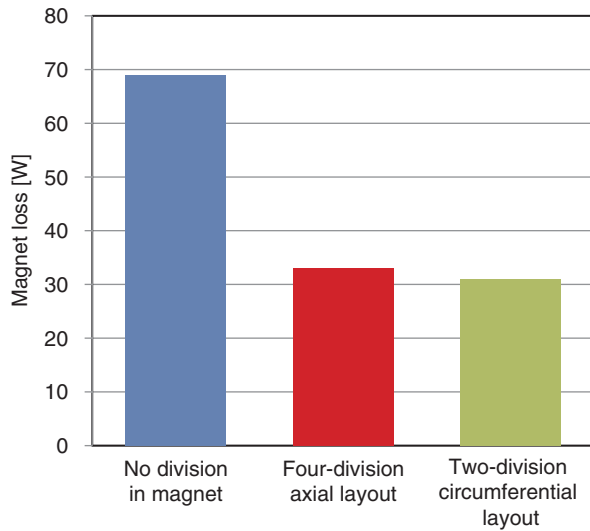


Fig. 12 Comparison of magnet loss

magnets halves iron loss, the results indicated that it would be possible to realize the same or a lower level of loss than the previous motor.

6. Results of Motor Loss Evaluation

Figure 13 shows a comparison of the results of motor loss measurements for the previous motor and the new motor. The depth of color shows the difference in loss when loss in the new motor is subtracted from loss in the previous motor. The new motor achieves the same loss as the previous motor in the JC08 fuel economy mode operating range. In addition, loss has been reduced against the previous motor in the high-loss high-rotation and high-torque regions.

Figure 14 shows the effect on motor loss during JC08 mode operation. Here, motor loss per unit time was integrated, and the previous motor was used as the base (100%). These results demonstrate that while the use of generally available materials for the stator cores increased

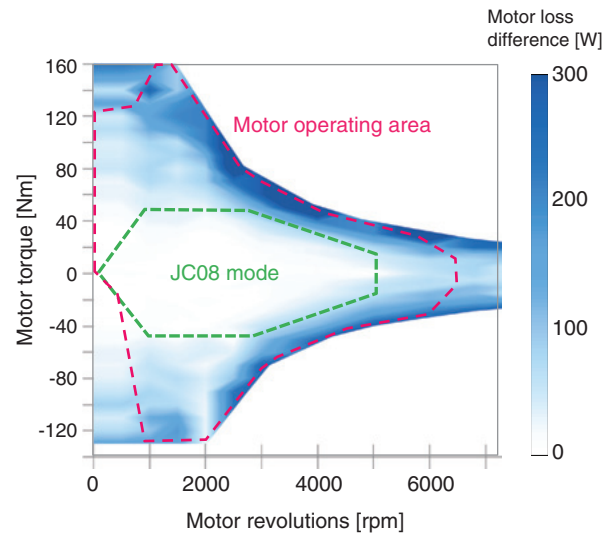


Fig. 13 Comparison of motor loss

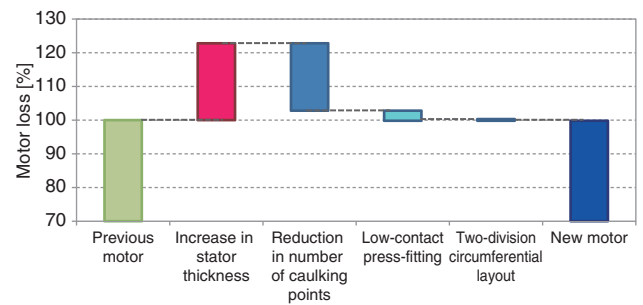


Fig. 14 JC08 mode motor loss

motor loss against the previous motor, the use of single caulking dowels and low-contact press-fitting, and the method of dividing the magnets, realized the same or a lower level of loss in the new motor as in the previous motor.

7. Conclusion

The employment of low-loss technologies in a new motor made it possible to realize the same level of loss as the previous motor in a framework of the same size without the use of heavy rare earths.

- (1) Iron loss was reduced by employing single stator caulking dowels in positions of low magnetic flux density. In addition, reduction of the number of contact points where the stator cores are press-fitted into the stator holder reduced loss by an average of 11%.
- (2) Optimization of the layout of the divisions in heavy rare earth-free magnets realized the same level of loss as the previous products using the minimum necessary number of divisions.

The use of generally available grades of materials in the electromagnetic steel sheets employed in the stator cores and the reduction of the number of divisions in the magnets reduced costs against the previous motor.

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Estimation of Probability Distribution of Li-ion Battery Performance for Electrically-propelled Vehicles

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ABSTRACT

The usage and performance status of Li-ion batteries installed in hybrid electric vehicles were collected by means of fault diagnosis devices. Analysis of the collected data showed the existence of a margin between the Li-ion battery capacities in users' usage conditions and the estimated capacity degradation line that is foreseen during development to show the most rapid degradation. The distribution of the actual Li-ion battery performances in the users' usage conditions is composed of the initial performance distribution, the degradation distribution created by different usage patterns, the degradation distribution of Li-ion batteries within an identical set, and the performance calculation errors made by the electric control units. The capacity margin occurred as a result of the estimated performance degradation line foreseen during development being calculated under conditions in which the distributions of the above performance factors were simultaneously positioned at severe extreme values.

A formula, which reflects the actual distributions and the correlations between the distributions, was created to calculate the probability distribution of performance degradations of Li-ion batteries. Usage data and capacity data on 126,742 cars of the 2013 model FIT HYBRID for the Japanese market were used to verify the validity of the formula that was created. The results show that the probability distribution of real capacity at 1.5 years after a vehicle is registered agrees with the probability distribution of estimated capacity after 1.5 years as calculated using the created formula. This verified the validity of the formula. This also successfully quantified the position of the capacity estimated using the estimated capacity degradation line foreseen during development with respect to the estimated probability distribution of performance after a target use period as 9.6σ . As it became possible to calculate the probability distribution of performance after degradation, this enabled optimal cost design of Li-ion batteries, bringing out the maximum vehicle performance of hybrid electric vehicles during the target use period.

1. Introduction

The performance of a Li-ion battery (LIB) means its capacity as well as its input and output power characteristics. A LIB degrades as it is used and as time passes. This has an influence on fuel economy and other such factors in hybrid electric vehicles (HEV) that have a LIB installed. Therefore grasping LIB usage and the extent of performance degradation in the users' usage conditions is crucial for the function design of LIB.

Honda started LIB installation in HEV with the 2012 model of Civic Hybrid for the North America market. Function design of LIB is conducted on the foundation of surveys of the past users' usage conditions and engineering expertise. In order to obtain users' usage conditions and performance statuses of LIBs, all HEVs equipped with

LIBs store the data of their performance status and usage in their on-board electric control units (ECUs), which are measured by on-board sensors and calculated by the ECU. The accumulated data is collected non-periodically at Honda dealers during vehicle inspections and other such occasions by means of the Honda Diagnostic System (HDS)⁽¹⁾. The collected data is sent to Honda servers for analysis and use⁽²⁾. When the collected data was analyzed, it became apparent that there was a margin between the LIB capacities in the users' usage conditions and the estimated capacity degradation line that is foreseen during development to show the most rapid degradation, and between the input and output power characteristic values in the users' usage conditions and the line of input and output power characteristics degradation estimation that is foreseen during development to show the most rapid degradation.

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As an example, Fig. 1 shows the estimated capacity degradation line foreseen during development and the capacity calculated by ECU in 126,742 cars of the 2013 model FIT HYBRID for the Japanese market.

It is apparent from Fig. 1 that comparison shows that there is a margin between the estimated capacity degradation line foreseen during development and the capacities in the users' usage conditions.

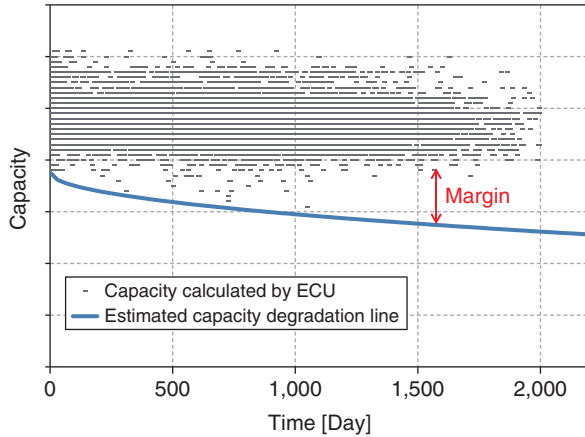


Fig. 1 LIB capacity of FIT HYBRID calculated by ECU

2. Current Issues

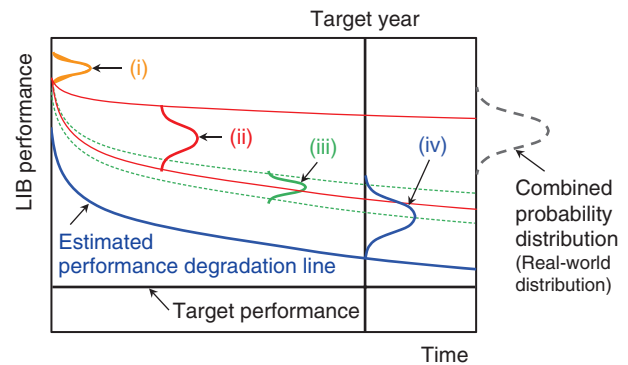
In order to analyze the causes of the margin noted in the previous chapter, the factors in LIB performance after degradation were broken down into the following four component factors of performance: (i) initial performance distribution, (ii) degradation distribution created by different usage patterns, (iii) degradation distribution of LIB within an identical set, and (iv) distribution created by ECU calculation errors.

The (i) initial performance distribution is due to variations between individual batteries, found in component materials that occur during the LIB manufacturing process and that affect initial LIB performance. The (ii) degradation distribution created by different usage patterns is defined as the distribution in the extent of degradation in LIB performance caused by HEV use by various different users under various different driving conditions and environmental conditions. The main factor in occurrence of the degradation distribution created by different usage patterns is the differing rates of LIB degradation that are due to the differences in current load on the LIB during driving and differences in the ambient temperatures of the LIB. The (iii) degradation distribution of LIB within an identical set is defined as the distribution in the extent of degradation in LIB performance that occurs when LIBs that initially have identical performance are used under identical usage conditions and identical environmental conditions.

The cause of degradation distribution of LIB within an identical set is the variation in LIB component materials that occurs during the manufacturing process and influences the rate of degradation. The (iv) distribution created by ECU's calculation errors is the error that occurs when the ECU calculates LIB performance, and it includes sensor error and control error. Use of these four distribution factors makes it possible to break down LIB performance after degradation into its component factors without omission or repetition.

As shown in Fig. 2, the estimated performance degradation line foreseen during development is defined by conditions under which every distribution factor simultaneously shows severe extreme values. On the other hand, once the probability distribution of LIB performance after a target use period, which is made up of these distribution factors, as estimated during development, had been calculated, nothing had been done to confirm where the estimated performance degradation line foreseen during development would be positioned on the estimated probability distribution.

Generally, the factors that accelerate LIB performance degradation are said to be the LIB temperature, charge and discharge current values, and the usable state of charge (SOC) or voltage width⁽²⁾. Examination of the (ii) degradation distribution created by different usage patterns, such as the performance degradation line foreseen during development for the LIB installed on the FIT HYBRID, shows that they have been calculated for conditions in which the most severe corner-case values that could be foreseen occur simultaneously for each of these degradation accelerating factors (Table 1).



	Distribution factor	Value for estimation
(i)	Initial performance distribution	Lower specification limit
(ii)	Degradation distribution created by different usage patterns	Most severe usage profile
(iii)	Degradation distribution of LIB within an identical set	-3σ of distribution
(iv)	Distribution created by ECU's calculation errors	-3σ of distribution

Fig. 2 Factors of LIB performance degradation

Table 1 Usage factors in performance degradation for FIT HYBRID LIB

Usage factors in performance degradation		Test condition of durability test based performance estimation line
Drive	LIB temperature	Highest operational limit
	Charge and discharge pattern	Follows hardest pattern among all drive patterns
	Charge and discharge time	Longest time among real-world data
Park	LIB temperature	Highest temperature profile among major cities
	Voltage or SOC	Highest operational limit

However, analysis of LIB usage began to make it clear that the main degradation factors showed a margin between the most severe usage conditions foreseen during development and the actual usage conditions experienced by users (Figs. 3, 4, and 5).

It can also be seen from Figs. 3 and 4 that LIB temperature and charge and discharge current both show a margin between the upper limit values and lower limit values of LIB usage in the zone of accelerated performance

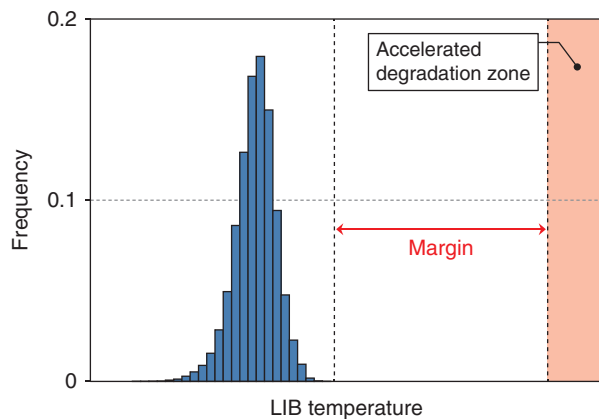


Fig. 3 LIB temperature during operation

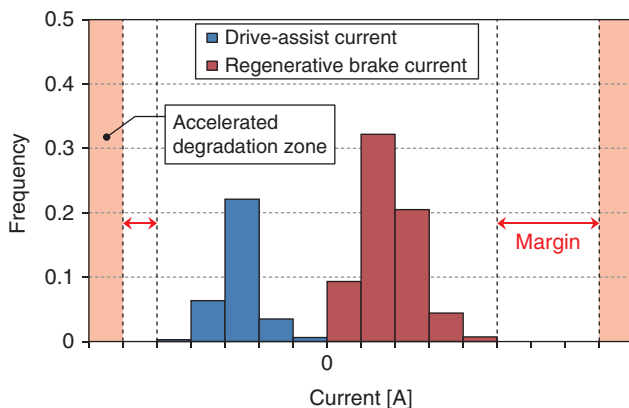


Fig. 4 Current during operation

degradation and the users' usage conditions. Similarly, Fig. 5 shows that there is a margin between the SOC envisioned as undergoing the most severe degradation and the upper limit value for SOC in the users' usage conditions.

As these findings suggest, LIB function design was carried out for conditions that can be expected to cause the most severe degradation among the conditions foreseen because of the desire to provide satisfactory LIB target performance at a high reliability level during the target use period.

On the other hand, HEV design is carried out on the assumption that fuel economy and other such factors of vehicle performance will be maintained during the target use period. Since it is equipped with a LIB that degrades over time, the HEV is designed according to the criteria of LIB performance values after the target use period. If we take the hypothetical case of a LIB that is under-valued for performance after target use, then this would mean that the vehicle performance during the target use period is under-configured.

In order to extract the maximum HEV performance during the target use period, it is necessary to accurately estimate the LIB performance after the target use period, and to design the vehicle performance according to those accurate performance values. For that purpose, it is necessary to accurately estimate the changes in LIB performance distribution according to how they occur in the actual users' usage conditions and to design LIB performance following target use with adequate reliability. In order to design LIB performance and reliability quantitatively, it is necessary to calculate LIB performance after degradation in the users' usage conditions as a probability distribution.

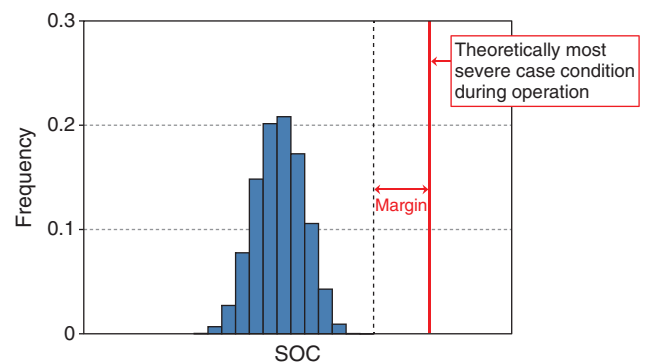


Fig. 5 SOC during park

3. Development Aims

For the purpose of extracting the maximum HEV performance during the target use period, the probability distribution of LIB performance degradation in the users' usage conditions needs to be calculated. The distribution created by ECU calculation errors has an influence on

the values calculated for LIB performance when installed in a vehicle, but it does not have any influence on LIB performance itself. Therefore it was excluded from the examination in this paper, and the following three points were taken as the main aims.

- (1) To accurately grasp the three factors of distribution that make up LIB performance: (i) initial performance distribution, (ii) degradation distribution created by different usage patterns, and (iii) degradation distribution of LIB within an identical set.
- (2) To accurately grasp the correlations among the above factors (i), (ii), and (iii) of distribution (to include non-linear correlations).
- (3) To create a method for convolution of distributions that incorporates (1) and (2), and to calculate LIB performance after degradation in the users' usage conditions as a probability distribution.

4. Creation of a Method for Calculation of the Probability Distribution of Performance after Degradation

4.1. Method for Grasping Correlations Between Distribution Values and Distribution

Table 2 summarizes the methods used to achieve the aim given in the previous chapter by grasping the distribution values that make up LIB performance as well as the correlation between the distributions.

The (i) initial performance distribution can be grasped from the data provided by LIB manufacturers on LIB performance values during the production process. When the number of samples and the period of initial performance distribution data are inadequate, it is also possible to use the initial performance distribution estimated from the process

Table 2 Methods to find distributions or correlations

Distribution or correlation		Method to find
Distribution	(i) Initial performance	Production history or production process
	(ii) Usage degradation	Models -Vehicle performance -LIB degradation
	(iii) Degradation within identical set	Durability tests
Correlation	(i) and (ii)	Models -Vehicle performance -LIB degradation
	(ii) and (iii)	Durability tests under various usage conditions
	(iii) and (i)	Durability tests of LIB with various initial performance levels

control values (for example, design target centers, upper and lower specification limits, and production capacity index) for the production process.

The (ii) degradation distribution created by different usage patterns, and the correlation between (i) and (ii), are derived using the vehicle model and LIB degradation estimation model (Fig. 6). The vehicle model will take LIB initial performance and time series speed, outside air temperature, and amount of solar radiation as its input, and will output the LIB applied voltage changes for the corresponding vehicle. The LIB degradation estimation model calculates the LIB voltage, current, and temperature in time series corresponding to those applied voltage changes, and based on the changes in those calculated values, it outputs the amount of LIB degradation.

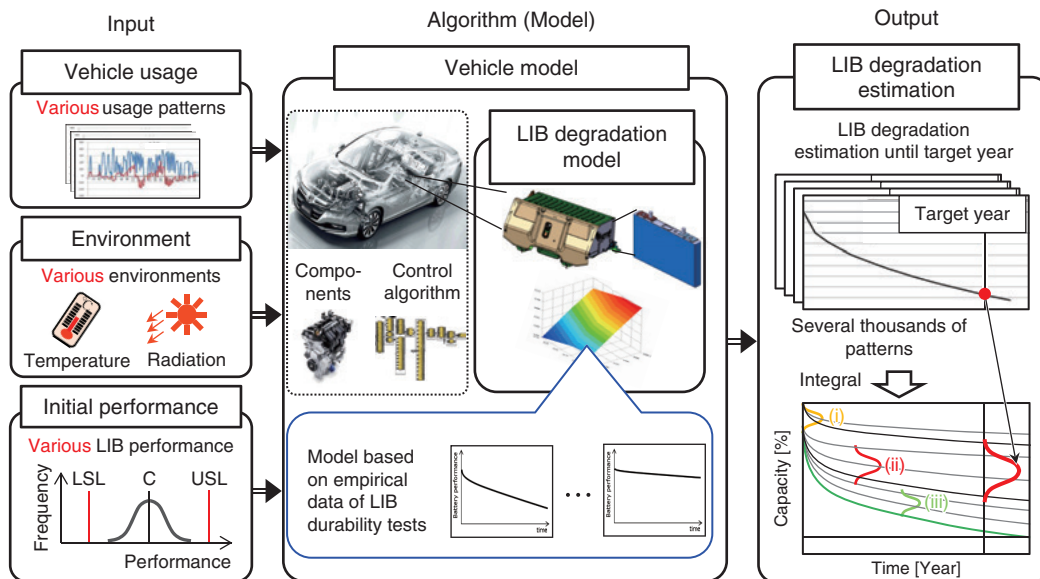


Fig. 6 Models for estimating performance degradation

As to the degradation distribution created by different usage patterns, this occurs as a result of vehicle usage under a variety of different conditions. Given constraints on resources, however, patterns of voltage changes in an enormous number of vehicles cannot readily be applied to an actual LIB to determine the distribution of degradation. Therefore models are used to calculate this distribution. In order to determine the degradation distribution created by different usage patterns in the case of a certain initial performance, a variety of different usage conditions are input to the model, with the initial performance held constant. This yields a variety of LIB degradation changes corresponding to the usage. Taking the frequency of occurrence into consideration, the numbers of iterations are added together from the data obtained, which is in the range of several thousands of items, and this makes it possible to grasp the degradation distribution created by different usage patterns. As to a grasp of the correlation between (i) and (ii), a variety of different usage conditions are similarly input into the model, but the initial performance is varied when this is done. Doing this makes it possible to grasp the influence on the degradation behavior when the initial performance is varied, or in other words the correlation between (i) and (ii).

The (iii) degradation distribution of an LIB within an identical set, as well as the correlation between (ii) and (iii) and the correlation between (iii) and (i), can be grasped by means of durability testing of multiple LIBs. As shown in Fig. 7, durability tests that keep the initial performance fixed and vary the usage, as well as durability tests that keep the usage fixed and vary the initial performance, are both implemented. This makes it possible to grasp the correlation with the distribution values. The causal factor for occurrence of degradation distribution of LIB within an identical set is the distribution of the LIB process factors that have not emerged in the initial performance. This means that in either test, the initial performance is made generally identical for multiple cells, and those trial objects should be randomly selected from the process line.

4.2. Creation of a Method for Convolution of Distribution Factors

A method for convolution of the distribution factors (i), (ii), and (iii) was created on the basis of the correlations that were grasped.

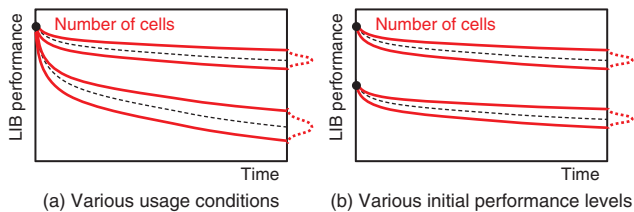


Fig. 7 LIB durability tests to obtain degradation distribution within identical set

Regarding the correlation of (i) and (ii), the results of simulation performed using models have shown that this is not a simple linear correlation, but rather a conditional probability distribution. This means that if the initial performance differs, then the probability distribution of performance degradation, created by different usage patterns obtained from applying multiple differing power changes to the LIB, will differ. This is because even if the same power changes are applied to the LIB, if the initial performance is different, then there will be differences in the LIB usable SOC range, the applied current, the resulting LIB temperature, and other such quantities.

With regard to the correlations between (ii) and (iii), and between (iii) and (i), it was also found from durability tests that here, too, the correlation is not linear, but is a conditional probability distribution. This means that even if durability tests are conducted from the same initial performance, if the usage differs, then the probability distribution of performance after degradation distribution will differ. Also, even if the usage is the same, if the initial performance differs, then the probability distribution of performance after degradation distribution will differ.

Consequently, vehicle usage is divided into environmental conditions and driving conditions, and put as follows.

Initial performance: Per_{ini}

Environmental conditions (time series data set for air temperature and amount of solar radiation): Env

Driving conditions (time series data set for vehicle speed, etc.): $User$

Performance after degradation: Per

The conditional probability density function for performance, after degradation when a certain initial performance, environmental conditions, and driving conditions are given, including (iii) degradation distribution of LIB within an identical set, can be defined as follows.

$$g(Per|Per_{ini}, Env, User) \quad (1)$$

This means that when certain initial performance, environmental conditions, and driving conditions are assigned, the probability distribution of the corresponding performance after degradation distribution will be unique. For the probability density function $f(Per)$ of performance after degradation, which is what is ultimately desired here, it will suffice to use the approach of convolution, applying the probability density function formed from initial performance, environmental conditions, and driving conditions to this formula and convoluting it over the whole range. This can be expressed as follows.

$$f(Per) = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} g(Per|Per_{ini}, Env, User) h(Per_{ini}) u(Env, User) dPer_{ini} dEnv dUser \quad (2)$$

Here $h(Per_{ini})$ is the probability density function of initial performance and $u(Env, User)$ is the simultaneous

density function for environmental conditions and driving conditions. Generally, there is no correlation between LIB initial performance and environmental conditions or driving conditions. However, since environmental conditions and driving conditions can be considered to have a correlation, a simultaneous density function is used for the expression.

The conditional probability density function in Eq. (1) is created from the simulation results with a model and a test of degradation distribution of LIB within an identical set. The probability density function for initial performance on the right side of Eq. (2) was established on the basis of data provided by LIB manufacturers. The simultaneous density function for environmental conditions and driving conditions was established from vehicle data collected in actual environments. However, it is permissible to use an estimated probability density function when development is still underway and fully reliable data is not available. It will be necessary to formulate an appropriate probability density function in accordance with the purpose.

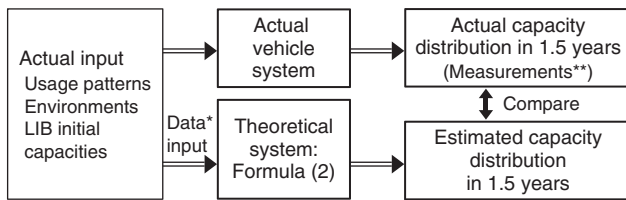
5. Equation Validity and Estimated Calculation

5.1. Verification of the Validity of Equation for Probability Distribution of Performance after Degradation

In order to verify the validity of Eq. (2) for the probability distribution of performance after degradation of a LIB in the users' usage conditions, a comparison was made of the probability distribution of real capacity of a LIB installed in an actual vehicle, and the probability distribution of estimated capacity calculated from data on actual LIB usage. The flow of comparison between the two is shown in Fig. 8.

When the probability distribution of estimated capacity becomes close to the probability distribution of real capacity, this means that the performance distribution is being correctly calculated and the validity of the equation can be demonstrated. As in a previous chapter, the validity of the equation was verified using data from the 2013 model FIT HYBRID for the Japanese market.

A vehicle model of the FIT HYBRID as described above was created for use in behavior analysis was used.



* Input data acquired through HDS or by LIB manufacturer

** Measurements acquired through HDS

Fig. 8 Analysis flow of comparison between actual and estimated capacity distributions

A model created for the LIB installed in the FIT HYBRID was used as the model for LIB degradation. Driving patterns, environmental conditions, and actual power data were collected by means of HDS, and the data on LIB initial capacity was obtained from the manufacturers of the installed LIB. The HDS's actual power data is for capacity calculated by the on-board ECU, so it includes estimation errors. In order to align the conditions of comparison, the distribution for capacity estimation errors obtained in previous testing was assigned for the probability distribution of estimated capacity.

Figure 9 shows a comparison of the probability distribution of real capacity and the probability distribution of estimated capacity at a point 1.5 years after vehicle registration.

The histogram in blue shows the probability distribution of real capacity, and the probability distribution marked in red shows the probability distribution of estimated capacity. It is apparent that the median values, the distribution

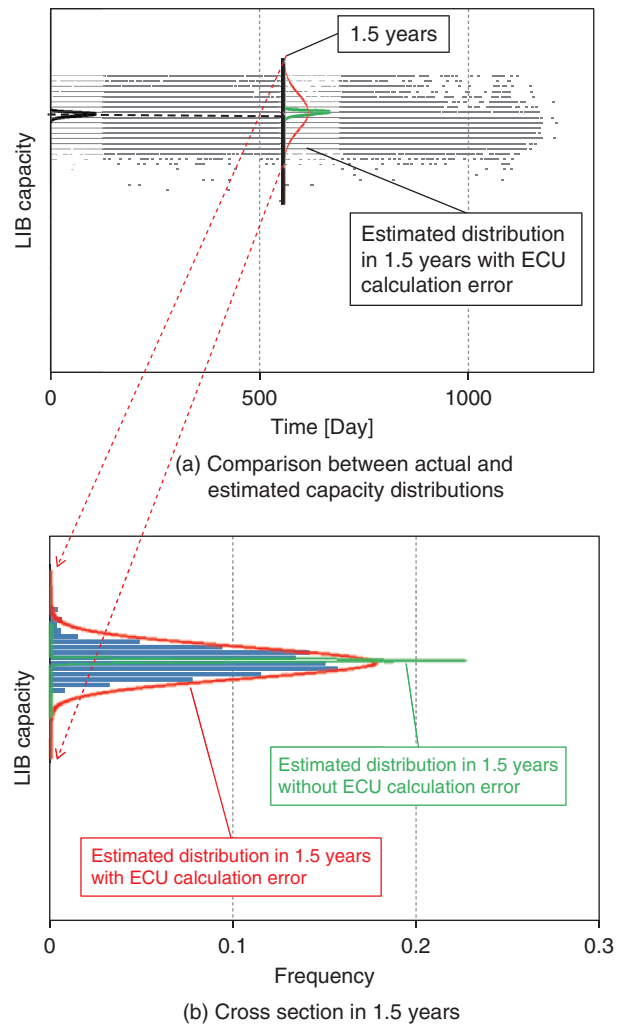


Fig. 9 Comparison between actual and estimated capacity distributions of LIB for FIT HYBRID

widths, and the distribution profiles for the probability distribution of real capacity and the probability distribution of estimated capacity generally coincide. This can be taken as demonstration that the probability distribution of performance after degradation is correctly calculated using the created equation.

5.2. Probability Distribution Estimation of LIB Performance after Target Use Period

Next, the probability distribution of LIB performance after a target use period is calculated. By comparing the probability distribution of performance after degradation with the estimated performance degradation line foreseen during development, the position of the estimated line in the users' usage conditions was quantified. Figure 10 shows the flow of comparison between these two.

In calculating the estimated performance degradation line foreseen during development and the probability distribution of performance after degradation in the users' usage conditions, the same models as those described in previous sections were used, vehicle models and LIB degradation models alike. The estimated line was calculated so that the (i) initial performance distribution, the (ii) degradation distribution created by different usage patterns, and the (iii) degradation distribution of LIB within an identical set would simultaneously show severe values, as described in chapter 2. On the other hand, in calculating a degradation distribution reflecting the actual environment, a continuing target period of use was assumed for the patterns of driving conditions and environmental conditions envisioning the actual environment that are for the purpose of calculating the (ii) degradation distribution created by different usage patterns, and the distribution obtained from the LIB manufacturers was used as the LIB data for (i) initial performance and for (iii) degradation distribution of LIB within an identical set.

Figure 11 shows the estimated probability distribution of LIB performance, after the target use period and the estimated performance degradation line foreseen during development to show the most rapid degradation both

plotted against capacity and input and output power characteristics.

The new creation of Eq. (2) and the distribution of input data made it possible to calculate LIB performance after the target use period as a probability distribution. With regard to the estimated probability distribution of LIB performance after the target use period, estimation performance using the estimated degradation line foreseen during development as indicating the most rapid degradation was quantified at 9.6σ for capacity and at 9.1σ for input and output power characteristics.

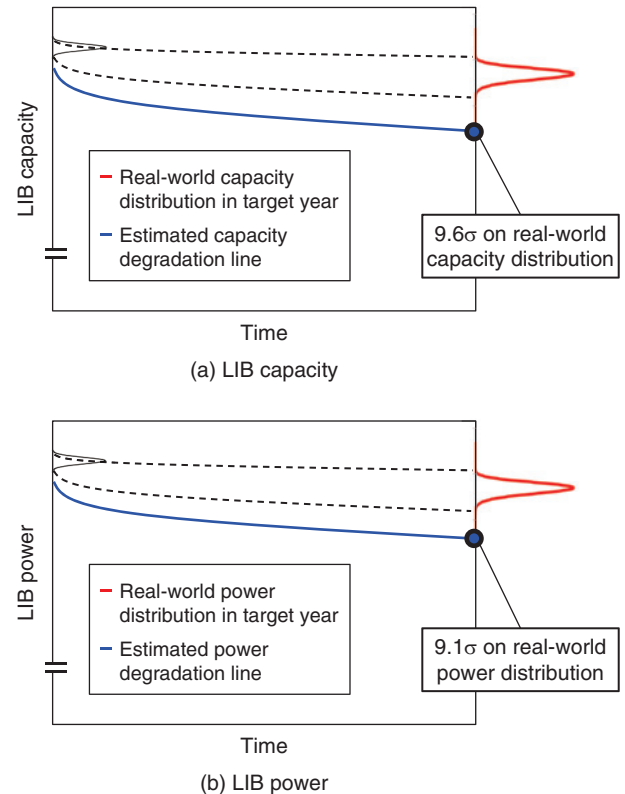


Fig. 11 Comparison between real-world performance distribution and estimated performance degradation line in target year

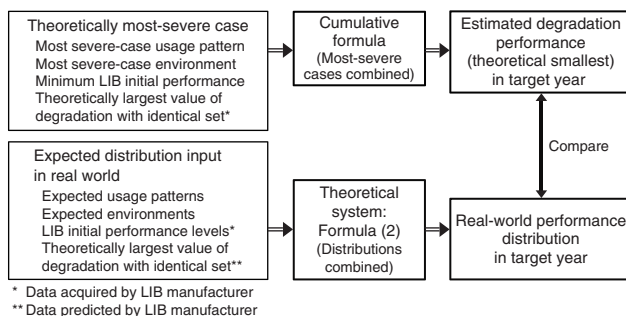


Fig. 10 Analysis flow of comparison between real-world performance distribution and theoretical smallest performance in target year

6. Value

Enabling calculation of LIB performance after the target use period, as a probability distribution, it became possible to design LIB performance and reliability in a quantitative manner. In a hypothetical case of LIB performance designed with excessive reliability in respect to the estimated probability distribution of LIB performance, optimization of the excessive reliability would yield the following two points of value.

The first value would be that, by reducing design performance until it is at an appropriate level of reliability,

LIB cost and LIB weight could be reduced (Fig. 12). When parts costs become more reasonable, it becomes possible to lower the HEV sale price, and that value can return to the user.

The second value would be in increasing the target for LIB performance after target use until it is at an appropriate level of reliability (Fig. 13). Doing this would make it possible to increase the value set for LIB performance in the vehicle that is to have the LIB installed, thereby making it possible to provide an HEV that has a higher performance in terms of fuel economy and other aspects of product appeal.

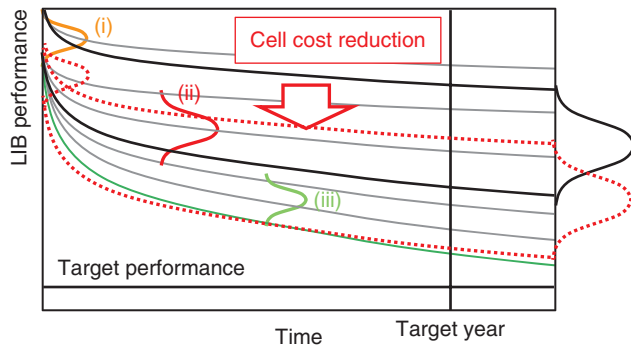


Fig. 12 First value option: Cell cost reduction

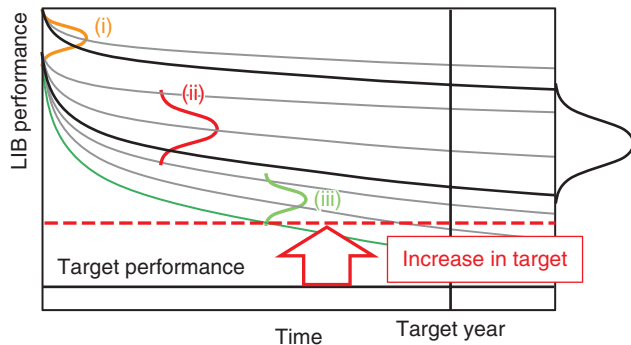


Fig. 13 Second value option: Increase in target

7. Conclusion

LIB usage and performance data for LIBs installed in user HEVs were collected by means of HDS and analyzed, yielding the following results.

- (1) The correlations between the (i) initial performance distribution, (ii) degradation distribution created by different usage patterns, and (iii) degradation distribution of LIB within an identical set were accurately grasped, and a formula was created to calculate the probability distribution of performance after degradation of a Li-ion battery that reflects those correlations.

- (2) Data on 126,742 FIT HYBRID cars was used to verify the validity of the created formula. In regard to the estimated probability distribution of LIB performance after the target use period, an estimation performance using the estimated degradation line, foreseen during development as indicating the most rapid degradation, was quantified at 9.6σ for capacity and at 9.1σ for input and output power characteristics.
- (3) Calculating the probability distribution of LIB performance enabled carrying out an optimal LIB cost and reliability design, as well as bring out the maximum vehicle performance of an HEV during the target use period.

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Aerodynamics Development for Bonneville Race Car Using Fluid Simulation

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ABSTRACT

Honda participated in both Bonneville Speed Week, held in August 2016, and Mike Cook's Bonneville Shootout, held in September 2016, at Bonneville Salt Flats near Salt Lake City, Utah (USA) using a special vehicle equipped with a 658 cm³ displacement engine for a Kei car, which is an original Japanese vehicle category. Fluid simulation was used to perform aerodynamics development for the race car to create a body shape with aerodynamic drag that enables to achieve the target speed with limited engine power and to secure driving stability. The goal was to achieve a speed of 450 km/h, which would be a new speed record for the participation category. A body shape with the target drag was designed using a prototype model, and models of record holders, as references. Vertical and horizontal wings were attached to the race car to suppress vehicle spin and flipping, in addition to increasing driving stability at high speeds. On site, it became necessary to change the shape for increased visibility while driving, but the developed process allowed for a rapid body shape change, keeping vehicle stability in consideration. As a result, the official world speed record of 421 km/h in the Category A, Group 1, Class 4 was set at Mike Cook's Bonneville Shootout (International Automobile Federation World Land Speed Records).

1. Introduction

Honda challenged the Bonneville Speed Week held in August 2016 at the Bonneville Salt Flats near Salt Lake City, Utah (U.S.A.) using a race car consisting of a special body equipped with an engine having the same displacement as that of a Kei car, which is an original Japanese vehicle category.

The top speed set for this participation category was 433.686 km/h (269.480 mph) recorded by team Costella Yacoucci during the August 2007 Bonneville Speed Week. Therefore, race car development was performed with a target speed of 450 km/h, which would be a new world speed record in this category.

The dominant vehicle running resistance when driving at high speeds is aerodynamic drag, so a target drag was set with the body shape designed to achieve the target speed with limited engine power.

The Bonneville Salt Flats used for the race venue are located to the west of Salt Lake City, Utah (U.S.A.), and are vast salt plain highlands covering some 260 km² at an elevation of approximately 1,200 m. Mountains rise to the northwest of the course location, measured in the 2,000 m class, and gusty winds are known to blow down from them.

Investigation of past races revealed cases where cars

spun and crashed while driving. The causes of these incidents were investigated, and it was found that although the event organizers level the course track surface during the event period, the track surface condition easily changes between states ranging from watery sherbet to free-flowing sand, etc. Furthermore, the track surface gradually becomes rougher as the races proceed, with rutting and level differences occurring in some places.

To hit the target speed, it is important to achieve the target drag and to secure vehicle stability so that disturbances such as wind or road surface inputs do not produce spinning or flipping. Therefore, fluid simulations were used to design a body shape for the target drag, performing aerodynamics development for the race car with the goal of securing vehicle stability in consideration of the driving environment.

As a result of participating in Bonneville Speed Week, although the target speed was not achieved, Honda was invited by the organizers to participate in Mike Cook's Bonneville Shootout (International Automobile Federation (FIA) World Land Speed Records) held in September, successfully setting the official world speed record then and there at 421 km/h in the Category A, Group 1, Class 4.

This report examines the race car aerodynamics development using fluid simulation.

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Table 1 Bonneville Speed Week of participation category

Body	BFS class (Blown Fuel Streamliner)	Turbochargers, superchargers and any choice of fuel are allowed in streamliner car
Engine	J class	508-753 cm ³

Table 2 Specifications of Honda S-Dream Streamliner

Body	Car name	Honda S-Dream Streamliner
	Length	8,500 mm
	Width	840 mm
	Height	1,185 mm
	Vehicle weight	830 kg
	Wheel base	4,800 mm
	Tire size (front, rear)	125/60R15, 115/110R15
Engine	Displacement	658 cm ³
	Bore × Stroke	66.0 × 64.0 (mm)
	Power	184 kW (250 PS)/10,000 rpm
	Torque	200 Nm (20.4 kgf.m)/9,000 rpm
	Cooling system	Water RAD, I/C
	Turbocharger	Garrett

2. Participation Category and Vehicle Specifications

2.1. Participation Category and Regulations

At Bonneville Speed Week, Honda participated in the category of special cars equipped with supercharged Otto-cycle engines containing a displacement of 508 to 753 cm³⁽¹⁾. Table 1 shows the participation category.

The flying start method of pushing the race car from behind with another car was selected as the starting method.

2.2. Vehicle Specifications

A special Bonneville race car equipped with an engine displacement of 658 cm³ and a power of 184 kW was developed in accordance with the SCTA official rulebook⁽¹⁾ in order to qualify for participation. This race car was named the Honda S-Dream Streamliner.

Table 2 shows the specifications and Fig. 1 shows the appearance of the vehicle.



Fig. 1 Appearance of Honda S-Dream Streamliner

3. Aerodynamic Performance Design

Aerodynamic performance requirements that would enable to achieve the target speed and stability were set and vehicle development was performed on the assumption of the mounted engine power.

3.1. Body Drag

Vehicle traction force and running resistance have an equilibrium relationship during driving, so to achieve the target speed of 450 km/h with limited engine power, it is necessary to reduce the running resistance (rolling resistance and drag) at the target speed to less than traction force.

Drag D is produced by uneven shapes such as the body exterior shape and protrusions, air flows entering and exiting the body, and friction between the body surface and the surrounding air. Drag increases proportionately to the square of vehicle velocity as shown in Eq. (1), so it becomes dominant during high-speed driving.

$$D = \frac{1}{2} \rho v^2 CDA \quad (1)$$

Here, ρ is the air density, v is the vehicle velocity, CD is the drag coefficient, and A is the frontal projected area of the body.

Therefore, to achieve the target speed of 450 km/h with 184 kW engine power, the target drag excluding rolling resistance was set to $CDA \leq 0.09$ (Fig. 2).

3.2. Lift Suppression

The target speed for this vehicle is at the level of, or greater than, aircraft takeoff speed, so it is necessary to generate negative lift (downforce) on the body to enable driving without the vehicle separating from the ground. Therefore, the lift coefficient (CL) target was set to < 0 .

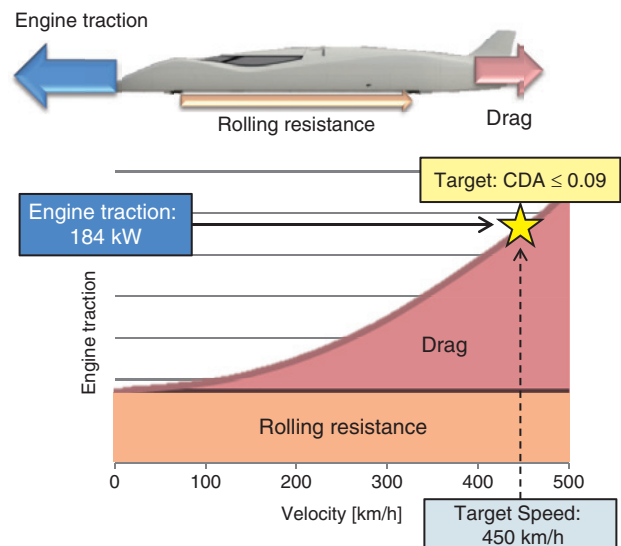


Fig. 2 Relationship between engine traction and total resistance

3.3. Spin Suppression

Disturbances such as vehicle vibration due to road surface unevenness, unexpected cross winds, and gusty winds may produce the spin phenomenon where the vehicle turns excessively. For this reason it is necessary to provide stability that will enable the vehicle to travel straight even when disturbances occur.

It is known that when a vehicle travels at high speeds, the aerodynamic characteristics of the lateral force and the yawing moment relative to the lift acting on the front and rear wheels and the yaw angle contribute to vehicle stability. In the range of a small body slip angle when travelling in nearly a straight line, these characteristics can be assessed using the stability factor, which is an indicator of the dynamic characteristics of the vehicle^{(2), (3)}.

Equation (2) shows the equation for calculating the stability factor A_{aero} in consideration of aerodynamic characteristics as shown in Fig. 3.

$$A_{aero} = -\frac{m}{2l^2} \frac{l_f(K_f + \Delta K_{aero_f}) - l_r(K_r + \Delta K_{aero_r})}{(K_f + \Delta K_{aero_f})(K_r + \Delta K_{aero_r})} \quad (2)$$

Here, m is the vehicle mass, l is the wheelbase length, l_f and l_r are the respective distances from the front and rear wheels to the center of gravity position, and K_f and K_r are the respective cornering powers of the tires per unit slip angle generated at the front and rear wheels. This equation takes into account the influence of aerodynamic characteristics including the lateral force produced during steady-state cornering, so it uses the ΔK_{aero_f} of Eq. (3) and ΔK_{aero_r} of Eq. (4) as the respective equivalent cornering powers acting on the front and rear wheels (Fig. 3).

$$\Delta K_{aero_f} \cong -\frac{1}{2l} \frac{l_f K_f}{l_r K_r} \left(l_r \frac{\partial F_{aero_y}}{\partial \beta} + \frac{\partial M_{aero_z}}{\partial \beta} \right) \quad (3)$$

$$\Delta K_{aero_r} \cong -\frac{1}{2l} \left(l_r \frac{\partial F_{aero_y}}{\partial \beta} - \frac{\partial M_{aero_z}}{\partial \beta} \right) \quad (4)$$

Here, β is the slip angle when cornering, F_{aero_y} is the lateral force acting on the vehicle, and M_{aero_z} is the yawing moment around the vertical axis of the vehicle center of gravity.

Understeer characteristics result when A_{aero} is positive, and oversteer characteristics when A_{aero} is negative. Therefore, the target was set with an A_{aero} that is always greater than zero at the target speed of 450 km/h or less,

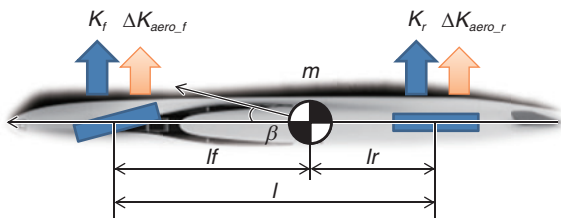


Fig. 3 Stability factor model diagram

Table 3 Aerodynamics design requirement

Category	Item	Target
Target speed		450 km/h
Aerodynamics	Specific drag	CDA < 0.09
	Body lift	CL < 0
Vehicle stability	Stability factor	$A_{aero} > 0$
	Wheel load variation at front and rear wheels	$\Delta Wtf_{-\alpha} > 0$ $\Delta Wtr_{-\alpha} > 0$

ensuring the vehicle to drive stably in a straight line even when disturbances occur.

3.4. Flipping Suppression

When vehicle attitude is disturbed by road surface input due to rutting and level differences, the vehicle nose may rise up (pitching), and air flowing to the underside of the body may generate lift on the body and further promote pitching, with the result that the flipping phenomenon occurs. This calls for some force that acts to return the vehicle to the original attitude when pitching occurs in order to secure stability.

Therefore, the target was set as front wheel load variation $\Delta Wtf_{-\alpha}$ and rear wheel load variation $\Delta Wtr_{-\alpha}$, ones that are always positive even when the pitching angle (α) changes, as shown in Eq. (5) and Eq. (6) (Fig. 4).

$$\Delta Wtf_{-\alpha} = Wtf_{-\alpha} - Lf_{-\alpha} > 0 \quad (5)$$

$$\Delta Wtr_{-\alpha} = Wtr_{-\alpha} - Lr_{-\alpha} > 0 \quad (6)$$

Here, $Wtf_{-\alpha}$ and $Wtr_{-\alpha}$ are the respective vehicle wheel loads at the front and rear wheels, and $Lf_{-\alpha}$ and $Lr_{-\alpha}$ are the respective lift forces acting on the front and rear wheels.

Table 3 summarizes the aerodynamic performance design requirements needed to achieve both the target speed and vehicle stability described in this chapter.

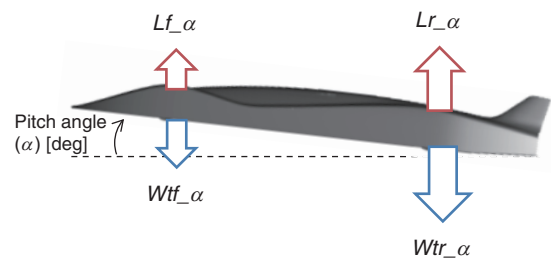


Fig. 4 Wheel load variation of car weight and lift force when pitching

4. Body Shape Design

Fluid simulation was used to investigate a body shape that achieves the target drag and lift, using a prototype model devised from initial investigations, and as references,

three models with different features selected from among the top record holder Bonneville machines. Figure 5 shows the respective body shapes and section pressure distributions obtained by fluid simulation and Fig. 6 shows the CD and CL results.

These results show that the prototype model has the smallest CD, and that reference model 2 has the smallest CL. Comparison of CL for the prototype model and reference model 2 revealed that the top position of the prototype model body shape is located toward the front of the body, so positive lift is generated at the front wheels. In addition, the greater slope angle from the nose to the top position also increases lift. Furthermore, reference model 2 results show that the incline (diffuser) from the underfloor to the rear end generates negative lift. Therefore, the contributions of the top position and height and the incline

angle were investigated to achieve a negative CL value based on the prototype model shape that has the smallest CD. Fig. 7 shows this modified model.

The modified model had a CDA of 0.085 and a negative CL value, so a body shape that achieves the target drag and lift could be designed.



Fig. 7 Shape and section pressure distribution of modified model

5. Vehicle Stability Confirmation

5.1. Stability Factor Confirmation and Countermeasures

Simulations were performed to assess whether vehicle stability could be secured while driving at high speeds. Figure 8 shows the A_{aero} calculation results for the modified model shown in Fig. 7. This shows that the A_{aero} of the modified model body shape falls below zero and results in the vehicle becoming unstable (oversteer characteristics) at velocities greater than 400 km/h.

The reason for this was investigated, and it was found that the M_{aero_z} coefficient CYM/ β (yawing moment coefficient (CYM) per unit slip angle (β)) was a large value, indicating that a moment of excessive turning force is produced on the vehicle (Fig. 9).

In addition, investigation of the lift coefficients (CLf, CLr) acting on the front and rear wheels shown in Fig. 10 revealed that the downforce on the front wheels is larger than that on the rear wheels, so the cornering force of the front wheels is stronger than that of the rear wheels and the stability factor A_{aero} drops as the velocity increases.

Therefore, measures focused on CYM/ β , CLf and CLr so that $A_{aero} > 0$, even at the target speed.

A vertical wing was attached to the rear of the body to reduce CYM/ β . In addition, horizontal wings were attached to the vertical wing and measures were taken to increase the downforce on the rear wheels, in order to reduce CLf and increase CLr while maintaining a negative CL value. Figure 11 shows the vertical and horizontal wing shapes.

In addition, the nose cone shape and the shape around the tires and other areas were modified to enhance the balance between CD, CLf and CLr, and the body shape of the race car was decided. Figure 12 shows the body shape and section pressure distribution of the race car model.

Figure 8 shows the A_{aero} , Fig. 9 shows the CYM/ β , and Fig. 10 shows the CLf and CLr of the race car model. The results in Fig. 8 confirmed that the race car model has an A_{aero} greater than zero even at velocities of 450 km/h or more.

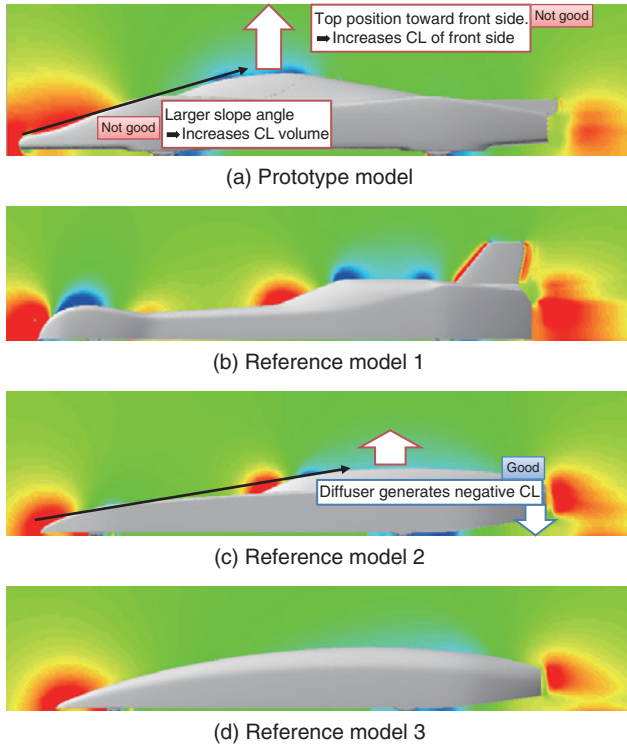


Fig. 5 Comparison of section pressure distribution of 4 models

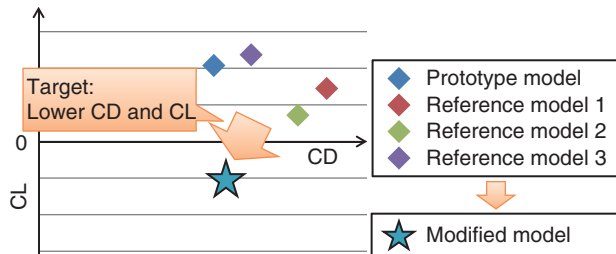


Fig. 6 CD and CL of 5 models

5.2. Confirmation of Flipping Suppression

The wheel load variation was confirmed over a pitching angle range from 0 deg to 5 deg with the rear wheels as the fulcrum for when vehicle pitching occurs at the target speed of 450 km/h.

Figure 13 shows the calculation results for the race car model. Both the front wheel load variation $\Delta W_{tf_}\alpha$ and rear wheel load variation $\Delta W_{tr_}\alpha$ are constantly positive values at each pitching angle, which confirmed that this body

shape suppresses flipping.

The vertical and horizontal wings are drag factors, but were added to the race car model to enhance the CYM, CLf and CLr characteristics compared to the modified model. The resulting CDA was 0.089, which met the target, so the race car cowl was manufactured based on the body shape of the race car model shown in Fig. 12.

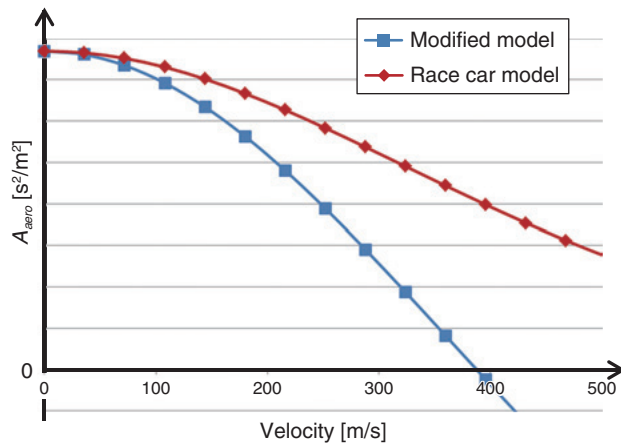


Fig. 8 Comparison of stability factor of modified model and race car model

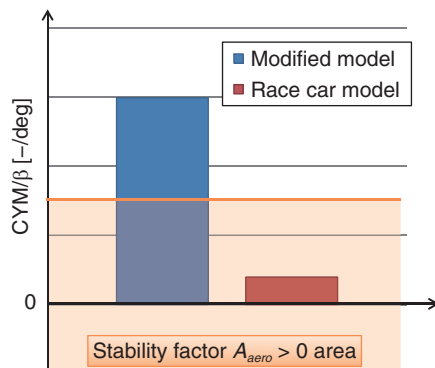


Fig. 9 Comparison of CYM/β of modified model and race car model

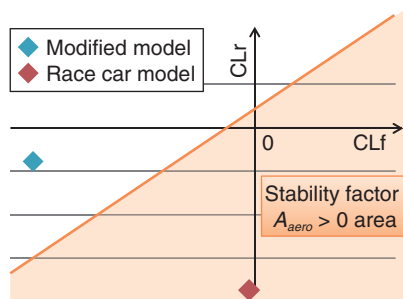


Fig. 10 Comparison of CLf and CLr of modified model and race car model

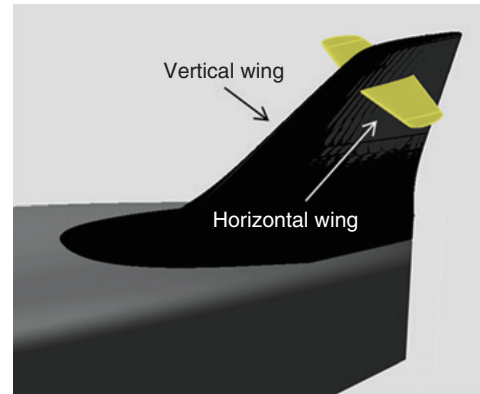


Fig. 11 Attached vertical and horizontal wing



Fig. 12 Shape and section pressure distribution of race car model

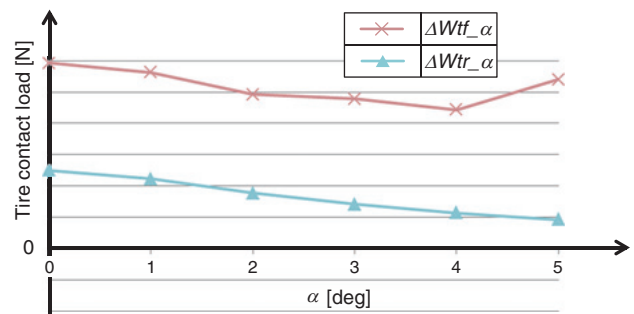


Fig. 13 Relationship between pitching angle and wheel load variation of race car model at 450 km/h

6. Body Shape Design Change

Test runs were conducted by the driver on a test course in Japan before transporting the race car to the Bonneville race site, and confirmed that there were no issues with vehicle stability, maneuverability, visibility or other factors that might hinder driving.

The team then participated in Mike Cook's Bonneville

Test & Tune, held during the two weeks prior to Speed Week, and conducted test runs on the race course. The Bonneville Salt Flats are an environmental conservation district, so lines were not drawn for the Speed Week race course and the only landmarks were traffic pylons placed at 1/4-mile intervals on the white, salt course surface. Furthermore, the vibration felt when driving reduced pylon visibility and revealed that course deviation was an issue. To address this issue, the body shape design was changed to provide the driver sufficient visibility to recognize the pylons as well as secure the vehicle aerodynamic performance and stability needed to achieve the target speed.

Figure 14 is the revised body shape and the fluid simulation results of the section pressure distribution. Figure 15 presents the CD and CL calculation results, Fig. 16 displays the CLf and CLr, Fig. 17 shows the change in A_{aero} due to vehicle velocity, and Fig. 18 shows the wheel load variation.

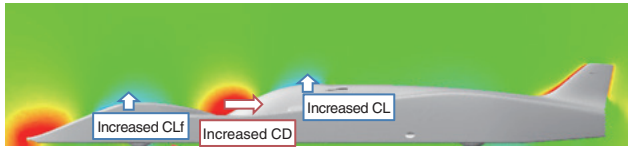


Fig. 14 Shape and section pressure distribution of race car revision model

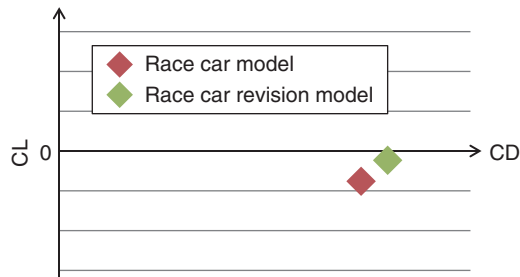


Fig. 15 Comparison of CD and CL of race car model and race car revision model

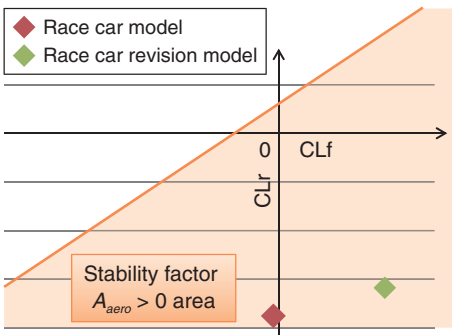


Fig. 16 Comparison of CLf and CLr of race car model and race car revision model

The shape change was confirmed to increase CD and bring CL close to zero, as shown in Fig. 15.

The reasons were because the newly attached windshield had a larger angle of inclination, which increased the drag, and cutting down the area around the front wheels to secure forward visibility increased the lift.

In addition, since the lift around the front wheels increased, CLf became a positive value as shown in Fig. 16. However, this was confirmed to make A_{aero} more stable at higher velocities, as shown in Fig. 17.

The shape change also altered the pitching angle, which increased the wheel load variation as shown in Fig. 18, but it was confirmed that the target requirement was met.

The race car revision model provided sufficient visibility and met vehicle stability requirements, but the CDA was 0.097, which did not achieve the target.

A check process using fluid simulation had been developed, so that shape design changes could be made, and vehicle stability was checked in a short period of just three days.

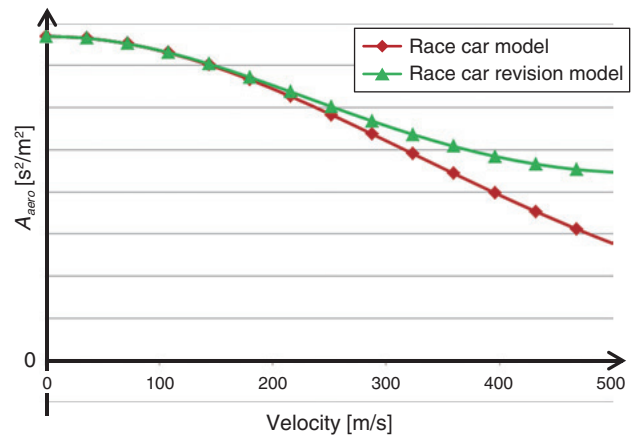


Fig. 17 Comparison of stability factor of race car model and race car revision model

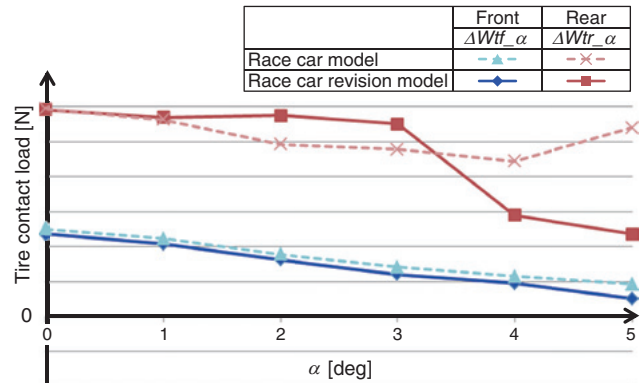


Fig. 18 Relationship between pitching angle and wheel load variation of race car model and race car revision model at 450 km/h

Table 4 Mike Cook's Bonneville Shootout (FIA recognized) participation category

Category A	Race car
Group 1	Otto cycle engine with supercharger
Class 4	Engine displacement 500-750 cm ³
Start	Flying start

Table 5 FIA Land Speed Record result

Vehicle	Honda S-Dream Streamliner
Constructor	Team Honda R&D
Driver	Hikaru Miyagi
1 mile record	261.875 mile/h (421.446 km/h)
1 km record	261.966 mile/h (421.595 km/h)

7. Race Participation Results

A new record in the target participation category was not achieved during Bonneville Speed Week, however, the team was invited to Mike Cook's Bonneville Shootout (FIA World Land Speed Records) held in September, and participated in the Category A, Group 1, Class 4 race. Table 4 shows the participation category⁽⁴⁾.

As a result, a speed of 421 km/h was achieved⁽⁵⁾, which is the top speed record in the participation category (Table 5).

8. Conclusion

The following aerodynamics development was performed for a Bonneville race car to achieve a set target speed of 450 km/h.

- (1) Aerodynamic performance was compared and investigated with the goal of achieving the targeted speed, and these results were used to design a body shape with a body drag coefficient * frontal projected area (CDA) and a lift coefficient (CL) that were at the targeted values, or less.
- (2) Vertical and horizontal wings were attached to the vehicle, which enabled to suppress spin and flipping while securing high-speed driving stability.
- (3) A developed process allowed the body shape design changes needed to secure visibility while taking into account aerodynamics and to confirm the vehicle stability in a short time.
- (4) The target speed was not achieved during Bonneville Speed Week, but the team was invited to Mike Cook's Bonneville Shootout held afterwards, setting an official FIA World Speed Record of 421 km/h in the participation class.

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Intelligent System Using Beacon Model for Autonomous Wheelchair

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ABSTRACT

The system proposed is an intelligent system for autonomous wheelchairs using Bluetooth low energy beacons. A beacon model for estimating wheelchair position is generated by applying machine learning to received signal strength indicators from the Bluetooth low energy beacons. This beacon model reduces response lag for autonomous locomotion control, resulting in smooth driving and improving the destination arrival rate.

1. Introduction

In recent years, there is much talk about autonomous driving technology. With autonomous driving, vehicles will be capable of driving automatically without any human driving operation. The goals of autonomous driving are to help in resolving our social issues: reducing traffic accidents, mitigating traffic congestion, assisting in mobility for the elderly, and more. The key technology and a road map⁽¹⁾ for autonomous driving are given in Fig. 1. Autonomous driving can be categorized into 4 levels. Levels 1 and 2 center around advanced driver assistance systems (ADAS), level 3 is conditional autonomous driving, and level 4 is fully autonomous driving. Recently, in order to achieve autonomous locomotion equivalent to levels 3 and 4 autonomous driving, model predictive control (MPC) has been devised using machine learning^{(2), (3)}.

In terms of one social issue, elderly mobility assistance, elderly wheelchair usage is expected to increase in the future as the world accelerates toward a super-aged society. However, the elderly's action range is limited as they sometimes have trouble operating their wheelchairs as they wish. There are also concerns that those around the elderly will be burdened by having to assist in wheelchair locomotion. Thus, there is demand for autonomous wheelchairs applying autonomous driving technology.

The general approach in autonomous driving is to detect white lines or other partition with a camera and drive tracing that line. With wheelchairs, however, the traveled hallway or sidewalk will often have multiple

obstacles, making it difficult to draw lines. Also, traveling toward a destination will require wheelchair position to be estimated. Since GPS positioning cannot be used indoors, alternative means should be required. One such alternative is position estimation technology using received signal strength indicators (RSSI) from Bluetooth low energy (BLE) beacons⁽⁴⁾. BLE beacons are relatively low cost and have a good battery life. However, depending on where they are installed, BLE beacons are affected by electromagnetic interference, making precision the issue to address for use in autonomous locomotion control.

Thus, for the beacon model proposed in this research, the RSSIs from the BLE beacons are categorized with machine learning to generate a map of positional relationships. As a result, wheelchair position can be reverse-estimated in environments with electromagnetic interference. In parallel with cameras to detect obstacles, this proposed system is capable of bringing into play autonomous wheelchair locomotion. Proposals to date have combined a beacon model for estimating position with cameras for detecting wall corners and other obstacles for a smooth cornering control method with low acceleration and deceleration⁽⁵⁾. Given how using the beacon model allows for smooth autonomous wheelchair locomotion with low acceleration and deceleration change, lowered battery power consumption was also achieved⁽⁶⁾.

This paper will discuss the characteristics of the beacon model generated through machine learning and the travel stability when using this beacon model for autonomous wheelchair locomotion.

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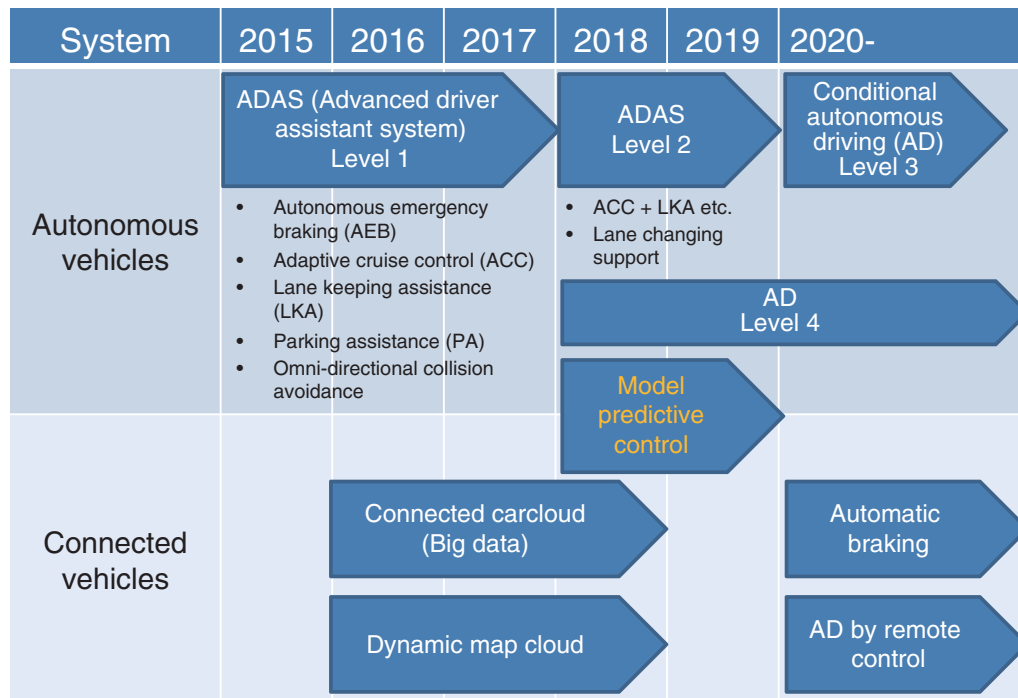


Fig. 1 Road map for autonomous driving

2. Development Aims

An example of RSSI is given in Fig. 2 which has shown where the wheelchair is located when it travels near the two BLE beacons. In the figure, the horizontal axis is for time, and the vertical axis is for RSSI. Conventionally, BLE beacons would be employed for position estimation by setting a RSSI threshold as given in Fig. 2(a) and judging that the wheelchair was approaching a nearby BLE beacon when the RSSI measured by the wheelchair in motion exceeded the threshold (a process called “checking in”). Depending on the environment, however, electromagnetic interference prevents the measured RSSI, makes the checking in between the wheelchair and the beacon inaccurate. This is illustrated in Fig. 2(b). Therefore, in our study, the beacon model was generated by pre-collecting the measured RSSIs for the travel environment on a tablet

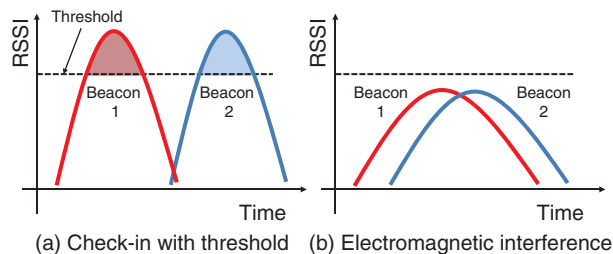


Fig. 2 Electromagnetic interference of two BLE beacons

device and then categorizing the RSSIs by training machine learning.

An overhead map of the indoor test course is shown in Fig. 3. In the map, the wheelchair test course is given by arrows, and the BLE beacon positions are given by the red diamonds. The BLE beacons were positioned around corners, near the elevator, and along the predetermined course.

The goal this time was to combine beacon model position estimation and smooth cornering to increase the stability rate of autonomous wheelchair locomotion. Here, the travel stability of an autonomous wheelchair is defined

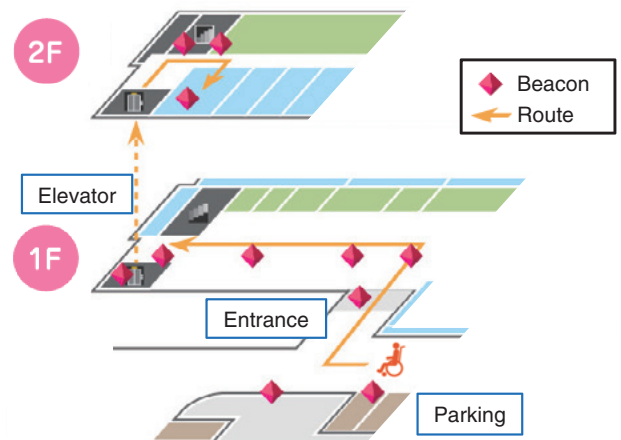


Fig. 3 Indoor map for preliminary experiment

as ability to reach the destination as set, and possible moves to reach the predetermined destination.

3. System Construction

3.1. Overview of Autonomous Locomotion Control

The wheelchair and BLE beacons used are shown in Fig. 4. The wheelchair is equipped with a tablet device for collecting RSSI information from the BLE beacons and a stereo camera for detecting obstacles. The BLE beacons are manufactured by Hosiden Corporation and measure 5 cm in diameter and weigh 28 g. The beacons use coin-shaped CR2450 batteries and can operate for approximately 1 year without battery replacement.

The control portion of the proposed autonomous wheelchair locomotion is given in Fig. 5. Control is performed by combining position estimation with the beacon model and obstacle detection using stereoscopic vision.

For example, if the beacon model estimates the wheelchair position as being in a corner area, the stereo camera installed on the front of the wheelchair detects the wall and obstacles to the left and right, then finely adjust the amount of steering to make the wheelchair turn the corner. As error for traveling direction and distance are cumulative, the positional relationships between the BLE beacons and wheelchair are calculated and corrected with image processing.

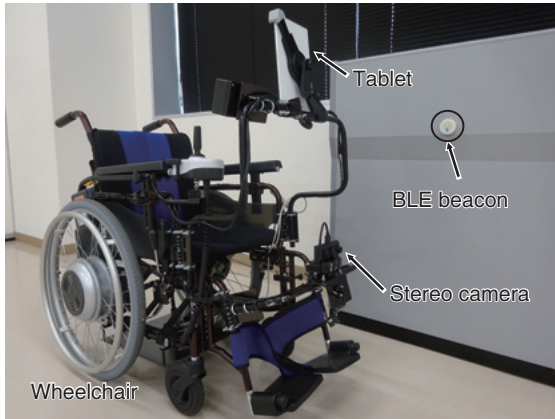


Fig. 4 Motorized wheelchair and BLE beacon

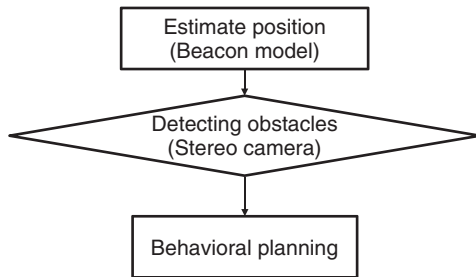


Fig. 5 Block diagram of autonomous wheelchair

These autonomous locomotion operations remain ongoing while travelling, and wheelchair operation is stopped when the position is estimated to be at the destination.

3.2. Beacon Model

The flow for autonomous locomotion control as given above requires estimation of the wheelchair position in order to form an action plan. This position can be estimated with the objective function $f(X; \theta)$ shown in Fig. 6. Here, as f is an unknown objective function, it is approximated by density function $P(X|L)$ as represented by Eqs. (1) and (2). μ_{jL} is the mean value, σ_{jL} is the covariance value, L is the position label, and α is the learning coefficient. Parameter θ is modeled after the normal distribution function (hereinafter the “beacon model”), derived by the algorithm⁽⁷⁾ for expectation maximization (EM), representing statistical machine learning.

$$P(X|L) = \sum_{j=1}^K \frac{\hat{\alpha}_{jL}}{(2\pi)^{1/2} \sqrt{|\hat{\sigma}_{jL}|}} \exp \left[-\frac{1}{2} (X - \hat{\mu}_{jL})^T \hat{\Sigma}_{jL}^{-1} (X - \hat{\mu}_{jL}) \right] \quad (1)$$

Where learning coefficient α is taken as satisfying the following constraints:

$$\hat{\alpha}_{1L} + \hat{\alpha}_{2L} = 1.0 \quad (2)$$

An image depicting the RSSIs and labels for BLE beacons in a corner area is given in Fig. 7. First, BLE

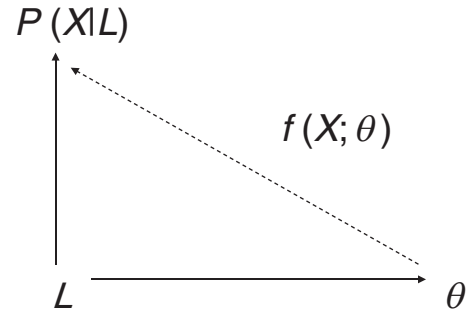


Fig. 6 Probability density function from label X

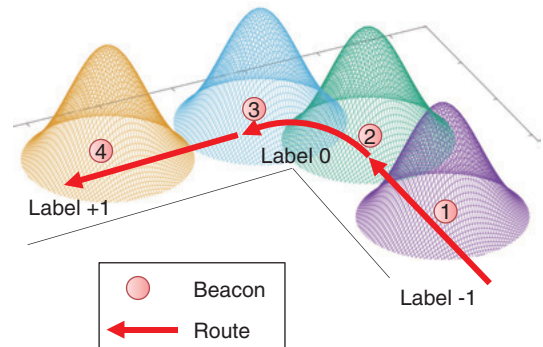


Fig. 7 Wheelchair position estimation with beacon models

beacons are positioned on the travel route, then RSSIs are pre-collected on the wheelchair's onboard tablet during travel for use as machine learning data. Next, the RSSI is artificially divided and labeled for 3 positions: before corner (Label -1), mid-corner (Label 0), and after corner (Label +1). These positions are derived by recording the cornering start and finish positions and times during travel and synchronizing them with the time axis for the collected RSSI. Based on these labeled RSSIs, the EM algorithm is applied to generate the beacon model.

The flow for the EM algorithm applied to the generation of beacon model is shown in Fig. 8. In statistics, the algorithm is a method for estimating the maximum likelihood of the parameters in a probability model and is used in cases where the probability model depends upon unobservable latent variables. The algorithm consists of two calculation steps: an expectation (E) step, represented by Eqs. (3) and (4), and a maximization (M) step, trained by Eqs. (5), (6), and (7). In the E step, the estimated likelihood of the probability model is calculated based on a distribution of the latent variables as currently estimated. Meanwhile, in the M step, the parameters needed to maximize the estimated likelihood as calculated in the E step are calculated. With the E step and M step recurring in alternation, if the probability model is taken as the mixed Gaussian function given by Eq. (1), the mean values μ_{jL} and covariance values σ_{jL} comprising the Gaussian functions can be estimated.

$$h_{ij} \equiv E [z_{ij} | x^i, \theta] \quad (3)$$

$$h_{ij} = \frac{a_j(t) / ((2\pi)^{n/2} \sqrt{|\Sigma_j(t)|}) \exp [-(1/2)(x^i - \mu_j(t))^T \Sigma_j(t)^{-1} (x^i - \mu_j(t))]}{\sum_{k=1}^G a_k(t) / ((2\pi)^{n/2} \sqrt{|\Sigma_k(t)|}) \exp [-(1/2)(x^i - \mu_k(t))^T \Sigma_k(t)^{-1} (x^i - \mu_k(t))]} \quad (4)$$

$$a_j(t+1) = \frac{1}{N} \sum_{i=1}^N h_{ij}(t) \quad (5)$$

$$\mu_j(t+1) = \frac{\sum_{i=1}^N h_{ij}(t) x^i}{\sum_{i=1}^N h_{ij}(t)} \quad (6)$$

$$\Sigma_j(t+1) = \frac{\sum_{i=1}^N h_{ij}(t) (x^i - \mu_j(t+1))(x^i - \mu_j(t+1))^T}{\sum_{i=1}^N h_{ij}(t)} \quad (7)$$

Taking the machine learned RSSI for BLE beacon 3, as measured in the Label 0 segment in Fig. 7, as an example, the relationship between the log likelihood and step number is given in Fig. 9. Log likelihood is a performance function for showing the convergence of learning. Here, looking to derive

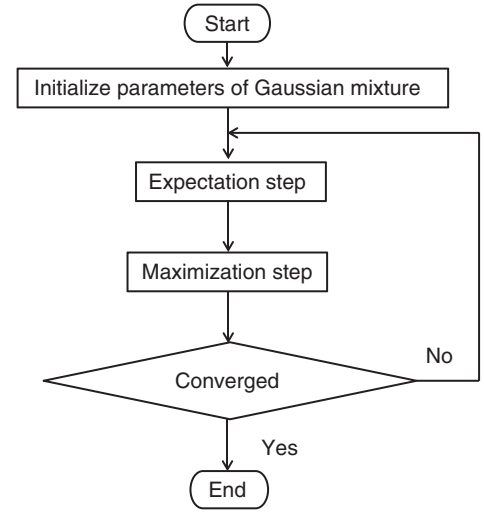


Fig. 8 Block diagram of EM-algorithm

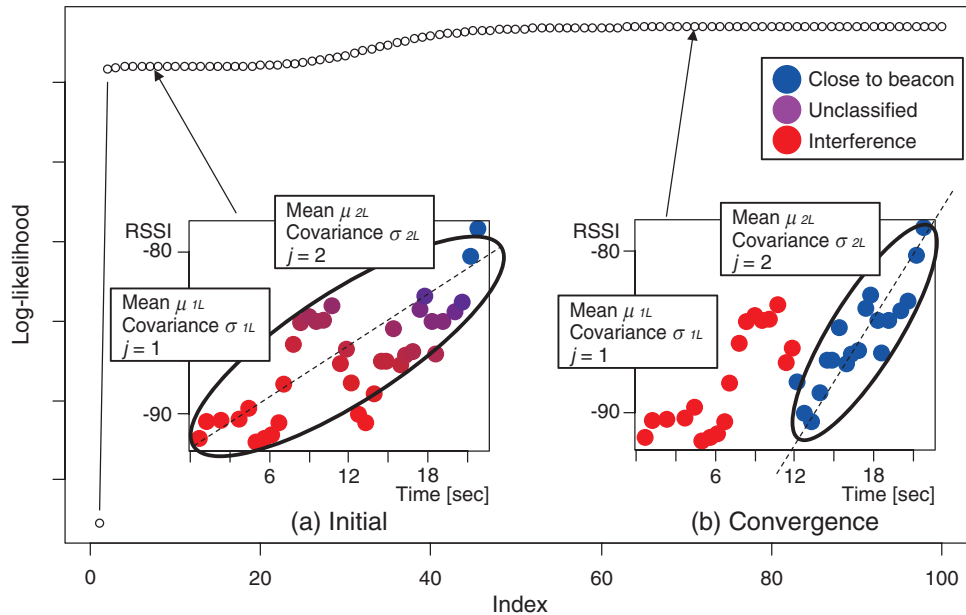


Fig. 9 Beacon models learned by machine learning and log-likelihood

the linear relationship between travel time and the RSSIs with machine learning, the two Gaussian functions contained in the ellipsoids of Figs. 9(a) and (b) were identified based on the Bayesian Information Criterion (BIC).

In Figs. 9(a) and (b), the blue RSSI dots represent the travel time range where the wheelchair is approaching the closest beacon. In the beginning of the learning process, RSSI data composition is not yet clearly categorized, as depicted in Fig. 9(a). Later, as shown in Fig. 9(b), the learning converges to group RSSI data composition into two categories. The RSSIs will interfere with each other due to multipath effects and other factors. Therefore, by using machine learning to selectively extract the RSSI corresponding to the travel time range for locomotion to the closest beacon, electromagnetic interference are expected to be greatly reduced compared to no separation, and model accuracy to be raised. As the relationship between the mutually interfering RSSIs and labels can be generated with the beacon model, this resolves the response lag in estimating positions with electromagnetic interference experienced by Kim⁽⁸⁾ et al.

4. Evaluation Results

A wheelchair was autonomously driven along the route from the overhead map in Fig. 3 from the parking lot to the destination on the second floor, estimating position with the beacon model. Next, the wheelchair was autonomously driven on the same route, this time estimating position using the threshold, to compare the rate at which the wheelchair reached its destination ($N=10$). The destination arrival rates were 90% with the beacon model and 10% with threshold judgments, showing the beacon model rate to be higher.

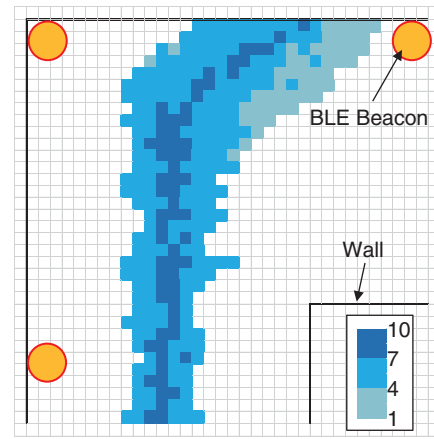
A frequency distribution chart for the travel path trajectories around corners is shown in Fig. 10. As seen in Fig. 10(a), the main factors in failure when traveling by threshold judgment were: 1) collision with the wall due to insufficient cornering control from delayed check-in judgment, and 2) collision with the wall due to inability to judge check-in, resulting in no cornering control. Meanwhile, as seen in Fig. 10(b), when traveling with the beacon model, cornering control was successful and had reduced control response lag. Further, the widened frequency distribution shows the deviation from the target travel path. Given that the frequency distribution for Fig. 10(b) is narrower than that for Fig. 10(a), using the beacon model was found to deviate less from the target travel path.

Next, the rates of correct check-in judgments by the wheelchair were compared for beacon model judgments and threshold judgments. Given that the BLE beacons used in this research are normally used to estimate position within a range of 3 m, the correct check-in rate was calculated for when the wheelchair was stationary in positions 3 m away from the BLE beacons. Rates of correct check-in judgments in the corner areas ($N=30$) were roughly the same for beacon model judgments and threshold judgments, averaging 93%

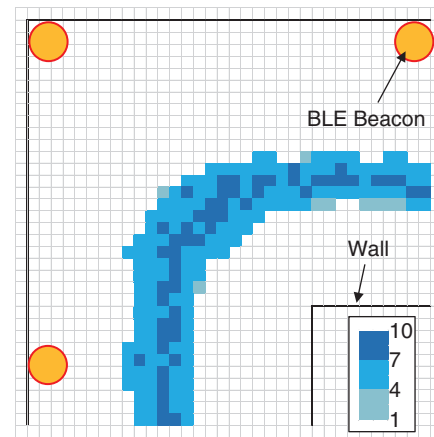
and 92%, respectively. From this, the generated beacon model was found to be estimating positions correctly.

Furthermore, the times taken until check-in judgment when traversing a certain corner section were compared between beacon model judgment and threshold judgment. Using 1 to represent the time required for threshold judgment, the mean values for the corner section ($N=30$) were 0.83 for the beacon model. Thus, check-in judgment times were shorter using the beacon model than when using the threshold. With a wheelchair traveling at 2 km/h, this is equivalent to cornering control starting approximately 800 mm earlier.

As the beacon model is generated from RSSIs for past trips using machine learning, by applying the beacon model to estimate wheelchair position, the wheelchair position is known in shorter time than if judged with a threshold. Therefore, this will presumably allow earlier detection for starting cornering control in corner sections and, as a result, increase destination arrival rates and lead to smooth driving with less deviation.



(a) Trajectory with threshold



(b) Trajectory with beacon model

Fig. 10 Comparison between trajectory with beacon threshold and with beacon model

5. Conclusion

This paper described an intelligent system for autonomous locomotion control of wheelchairs.

The findings are as follows:

- (1) By using machine learning to label BLE beacons used to measure signal strength and estimate position, wheelchair position can still be determined in the presence of electromagnetic interference. Because the beacon model is generated from historic data from past trips, it can judge check-in in shorter time than with threshold judgments, allowing it to cut response lag in wheelchair control.
- (2) The destination arrival rate is 10% when applying a threshold and 90% when applying the beacon model. The proposed approach is confirmed to have a higher destination arrival rate, driving the wheelchair with less deviation and higher travel stability.

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Study of Optimal Operation Control for Robotic Lawnmower

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ABSTRACT

It is necessary that robotic lawnmowers, the use of which has recently become more widespread, should be able to cover entire lawn areas. As the shapes and areas of lawns are highly diverse, in complex yards there will be areas challenging for robotic lawnmowers, and as such, the completion of work over the entire area may take some time. The research discussed in this paper sought to make it possible to complete work over the entire lawn area more quickly by modifying operation control.

As conventional operation control has been set to enable the mower to complete work in any possible yard, it is very likely that specific settings exist for specific types of yards which allow the work to be completed more quickly in that yard. The research therefore developed a method by which the robotic lawnmower automatically discriminates the characteristics of the lawn area and switches to the optimal operation control setting. Simulations and actual tests verified that the application of the control developed in this research reduces robotic lawnmower work time.

1. Introduction

From when Honda brought a cultivator to the market in 1959, the company has marketed a range of work machines including lawnmowers, brush cutters, mechanical trolleys, and snow blowers. These products have contributed to reducing the burden of heavy work.

Today's ongoing aging of populations around the world increases the need to complete jobs simply and with less labor. As a result, many companies have commenced selling automated lawnmowers. Honda itself began marketing its Miimo robotic lawnmowers in 2012.

Miimo lawnmowers are made up of a mower and a docking station, as shown in Fig. 1. The user defines the

operating area by surrounding the yard with a boundary wire. The mower is able to distinguish between the inside and the outside of the boundary wire, and then propels itself around, cutting the grass within that operating area⁽¹⁾.

The mower operates according to a schedule set by the user. If its battery power runs low during operation, it automatically returns to its docking station to recharge. By repeating these operations, it maintains the grass at a consistent length.

2. Purpose and Targets

It is necessary for the user to set the mower's operating schedule in order to maintain the grass at a consistent length. If the mowing time is set to a value shorter than the operating time necessary to maintaining the length of the grass, then it is not possible to ensure a tidy lawn. The necessary mower operating time is longer for a large yard or a complex yard. In a complex yard, some areas will be challenging for the mower, and the entire operation may take a longer time. The reason is because in these cases, the mower goes back over areas that it has already cut.

If the mower did not re-visit already cut areas, it would be possible to increase the area within which it could operate, and reduce operating time. This would allow users to maintain large yards and increase the amount of time they have available to enjoy their yards.

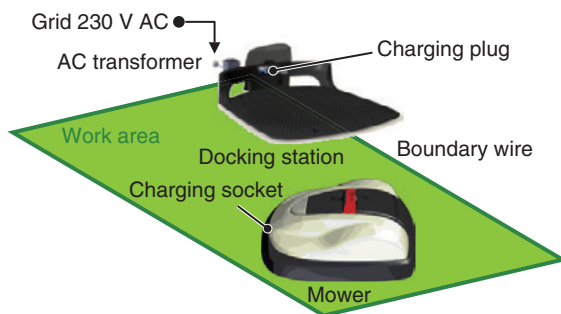


Fig. 1 Miimo configuration

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The purpose of the research discussed in this paper was to cover the entire lawn area quicker by modifying operation controls. The target was to increase the mower's operating area per unit time by 20% against the existing operation.

3. Operation Control

3.1. Conventional Operation Control

The mower operates within its operating area by repeatedly working in straight lines and turning. As shown in Fig. 2, when the mower reaches the boundary of the operating area, it turns, and runs straight ahead again.

The mower's turning angle is random, in order to help ensure that the mower does not work over the same area repeatedly. As Fig. 3 shows, when the mower arrives at the boundary wire at the same angle, it will then proceed to run straight ahead in a different direction.

In addition, a limit range is set for this turning angle. This control range is set to enable the mower to cut the entirety of a complex yard, and helps in completing work over the entire lawn area for a wide variety of yards.

3.2. Optimal Operation Control

Conventional operation control fixes the mower's turning angles within a limit range. Given this, it was assumed that limit ranges would exist for individual yards in which it would be possible to complete the entire lawn area more quickly.

Seeking to develop a method of completing mowing operations in a shorter time by providing the mower with multiple limit ranges for turning angles, and then allowing it to select the limit range that best suited the yard, the research approach encompassed the following four items:

- (1) Preparation of diverse yard samples
- (2) Classification of yard types
- (3) Determination of limit ranges for turning angles suitable in each yard type
- (4) Selection of limit ranges for turning angles best suited to the yard in which the mower is operating

3.2.1. Preparation of diverse yard samples

A market survey was conducted in order to determine what types of yards exist. Figure 4 shows a selection of the yards indicated by the survey. The yards feature both simple and complex shapes, and impediments such as trees, bricked off areas for home vegetable gardens, and trampolines positioned here and there.

As this indicates, the yards are composed of various elements, of which an unlimited number of combinations exist. In order to allow a study with a large number of yards, 200,000 yards were automatically generated from the several tens of yards indicated by the survey. For the present research, the maximum size of the yards was limited to 20 m × 20 m.

3.2.2. Classification of yard types

Histograms based on uninterrupted driving distance were employed in order to classify yards. As said before, the mower operates by repeatedly traveling in a straight line and turning. In a yard with a simple shape of the type shown in Fig. 5(a), for the majority of times, the uninterrupted distance is long; in a yard with a complex shape of the type shown in Fig. 5(b), for the majority of times, the uninterrupted distance is short. The histograms were determined by studying each uninterrupted distance within

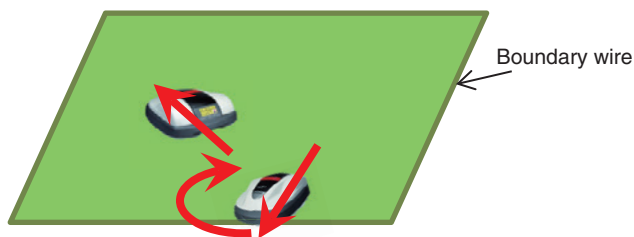


Fig. 2 Running pattern

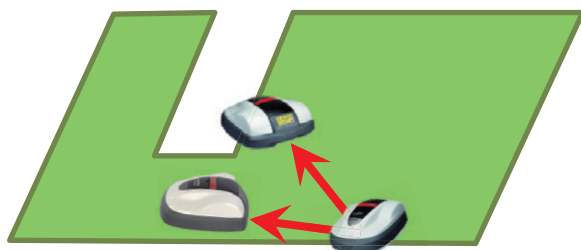


Fig. 3 Randomness of turn angle

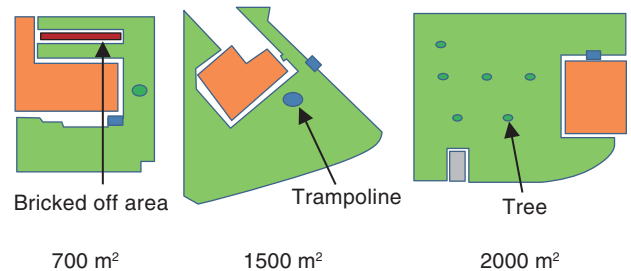


Fig. 4 Actual yard shape

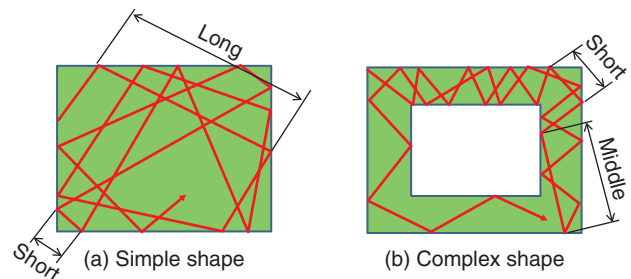


Fig. 5 Uninterrupted distance

the mower's mowing pattern of traveling straight ahead and turning, and then counting each distance.

Figure 6 shows histograms for the yard shapes shown in Fig. 4. For a simple yard, the number of times that the uninterrupted distance is short is small.

Using the produced histograms, the large number of yard samples were classified using the clustering method K-means++⁽²⁾. Figure 7 shows the results of classification.

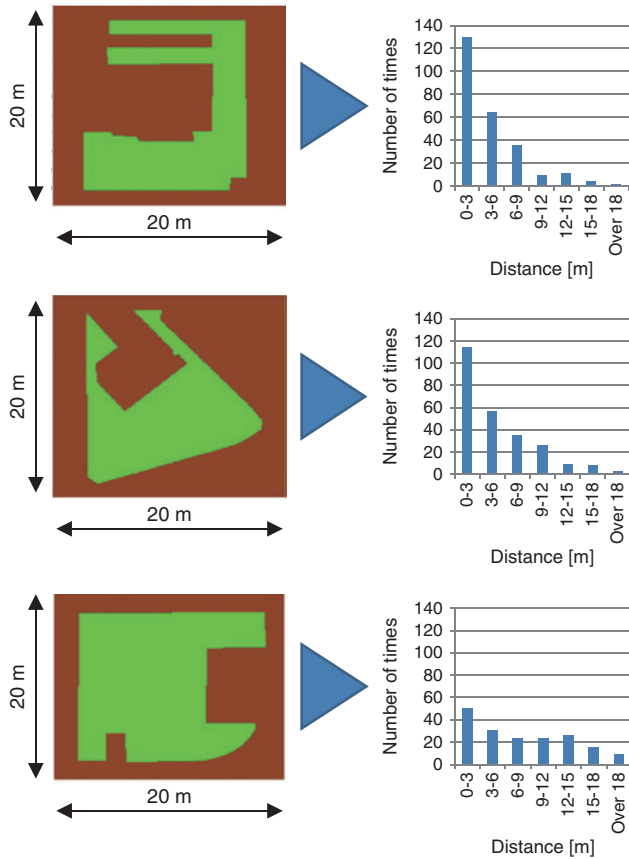


Fig. 6 Histogram for each yard shape

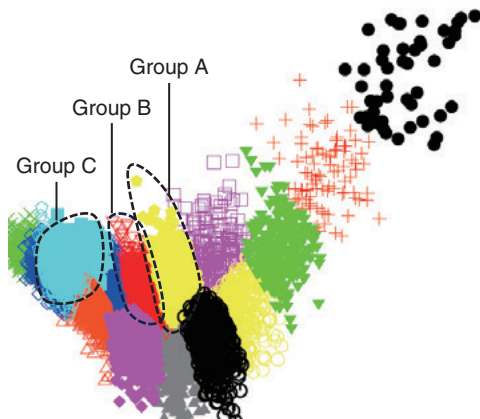


Fig. 7 Clustering

The number of groups was determined by repeated clustering, while changing the number of groups helped ensure that the histograms for each group did not, following classification, resemble each other. Figure 8 shows samples and histograms extracted from each group. As can be seen, yards with histograms that resemble each other have been grouped together.

3.2.3. Determination of limit ranges for the turning angles of each yard type

The optimum limit range for turning angles was determined for each group.

A Honda in-house parameter optimization tool was employed to determine the optimum limit ranges. The optimization method for conventional approaches is to search in the vicinity of an initial value when conducting

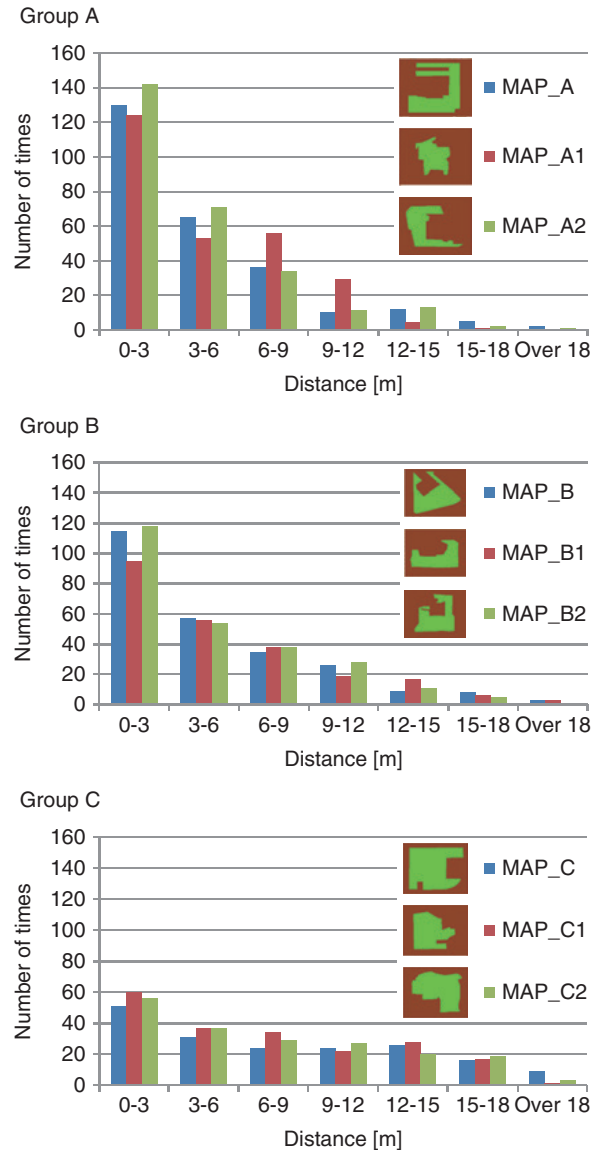


Fig. 8 Results of clustering

the optimization; by contrast, Honda's in-house tool is able to search for optimal settings over a wide range.

During the optimization, multiple yards of differing shapes were isolated from within each group, and the optimal limit range for each group was determined from the respective results. Optimization was conducted for each group, and the respective limit ranges were determined.

3.2.4. Selection of limit ranges for turning angles suited to yards

The mower compares the histogram for the yard in which it is operating against the histograms for each group, then judges which group the yard belongs to. It determines the histogram for its yard by measuring uninterrupted distances during operation. Using the determined histogram and the histograms for each group, the mower then calculates the differences in the number of times each uninterrupted distance appears, finally adding up their respective squares. The group for which this figure is the lowest is the group that is closest to the yard in which the mower is operating.

The histogram for the yard shown in Fig. 9 is closest to the histogram for Group C in Fig. 8.

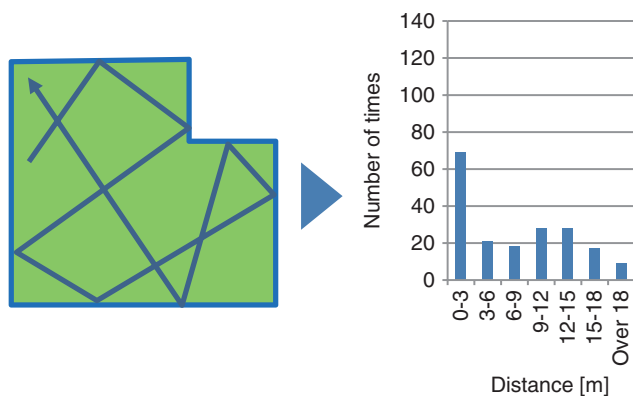


Fig. 9 Area shape and histogram

4. Verification Results

4.1. Verification by Simulation

A representative yard was selected from each group, and the effectiveness of the method was verified in simulations. The time until the entire yard was completed and the work area per unit time were both studied. Figure 10 compares results for the developed method and conventional operation control. "Yard ID" is a number applied to yards sequentially, beginning from the group with the most complex shapes.

Compared to conventional operation control, the new method increases work area per unit time for all of the yard shapes by an average of 20%.

4.2. Verification using Actual Mowers

The developed control method was tested using the yard shapes shown in Figs. 11, 12, and 13. The yards were all 200 m² in area, but displayed differing features. As with the

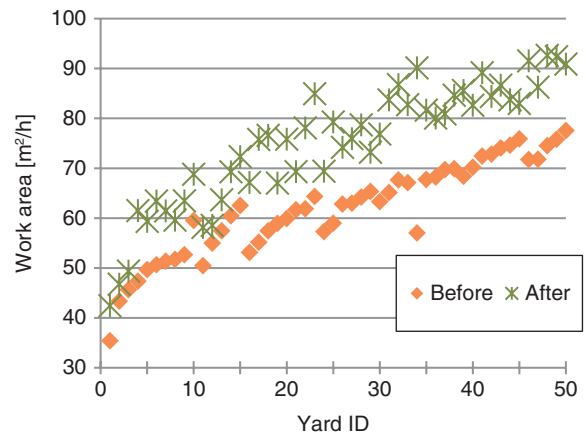


Fig. 10 Simulation analysis results

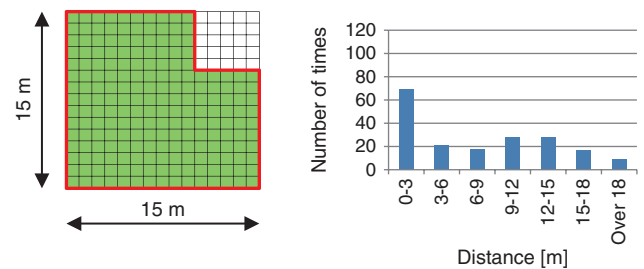


Fig. 11 Test result for yard shape 1

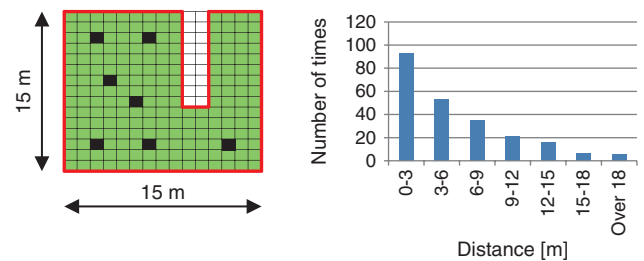


Fig. 12 Test result for yard shape 2

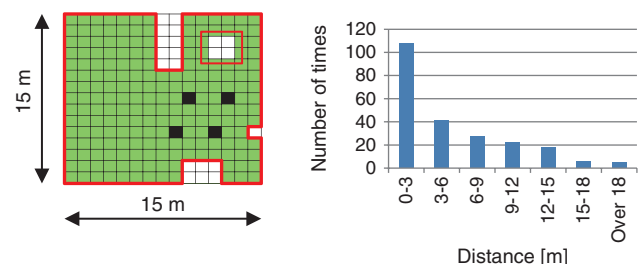


Fig. 13 Test result for yard shape 3

Table 1 Work area per hour for conventional control and optimal control

Yard shape	Before [m ² /h]	After [m ² /h]	Increased value [%]
Yard shape 1	98.9	122.6	24%
Yard shape 2	84.3	108.6	29%
Yard shape 3	91.8	117.7	28%

simulations, in these tests the time taken for the completion an entire yard was measured, and work area per unit time was the subject of evaluation. Table 1 compares results for the developed method and conventional operation control.

The use of the developed control method increased work area per unit time by an average of 27%.

5. Conclusion

Research studying optimal operation controls for a robotic lawnmower produced the following results:

- (1) Using histograms and clustering techniques, it was possible to classify a variety of yards in terms of shape complexity.
- (2) The turning angles employed in robotic lawnmower operation control were optimized for each classified group.
- (3) The robotic lawnmower was able to judge the complexity of a yard shape, then select the optimal turning angle during operation.
- (4) The work area per unit time of the robotic lawnmower was increased by an average of 27%.

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Development of Surface Treatment Composed of Chemical Conversion Treatment and Paint Coating for Black Bolts Used in Motorcycles

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ABSTRACT

This research relates to the development of black surface treatment bolts used for motorcycles. Conventionally, the surface treatments applied for black colored bolts have been, in many cases, the methods using hexavalent chromium. However, hexavalent chromium is designated as a hazardous substance, and its use is restricted. For this reason, the developments of technologies to replace the surface treatment using hexavalent chromium are under way. In the case of using such substitute technologies, the technology for realizing black-colored appearance did not fulfill the requirements, because of the obstacles to realize required appearance and fastening performances. As a result, those bolts were used only for limited applications. In order to cope with this situation, we developed black surface treatment for bolts which can be widely used for motorcycle applications. For the coating composition, a black trivalent chromium conversion coating film and a dip coating layer were formed on a zinc plating coating. The conditions that satisfy the requirements for individual films were also designed.

Moreover, the manufacturing conditions were examined and set as well. As a result, we established a surface treatment method that can satisfy the performance requirements as a black bolt for wider application to motorcycles.

1. Introduction

Bolts are frequently used to fasten mechanical parts of motor vehicles due mainly to the advantages such as the work efficiency, serviceability, and fastening performance. Also, in motorcycles, bolts are often used as parts of exterior parts. In such a case, bolts require adequate corrosion resistance, appearance quality, etc. in addition to the fastening performances. A surface treatment, therefore, is often applied to the bolts for motorcycles. To make the appearance matching with the parts in the proximity, the surface treatment that provides a metallic or black color is applied as an option to achieve an attractive styling design.

Conventionally, in order to impart corrosion resistance and appearance design to the bolt, it is common to combine electroplating and chemical conversion treatment using hexavalent chromium⁽¹⁾. For example, a target appearance

was attainable by overlaying various layers of chemical coating using the hexavalent chromium on the zinc or zinc-plated surface. The hexavalent chromium⁽²⁾, however, is an environmentally hazardous substance and its use is restricted throughout the world^{(3),(4)}. Accordingly, a chemical treatment using chemical compounds containing the hexavalent chromium is becoming virtually unlikely.

The chemical treatment using the trivalent chromium is an alternative for the chemical treatment using the hexavalent chromium^{(5),(6)}. In general, the trivalent chromium chemical conversion film is thinner than the hexavalent chromium chemical conversion film, and challenging to adequately color the surface by the coating itself. Therefore, the colorless chemical coating using the trivalent chromium aimed at providing of the metallic color of the base material was enhanced the quality of appearance. Contrary in the black chemical conversion film using the

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trivalent chromium, the base metal color has to be concealed by the black coating. The black chemical conversion film created by the trivalent chromium, however, is not adequately thick to conceal the base metal color, resulting in an inadequacy of blackness. Hence depending on the use site of the bolt applied to the motorcycle, there is a case that a sufficient black appearance can not be obtained.

On the other hand, as another method of imparting black appearance to bolts, there is a technique called dip coating⁽⁷⁾. Generally in a dip coating, the paint film thickness varies, causing color unevenness. The film thickness is often increased to deal with the said issue. Therefore, since a thick coating film is also applied to the threaded part of the bolt, it is not easy to obtain high thread accuracy.

It is therefore necessary to work out a new method that blackens the bolt without using the hexavalent chromium while obtaining both the appearance quality and the thread precision.

This project started to establish a black surface treatment method by combining a black chemical conversion film and a dip coating.

This paper describes the principle and design procedure of the newly developed surface treatment method and appropriate production conditions to achieve the target coating.

2. Issues in Conventional Method and Aims of Development

2.1. General Methods for Imparting Black Appearance to Bolts

The galvanization (also referred to as zinc plating) is the most commonly-applied surface treatment for bolts. The galvanization is a composite anti-rust treatment method that precipitates a zinc metal film on a material and precipitates a chemical conversion film on its surface. Firstly to create a metallic zinc film, the work piece is immersed in the plating solution containing zinc ions. Then, a certain electric charge is applied to cause metallic zinc to deposit on the surface by the effect of electro-reduction. As the surface easily becomes oxidized and discolored in the atmosphere if only a metallic zinc coating is provided, a chemical conversion film has to be overlaid. In other words, the work piece having a metallic zinc coating is dipped in the solution containing chemical compounds to have a film produced on the surface by chemical reactions to prevent oxidation of metallic zinc surface. To further enhance corrosion resistance, such a zinc alloy plating in that the metallic zinc is substituted by a zinc-nickel alloy or a zinc-iron alloy has been developed. Also in the case of these zinc alloy platings, it is common to apply a chemical conversion treatment film because the surface is easily oxidized. The chemical conversion treatment film permits adjustment of the color by control of chemical compounds in the solution. When black is required, the blackening chemical conversion treatment is applied⁽⁸⁾. Conventionally, hexavalent

Table 1 Blackening surface treatments for bolts

Hazardous material	Surface treatment	Requirement					
		Fastening		Appearance quality			
		Friction control	Thread precision	Appearance	Scratching resistance	Corrosion resistance	Weather resistance
Contained	Black Zn plating using Cr (VI)	3	3	3	3	2	3
	Black Zn alloy plating using Cr (VI)	2	3	3	3	3	3
	Black Cr plating using Cr (VI)	3	2	4	4	4	3
Not contained	Black Zn plating using Cr (III)	3	3	1	1	2	3
	Black Zn alloy plating using Cr (III)	2	3	1	1	3	3
	Dip coating	2	1	3	3	3	2

4 = excellent, 3 = good, 2 = average, 1 = poor

Cr (III): Trivalent chromium, Cr (VI): Hexavalent chromium

chromium was contained in this chemical conversion treatment film. However, at the present time, substitution with a trivalent chromium chemical conversion treatment film not containing hexavalent chromium is proceeding.

While the black chromium plating used to be applied in some cases for blackening, it is currently avoided because the treatment solution contains hexavalent chromium⁽⁹⁾.

Since the said method is a combination of electric plating and chemical conversion treatment, the control of film thickness is relatively easy. Accordingly, it is often used in bolts which are required to have high thread precision and more reliable fastening.

In the meantime, the blackening method by dip coating is also used in some cases. The dip coating is such a method in that the work piece is dipped in the paint, the extra paint is shaken off with a centrifuge or the similar, and the paint is finally baked or dried. As the paint film thickness is not easy to control, it is hard to ensure thread precision. When applying dip coating, it is therefore necessary to take special considerations in the thread shape design or perform additional machining to the bolt after the painting.

Table 1 shows various methods for blackening of bolts. As can be seen from this table, it can be seen that the surface treatment technology which imparts black without using hexavalent chromium can not satisfy the requirements of bolts used for motorcycles.

2.2. Issues in Current Blackening Method

2.2.1. Issues in chemical blackening using trivalent chromium

Figure 1 shows the cross section photographs of the films produced by typical blackening methods, i.e., the hexavalent chromium treatment and the trivalent chromium treatment. For easy comparison of chemically produced

films, the two pictures are of the same magnification rate. A zinc plating layer exists on the base metal surface of bolt, and a thin chemically-produced film is seen on it. While the thickness of film by the hexavalent chromium treatment is approximately 2 μm , it is as thin as 0.2 μm in the one by the trivalent chromium treatment. As the color has to be applied by a thinner film in the case of the trivalent chromium treatment than in the case of the hexavalent chromium treatment, it is challenging to realize uniform blackness.

The reason why the trivalent chromium chemical conversion treatment film can not be formed thick is explained hereafter from the principles of film formation while comparing to the hexavalent chromium chemical conversion treatment film. Figure 2 shows image pictures of chemical film formation in the hexavalent chromium chemical conversion treatment and the trivalent chromium chemical conversion treatment.

Regardless of hexavalent chromium contained or not, the formation of chemical conversion treatment film is triggered by the dissolving of zinc into the solution. As the zinc-plated work piece is immersed in the chemical treatment solution, a dissolving of zinc into the solution starts. In the case of hexavalent chromium, $\text{Cr}(\text{OH})_3$ and $\text{ZnCrO}_4(\text{H}_2\text{O})_x$, which serve as the matrix of coating, are produced as the chemical reactions take place⁽¹⁰⁾. While the $\text{Cr}(\text{OH})_3$ is a solid component, the $\text{ZnCrO}_4(\text{H}_2\text{O})_x$ is a soluble component, maintaining a semi-dissolved conditions in the solution. Accordingly, the chemical solution can come into contact on the zinc surface via the $\text{ZnCrO}_4(\text{H}_2\text{O})_x$, allowing continuation of the chemical reactions. As a result, the film can grow as thick as approximately 2 μm . In the case of trivalent chromium treatment, however, while the $\text{Cr}(\text{OH})_3$ is formed, the $\text{ZnCrO}_4(\text{H}_2\text{O})_n$ is not⁽¹¹⁾. As mentioned earlier, as the $\text{Cr}(\text{OH})_3$ is a solid component, it does not allow permeation of the chemical solution. Accordingly, once the zinc plating surface is covered with the $\text{Cr}(\text{OH})_3$, the chemical treatment solution cannot come in contact on the zinc plated surface, causing discontinuation of dissolving of zinc into the solution. Thus, the chemical reactions

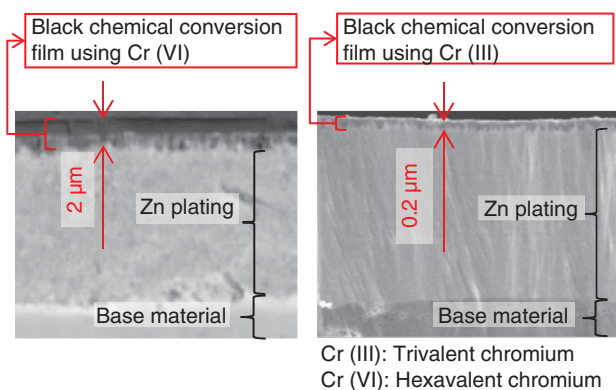


Fig. 1 Chemical conversion film using Cr (VI) and Cr (III)

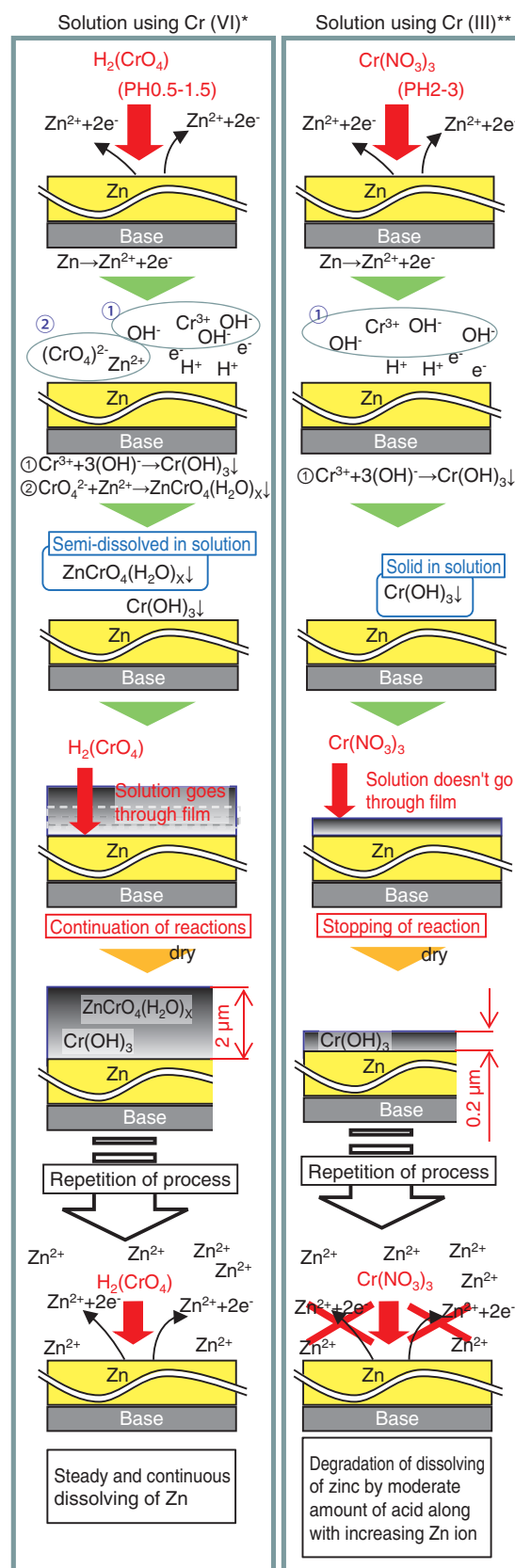


Fig. 2 Models of reaction of chemical conversion film using Cr (VI) or Cr (III)

finish when the chemical conversion film is as thin as approximately $0.2\ \mu\text{m}$.

Also, the chemical treatment solution containing the hexavalent chromium is a strong acid of $\text{PH}0.5 - 1.5$, which allows steady dissolving of zinc into the solution. Meanwhile in the trivalent chromium treatment, the solution is a weak acid of $\text{PH}2 - 3$. As the zinc ion concentration increases in the solution, less zinc is dissolved into the solution, causing unstable chemical reactions for film formation, which is another cause of inconsistent blackness.

For the reasons stated above, in the trivalent chromium chemical conversion treatment solution used for present bolts for motorcycles, the treatment solution is frequently exchanged in order to prevent the reaction from becoming unstable. In order to satisfy the minimum appearance required for motorcycle application, exchange is carried out every time the concentration of Zn ions in the treatment liquid reaches $5\ \text{g/L}$ in the case of the treatment liquid condition with the highest replacement frequency. This hinders productivity and increases management cost.

Moreover, due to the thin film, the insufficient corrosion resistance and the vulnerability to damages from use of tool are also issues. A finish treatment is often applied to the black film produced by the trivalent chromium treatment to enhance corrosion resistance, which is another cause of additional cost.

2.2.2. Issues in black dip coating

The dip coating using a black paint is another option for blackening. Figure 3 shows an example of the procedures.

The dip coating processes can be divided to three sub

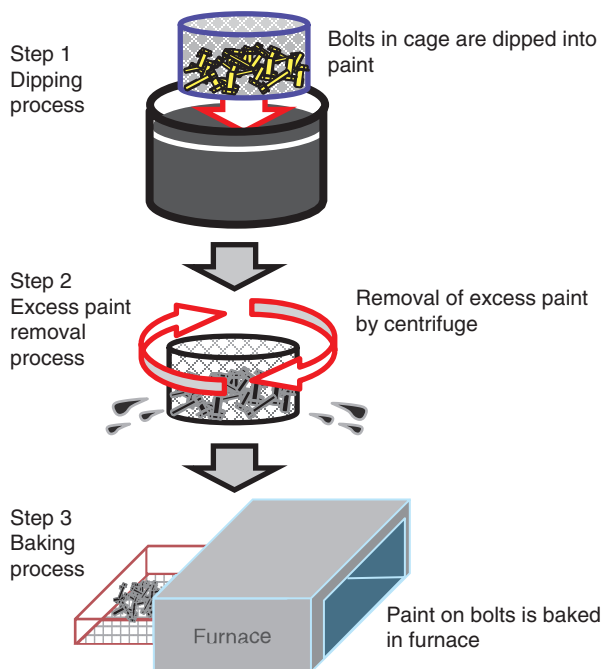


Fig. 3 Model of dip coating process

processes; the dipping process, the excess paint removal process, and the baking process.

In the dip coating, the necessary film thickness for coloring is attainable by the control of paint viscosity and the removing of excess paint using an appropriate centrifugal force. In actual practices, however, it is not easy to control conditions to attain uniform paint film thickness from the dip coating. The film becomes thin in some area of the bolt, causing exposure of base metal color. In other words, the bolt cannot be blackened uniformly in some cases. If the bolts are in contact with each other when dipping or removing, the paint will be inadequate or excessive in such a contacting area, causing a defect called the touch mark to occur in some cases. That means that some areas of the bolt are adequately colored while the base metal color is exposed in other areas. When an adequately colored area and an inadequately colored area come side by side, the color unevenness becomes apparent.

Therefore, in general, it is necessary to paint thick the entire bolt so that color unevenness does not occur, and in some cases it is necessary to paint more than twice as shown in Fig. 4. As a result, unnecessary coating films are formed on thread portions which are not subject to appearance requirements, and the threaded portions may not satisfy the standard tolerance in some cases⁽¹²⁾. To deal with the said issue, it is necessary to remove excessive paint on the thread after painting, to modify shape of the fitting female thread,

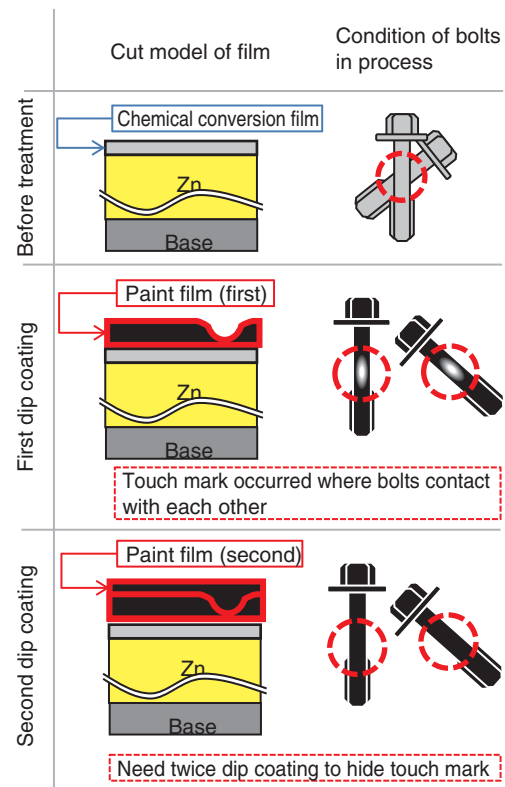


Fig. 4 Cross-sectional view of touch mark in conventional dip coating

or to modify the shape of blank material itself.

It is often the case that a paint not exclusively developed for motorcycle bolts is used for the dip coating. Accordingly, the durability requirements in sun light and/or corrosive environment are not satisfied in some cases. Moreover, the friction coefficient is often different from that of the conventional bolt surface treatment, sometimes requiring special processing conditions⁽¹³⁾.

2.3. Aims of Development

After sorting out the above-mentioned issues in the blackening operations taking into account the quality requirements of motorcycle bolts, the following requirements were set for the coloring of the bolts to be developed.

- An adequately black color shall be provided steadily without apparent unevenness of color
- Tool marks shall not be apparent after tightening of bolt
- The thread shall fit smoothly into the female thread
- An appropriate axial force shall be attainable from a bolt tightening torque
- The coloring shall be weather resistant and shall not be discolored by the sunlight
- The corrosion resistance shall be adequate
- The coloring shall not be deteriorated by the oil, fuel, and other chemicals used in a motorcycle

These requirements shall be satisfied without using the hexavalent chromium while coloring by such a method that allows mass production using the existing production equipment for low-cost manufacturing.

3. Structure and Method of Surface Treatment

3.1. Structure of Films Produced by Surface Treatment

Assuming that the above-mentioned goals were unachievable solely by the chemical blackening on the zinc plating or the dip coating, a combination of both methods were considered.

In order to obtain a sufficient black appearance while maintaining a thin film, firstly a black chemical conversion treatment film is applied on the zinc plating as an undercoat of painting. Further overlaying a thin black paint film, a three-layer structure should be employed. Conventionally, the purpose of a black chemical conversion treatment film was prevention of oxidation of the zinc plated surface. In this new method, the purposes are to provide coloring for suppressing color unevenness of paint applied as an undercoat of painting, and to ensure adhesion of the paint film. In the meantime, the purposes of painting are to be able to impart and maintain a sufficient black appearance while ensuring the fastening function of the bolt. With the said coating structure employed, since the black chemical conversion treatment film as the undercoat and the overlaid paint film are superimposed, it is possible to impart a sufficiently uniform black tint even if the paint film is thin, allowing to satisfy the appearance requirements. The bolt

colored by the newly-developed method can be treated in the same manner as for the conventional bolt when tightening.

3.2. Black Chemical Conversion Treatment Film as an Undercoat of Painting

3.2.1. Principles of coating design

As mentioned earlier, the black chemical conversion treatment film using the trivalent chromium is thinner than that of the hexavalent chromium and challenging to attain a sufficient black appearance. Accordingly, the chemical treatment is usually conducted two times to satisfy the quality of appearance while ensuring corrosion resistance. In the first chemical conversion treatment, a coarse surface film is formed, which intensifies the blackness taking advantages of the diffused reflection of light on the coated surface. However, on the coarse surface coating, water tends to accumulate on the surface, making it vulnerable to corrosion. To deal with this issue, the surface concealing treatment should be applied as the second chemical conversion treatment⁽¹⁴⁾, which smooths out the chemically coated surface to conceal the spots that trigger corrosion. As shown by Fig. 5, while the surface is coarse just after the first chemical conversion treatment, the surface is smooth after the concealing treatment. That said, as mentioned earlier, the purposes of chemical coating in this project are to color as an undercoat and to ensure adhesion of paint film. It was therefore considered that the second treatment for corrosion resistance could be eliminated.

It was also considered that as the coarse surface after the first chemical conversion treatment would have an anchoring effect to enhance adhesion of paint to be overlaid, the corrosion resistance would be better than painting after the second chemical conversion treatment. Figure 6 shows principles of the anchoring effect.

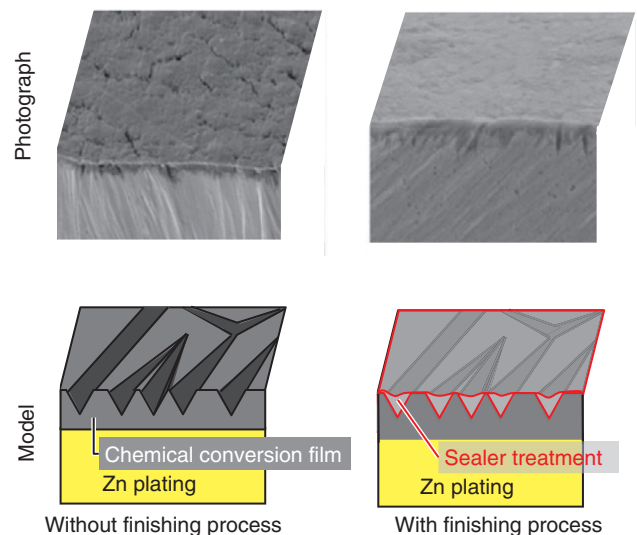


Fig. 5 Surface of chemical conversion films

To verify the model shown in Fig. 6, experiments were conducted using test pieces to measure the adhesion of paint film and the corrosion resistance. Surface And Interface Cutting Analysis System (SAICAS)⁽¹⁵⁾ was used for paint adhesion measurement. Figure 7 shows measurement

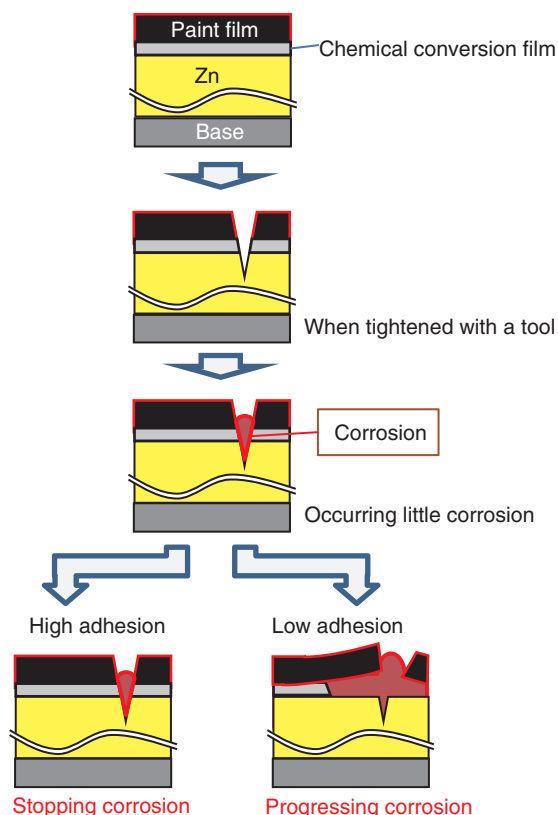
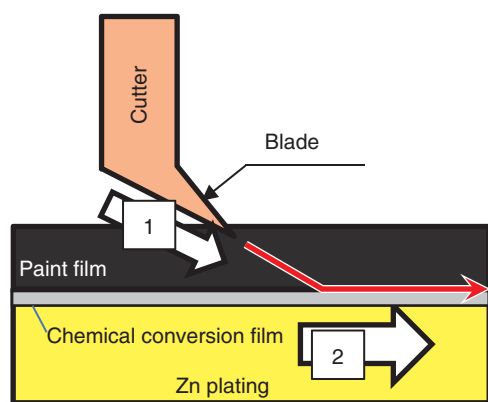


Fig. 6 Models of paint adhesion and corrosion resistance



1. The cutter advances along the direction of the blade.
2. Just after the blade touches the Zn plating layer, the cutter changes the direction to advance horizontally parallel to the paint surface.
3. The adhesion strength is measured by detecting the stress applied on the cutter.

Fig. 7 Model of SAICAS and test method

principles of SAICAS.

In the measurement using this equipment, the treated surface is firstly cut downward at an angle with a small blade, and as soon as the blade reaches the chemical conversion film, the blade is moved along the surface of the film. After that, peeling of the paint film is started by peeling load. When the movement of the blade is further continued, the peeling load increases and decreases each time the shearing of the paint film is repeated. Figure 8 shows the image picture of the load fluctuation. In this project, the value obtained by dividing the minimum value of the load, when the blade is moving along the surface of the zinc plating layer, by the blade width was defined as the adhesion strength. The corrosion resistance was measured by the length of time until white rusts occur in the Salt water Spray Tests (SST) chamber.

For the preparation of test pieces, firstly the zinc plating was applied to the mild steel sheet. Then, test pieces only with the chemical conversion treatment and those with further concealing treatment were prepared. After that, the surface of the test piece was painted with the polysiloxane paint (to be mentioned later). The difference of adhesion strength was measured using the test pieces. The corrosion resistance was also measured using the test bolts having the similar surface treatment. Figure 9 shows the test results. It has been proven from the tests that the paint adhesion is stronger on those having only the chemical conversion treatment than the ones having the concealing treatment, and so is the corrosion resistance.

Based on the findings, it was decided to eliminate the concealing treatment. Considerations, however, are necessary for the environment in the processes up to the painting after the chemical conversion treatment because the corrosion resistance is low from only the single chemical conversion treatment using the trivalent chromium, which requires painting before a start of corrosion. For validation, the test pieces were soaked under the conditions shown in Table 2 after applying the chemical treatment, and after

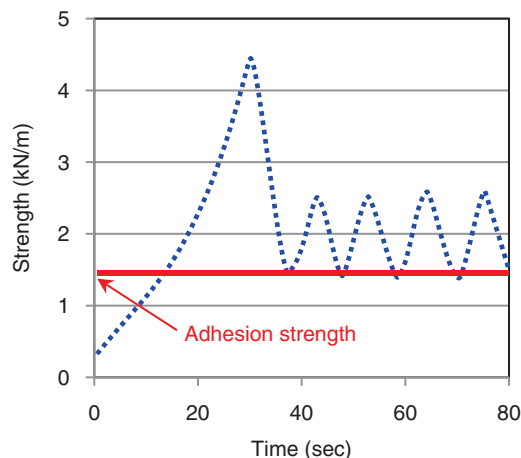


Fig. 8 Model data of SAICAS

Table 2 Storage condition until coating process after conversion process

	Finishing	Storage condition	
		Temperature	Humidity
Storage condition A	Dry	21°C	under 40%
Storage condition B	Dry	40°C	95%
Storage condition C	Not dry	40°C	95%

painting, the corrosion resistance and the paint adhesion were measured (Figs.10 and 11). After these tests, deterioration was found in those not dried after the under coating, i.e., the chemical conversion treatment, and those exposed to high temperatures and high humidity. It has thus been clarified that the work piece should be dried after the chemical treatment and should not be left in a high temperature, high humidity environment.

3.2.2. Blackness of black chemical conversion treatment film as undercoat

As mentioned earlier, in the method to be employed at this time, the final blackness of the surface is a mixture of the blackness of the undercoating black chemical conversion treatment film using the trivalent chromium and the blackness of the overlaid paint film. Therefore, in order to develop a paint for this application, it is necessary first to grasp the blackness that can be imparted by the black trivalent chromium chemical conversion treatment film, in particular, the level of the lowest blackness that can occur in the manufacturing process.

Meanwhile, as the thickness of black chemical conversion treatment film is affected by the zinc ion concentration in the chemical treatment solution, the resultant blackness depends on the zinc ion. It was therefore decided to clarify the zinc ion concentration in the most deteriorated chemical treatment solution, and quantifiably

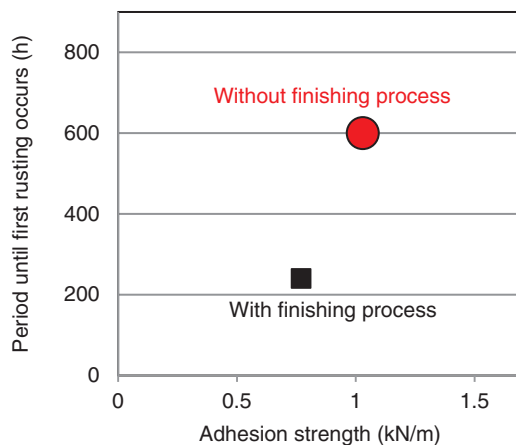


Fig. 9 Relationship between adhesion and corrosion resistance with and without finishing process after chemical treatment

evaluate the blackness of the black chemical conversion treatment film surface produced by the solution.

Usually, if the solution is not replenished at the time of chemical treatment, the zinc ion concentration keeps rising until saturation. However in an actual chemical treatment operation, some solution sticks on the work pieces and taken out of the treatment tank each time the treatment is completed as Fig. 12 shows. Consequently, the treatment solution is reduced slightly. By the replenishment of the same amount of solution as the consumed volume, a part of the treatment solution, in which the zinc ions are increasing toward saturation, is removed and replaced.

As shown by Fig. 12, when the chemical reactions, removal and replenishment of solution are repeated,

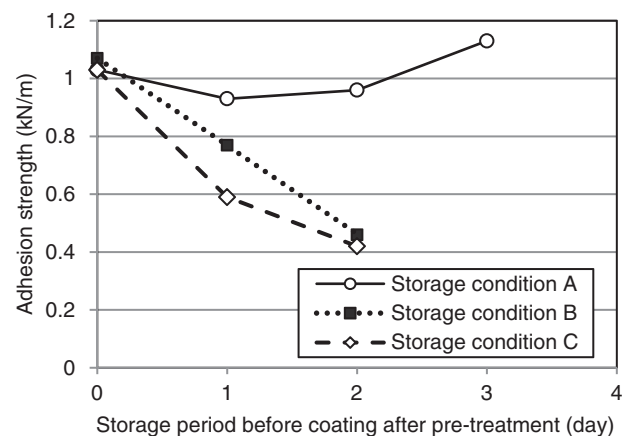


Fig. 10 Relationship between adhesion and storage period with various conditions

	Storage period			
	0 day	1 day	2 days	3 days
Storage condition A	 No rust	 No rust	 No rust	 No rust
Storage condition B	 No rust	 Whitening	 Whitening	—
Storage condition C	 No rust	 Whitening and peeling	 Whitening and peeling	—

Fig. 11 Relationship between corrosion toughness and storage period with various conditions

the amount of zinc ions at the n^{th} replenishment can be represented by Eq. (1).

$$A_n = A_{(n-1)} + x - y((A_{(n-1)} + x)/B) \quad (1)$$

- A_n : Amount of zinc ions [g] in the chemical treatment solution after treating n times.
 B : Amount of chemical treatment solution [L]
 x : Amount of zinc ions released in the solution during one treatment operation [g]
 y : Amount of solution taken out of the tank per one treatment operation (= replenishment volume) [L]

Equation (1) means that as the n increases, the zinc ion concentration gradually nears a certain level. When the n in Eq. (1) is increased infinitely large to calculate the amount of zinc ions that corresponds to the said level, the ultimate equation can be represented by Eq. (2).

$$\lim_{n \rightarrow \infty} A_n = x((B - y)/y) \quad (2)$$

Accordingly, when n is adequately large, the ion

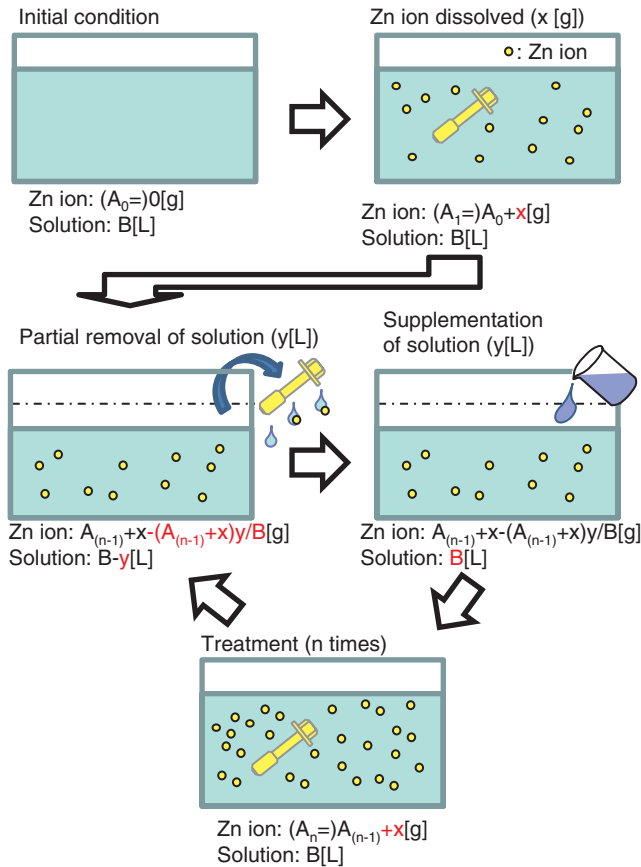


Fig. 12 Increase of zinc ion in solution and loss of solution in chemical treatment using trivalent Cr

concentration C_{Zn-ion} [g/L] can be represented by Eq. (3).

$$C_{Zn-ion} = x((B - y)/y)/B \quad (3)$$

The values x and y in Eq. (3) depend on the conditions of the treatment solution and the surface area of the work pieces. The zinc ion concentration becomes the highest when x is maximum and y is minimum. Upon the simulation under all the presumably conditions in mass production process, the highest zinc ion concentration has been determined as 14.7 g/L.

Assuming from these findings that the zinc ion concentration will not exceed 20 g/L even when estimated high in ordinary mass production operations, this level of concentration is considered as a precondition when determining the lower limit of the thickness of produced film. By setting this condition, it becomes possible to continue to use the chemical conversion treatment liquid which has been frequently replaced in the past almost without replacement, and it is possible to enhance the productivity.

For a quantitative evaluation of blackness of the black chemical conversion treatment film, it was decided to use L^* , which is the brightness index, of Hunter Color Scale. Note that the lower the L^* , the stronger the blackness.

The brightness of the black film produced by the chemical solution in which the zinc ion concentration reached the presumed upper limit of 20 g/L was measured. The L^* was approximately 33. Presuming from that finding that this brightness is the blackness when the film thickness becomes the smallest when designing the black paint for dip coating.

3.3. Designing of Paint Presuming Use of Chemically-produced Black Film as Undercoat

3.3.1. Paint film thickness

It was firstly decided to set a target film thickness for the dip coating. To determine the maximum film thickness, the target film thickness of the surface treatment was set from the thread precision standards (JIS B0209) of M6 bolt, which is the smallest bolt frequently used in motorcycles. Taking into account the conditions under which the clearance between the male thread and the female thread becomes the minimum, such a case is employed when the inside diameter of the female thread is at the lower limit and the outside diameter of the male thread is at the upper limit. At that time, the clearance becomes 13 μm . Under these conditions, the film thickness of the surface treatment on the male thread has to be 13 μm or less. As the total thickness of the zinc plating layer and the chemical conversion treatment film is 8 - 10 μm , the paint film thickness has to be 3 μm or less.

In view of the above, the target paint film thickness was set at 2 μm with a tolerance of ± 1 μm . As the film thickness in the thicker side is 2 - 3 μm in the time-proven chemical conversion treatment film using the hexavalent chromium,

the target film thickness set at this time is deemed appropriate.

3.3.2. Type of base paint material

Studies were continued for the type of base paint material. When selecting, from the standpoint of general applicability to motorcycles, it was decided to select from the conventional organic paint and the organically modified inorganic paint, and conducted evaluation.

Table 3 shows results of evaluation of various base paints from the standpoint of paint film quality requirements of dip coating of bolts.

Among the paint options, the polysiloxane paint, which features a low viscosity and allows easy control of thickness within the narrow range of $2 \pm 1 \mu\text{m}$, was selected as the base paint material. As the cross-link density of the paint film made of this material becomes high, a high blocking effect is attainable to protect the base metal from the oxygen in the atmosphere. The advantage of corrosion resistance is also considered as a benefit when selecting.

3.3.3. Amount of pigment in paint film

The selection was continued for the pigment to color the paint film black. As the bolts for retaining of exterior parts of a motorcycle are often exposed to sunshine, the black pigment mainly consisting of the carbon black has been selected as a pigment less prone to color fading. The amount of black pigment was determined as per the following steps.

The target of appearance quality was set at the same level as of the black chromium plating. Although the black chromium plating is no longer applicable as the hexavalent chromium is contained in the coating, it was the surface treatment that used to provide the highest appearance quality to bolts. Upon measurement of the blackness with the Hunter Color Scale, the L^* was approximately 28. Accordingly, the target blackness by L^* was set at 28 or lower.

To achieve the target figure, attempts were made to determine the amount of black pigment in the paint. Firstly in the black chemical conversion treatment process, the test pieces were prepared by producing a black chemical conversion treatment film using the chemical solution in which the zinc ion concentration was adjusted at 20 g/L. Then, preparing paints having various contents of black pigment, each paint was applied on five test pieces in such a manner that makes the paint film thickness $1 \mu\text{m}$, which is the lowest limit of specified film thickness.

Figure 13 shows the measured highest, lowest, and average L^* of the samples.

It is understood from the graph that the L^* will be under 28 if the black pigment is 2.3% or more in the paint. The level of appearance quality same or better than the black chromium plating is attainable if the chemical coating and the newly-developed paint film are combined.

However, while the pigment is dispersed in the paint matrix, it is not chemically combined with the components

Table 3 Assessment of base paint material for bolts

	General organic paint			Organically-modified inorganic paint	
	Acrylic paint	Epoxy paint	Urethane paint	Silicon paint	Polysiloxane paint
Thin film	1	1	1	1	3
Corrosion resistance	2	3	1	2	3
Pot life	3	3	1	3	3
Hardness	1	1	1	2	3
Coloring	3	3	3	3	2
Weather resistance	3	1	3	3	3

3 = good, 2 = fair, 1 = poor

of the matrix. There are areas where the material structure is non-continuous between the matrix and the pigment. Such an area permits easy permeation of water and/or component that accelerates corrosion. In other words, it can be considered that the corrosion resistance lowers when the non-continuous areas of matrix increases due to an increase of pigment. Accordingly, the confirmation tests were conducted to check if the earlier-specified pigment amount was appropriate from the viewpoint of corrosion resistance.

Using the treatment solution having a zinc ion concentration of 20 g/L, the test pieces were produced by providing the black chemical conversion treatment film. There, preparing paints having various rates of black pigment content, each paint was painted on five test pieces in such a manner that the film thickness became $1 \mu\text{m}$, which was the lowest limit of the specified film thickness. Figure 14 shows the average, maximum and minimum of the measured rate of corroded surface area after allowing the test pieces of various black pigment contents to corrode for 480 hours in SST chamber.

From these finding, it is considered that the corrosion resistance does not lower significantly if the rate of black pigment in the paint is 3.0% or lower. Combining the minimum amount of black pigment determined earlier, the content of black pigment is specified between 2.3% and 3.0%.

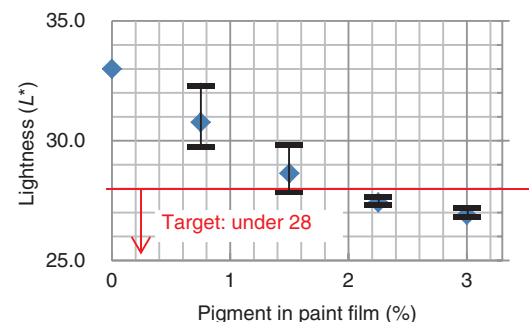


Fig. 13 Relationship between pigment content and L^* (Film thickness: $1 \mu\text{m}$)

3.3.4. Amount of friction modifier in the paint film

Then, taking into account the dispersibility in the paint, the friction modifier was selected to control friction coefficient. The relationship between the amount of friction modifier in the paint and the friction coefficient was measured, and the average value, the maximum value, and the minimum value in 5 samples are shown in Fig. 15.

From these findings and aiming at the same level of friction as of the conventional surface treatment, the rate of friction modifier in the paint has been set at 6 - 18%.

As the friction modifier is also dispersed in the paint matrix, the corrosion resistance may lower if the amount increases. Accordingly, it was decided to verify from the standpoint of corrosion resistance. Preparing paints having various contents of friction modifier, each paint was applied

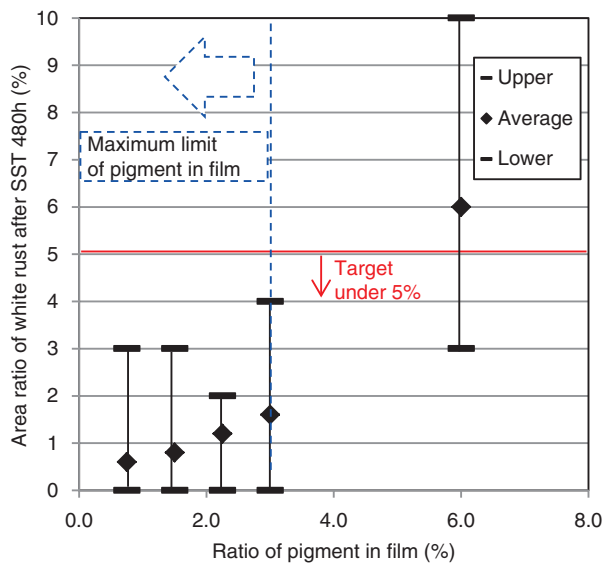


Fig. 14 Relationship between pigment content and corrosion toughness

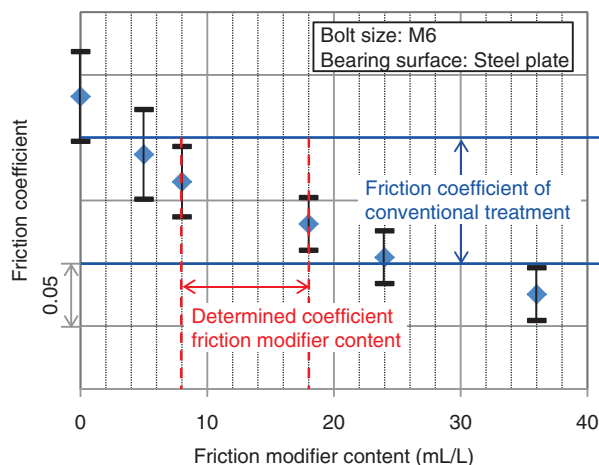


Fig. 15 Friction coefficients to friction modifier content

on five test pieces in such a manner that makes the paint film thickness 1 μm , which is the lowest limit of specified film thickness. SST of 480 hours was performed on these test pieces, and the area ratio of rust generated on the surface was measured. Figure 16 shows the average value, the maximum value and the minimum value.

It is clarified from the findings that the corrosion resistance does not lower significantly when the content is 22% or lower, and that the corrosion resistance is not affected if the rate of friction modifier is 6 - 18% as specified earlier.

3.4. Conditions of Dip Coating

3.4.1. Conditions of paint removal by flinging

The newly developed method is designed to maintain appearance and ensure quality when the paint film thickness is between 1 μm and 3 μm . Accordingly, proper conditions should be set in the processes where the bolts are immersed in the paint and the excess paint is removed by a centrifuge, which are the key processes of the dip coating to control film thickness.

To achieve the target paint film thickness steadily, we considered to select parameters highly affecting the film thickness. Accordingly, we decided to investigate the dip coating process into a simplified model.

In the dip coating, the work pieces are held in a cage, and after immersing in the paint, the excessive paint is flung off by the centrifuge to control film thickness. It is considered that the surface tension of paint on the work pieces maintains continuous flow of paint, allowing the paint to flow virtually freely on the work piece surfaces. Accordingly, the paint on the work pieces move toward the outer circumference of the cage due to the centrifugal force as shown by Fig. 17.

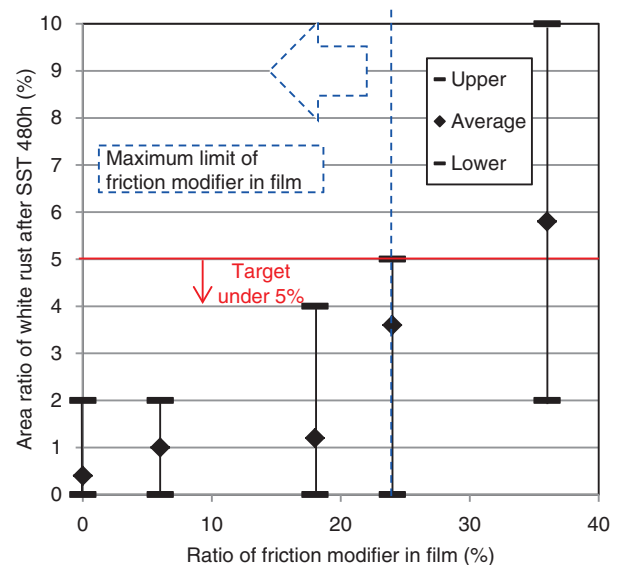


Fig. 16 Relationship between friction modifier content and corrosion toughness

In the outer-most part, the paint is flung off toward the outside of cage. Even when the paint on the bolt located near the outer circumference is flung off, the paint on the inner bolts moves toward the outside through the work piece surfaces due to the surface tension, replenishing paint. While the paint film thickness on various parts of the work piece decreases in the said manner, the paint stops flowing when the thickness reaches to a certain level due to the viscosity of paint, causing the paint to stay on the work pieces. Although the final paint thickness differs depending on the location of work piece in the cage, it is presumed that eventually the paint thickness of all work pieces in the cage is virtually determined by the balance of the centrifugal force F_c and the viscous force F_v in the outer most part of the cage due to the earlier mentioned effect of surface tension. Figure 18 shows image pictures of the principle.

On the basis of these presumptions, attempts were made to indicate the relationship among the parameters that affect film thickness using equations.

Firstly, the centrifugal force F_c can be represented by Eq. (4).

$$F_c = \rho \times S \times h \times r \times (2\pi N)^2 \quad (4)$$

ρ : Specific gravity of paint

S : Unit area where paint is adhering

h : Thickness of paint

r : Distance from the center of cage

N : Number of rotation of centrifuge

r is represented by the outer-most radius of cage r_{max} that affects film thickness.

Using Newton's law of fluid friction, the viscous force F_v can be represented by Eq. (5).

$$F_v = \frac{(\eta \times v \times S)}{h} \quad (5)$$

η : Viscosity of fluid

v : Flow speed of fluid

S : Unit area of area where paint is adhering

h : Thickness of paint

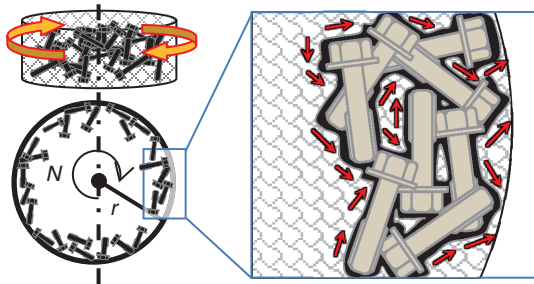


Fig. 17 Image of movement of paint in excess paint removal process by centrifugal force

v is the flow speed of paint. Since v is induced by the centrifugal force, it becomes maximum in the outer-most part where the centrifugal force becomes maximum. Also in the proximity of the outer-most part, the thickness gradually decreases, and the paint stops flowing when reaching a certain thickness. From Eq. (4) and Eq. (5), the centrifugal force acting on the paint on a unit area decreases along with a decrease of paint thickness while the viscous force increases. It can be considered that the flow of paint stops when the forces are balanced. If presumed $F_c = F_v$, the following Eq. (6) can be obtained to indicate paint thickness.

$$h = \sqrt{\frac{\eta \times v}{\rho \times r_{max} \times (2\pi N)^2}} \quad (6)$$

If the spinning of centrifuge is stopped under these conditions, the paint flows again on the work pieces, and the thickness of paint film becomes uniform. The paint is baked in the later process to form solid paint films. If the conditions are controlled in such a manner that the paint film thickness h becomes constant in the outer-most part when the flinging off of paint is discontinued, a constant paint film thickness is attainable on all the work pieces. Among the affecting parameters, controllable ones are the paint viscosity η and the spinning speed of centrifuge n . Although influences of other factors are obviously conceivable in actual practices, the validation was conducted in this project presuming the two parameters as the principal factors that determine film thickness.

In order to set processing conditions to attain the target film thickness on the basis of this theory, tests were conducted to analyze the relationship between the paint viscosity and the spinning speed of centrifuge. Figure 19 shows the test results.

The viscosity was measured with the widely-used simplified viscometer (Iwata Cup made by ANEST IWATA Corporation). The ambient temperature at the time of measurement was 35°C, and the paint temperature was 25°C.

It has been clarified from the test results that the film thickness is counter-proportional to the spinning speed nearly as per Eq. (6). If the working speed of 500 rpm of the centrifuge used in this project is deemed as a precondition,

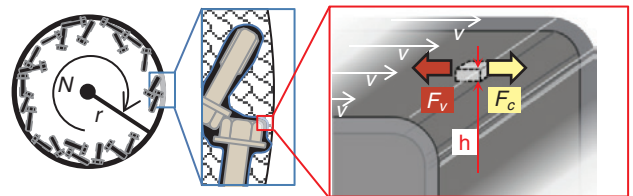


Fig. 18 Image of excess paint flinging off by centrifugal force

the paint viscosity should be 9.3 s to achieve the target film thickness of 2 μm .

Next, in an attempt to clarify how the seasonal factors such as the ambient temperature affect the film thickness, tests were conducted after changing the ambient temperature to 10°C under the earlier-mentioned test conditions. In that test, the film thickness was 1.5 μm when the paint viscosity was 9.3 s. A difference of about 0.5 μm to the film thickness of the target occurred. Accordingly, in order to get closer to the target, further processing conditions were considered.

The reason why the paint film thickness becomes thin when painting is performed at an ambient air temperature of 10°C is as follows. When the paint is flung off, the diluent also evaporates at the same time. At that time, if the ambient air temperature is low, less solvent evaporates and the viscosity increase of the paint slows down.

To back up the said principle, the difference of viscosity increase was measured when agitating 20 mL of the paint in a beaker of 65 mm diameter at various ambient temperatures. Figure 20 shows the test data.

It has been clarified from these findings that the viscosity increase is slow when the ambient temperature is low, and fast when high. It is therefore necessary to maintain increase of viscosity at a constant rate irrespective of the season. Another possible cause is that the amount of diluting solvent may differ even when the paint viscosity is rated the same when the ambient temperature is different. As this paint is an organic matter, the viscosity of paint itself changes along with a change of temperature. Hence the amount of diluting solvent to add to the paint differs to control the viscosity at a constant rate. Consequently, even when the paint film thickness just after flinging is the same, the thickness of paint film is not the same after the solvent evaporated and the paint hardened. To analyze difference from the amount of paint ingredient that produces actual paint film, the remaining component of the

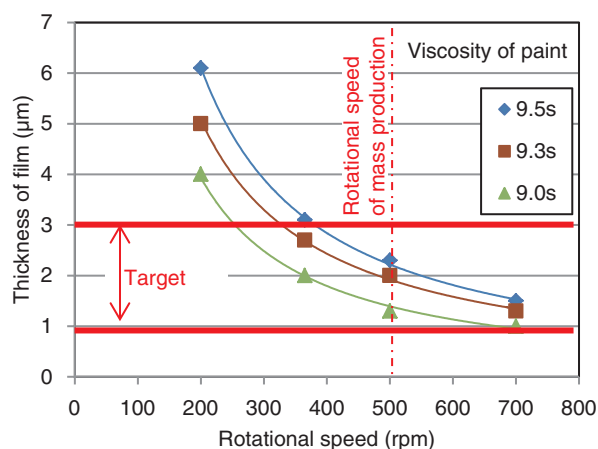


Fig. 19 Relationship between rotational speed of centrifuge and thickness of film for different paint viscosities

paint after heating was measured after adjusting in such a manner that the viscosity becomes the same under various ambient temperatures. The measurement was taken as per JIS K5601-1-2. The test data is shown in Fig. 21. A 3% difference was found in the amount of paint component remaining after heating between the viscosity adjustment at 15°C and at 25°C.

It has been clarified from the findings that the target film thickness is unattainable if only the spinning speed of the centrifuge and the viscosity of the paint are specified when the ambient temperature changes.

However, it is not easy to control conditions accordingly to various ambient temperatures, and it is not also easy to maintain a constant ambient temperature unlike in an ordinary spray painting. The measurement of remaining amount after heating takes a long time, and lowers production efficiency. It was therefore considered to maintain the temperature of the paint and the temperature of the object to paint at a constant level to exclude the influence of ambient temperature, aiming at a constant evaporation speed of the diluting solvent by equalizing the temperatures of the paint and the object to paint in order to eliminate influence of temperature. Also, when the paint temperature is constant, the amount of remaining component after heating can be controlled at a constant level only by adjusting the paint viscosity, allowing simplification of control of processing conditions. Figure

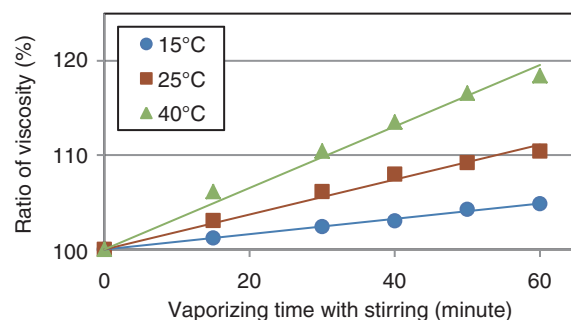


Fig. 20 Change viscosity of each temperature

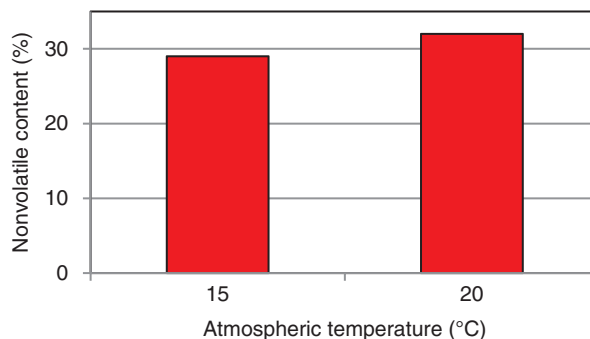


Fig. 21 Nonvolatile content of same viscosity paint under each room temperature

22 shows the film thickness when painted after increasing the temperatures of the paint and the object to paint up to 28°C from the ambient temperature of 10°C.

Even when the ambient temperature is 10°C, almost the same film thickness as at 35°C is attained by warming up the paint and the object to paint. As obvious from the findings, it has been confirmed that a constant film thickness is attainable by adjustment of temperatures of the paint and the object to paint to cope with the inconsistent film thickness caused by ambient temperature differences.

3.4.2. Conditions of baking for dip coating

Next, studies were conducted to determine the temperature conditions necessary for hardening of the polysiloxane paint selected as the paint matrix. As mentioned earlier, the cross-link density of this material is high, which means a high corrosion resistance is attainable. However, the bridging of this paint is by the dehydration condensation in which H_2O separates from the OH radical when the two siloxanes are heated, which means that the chemical reactions are advanced only by the heat. An appropriate amount of heat therefore must be applied at the time of the dehydration condensation to have the paint hardened.

For validation, baking was conducted under the heating conditions recommended for the selected polysiloxane paint. When the bolt was painted to a film thickness of 3 μm so that the chemical reactions take the longest time, and baked at 140°C for 20 min. as per the recommendation, an adequate corrosion resistance was confirmed.

However, it should be noted that in motorcycles, black bolts are often used in the hydraulic brake system. The bolt may be wetted with the brake fluid. As the brake fluid can damage paint film, the film on a black bolt should be resistant to the brake fluid. Accordingly, the brake fluid was heated up to 200°C, and the bolt was immersed in it. 200°C is the highest allowable working temperature of the brake

fluid. The paint film was found damaged in the test. It was therefore concluded that the paint film baked at 140°C for 20 min. was not applicable to the brake system. The cause was presumed in some areas where chemical reactions were incomplete. In the general painting, appearance faults tend to occur from the dust, etc. in the atmosphere sticking on the paint surface before hardening⁽¹⁶⁾. In such a case, the repair referred to as recoat, in which only the faulty part is ground and repainted, is conducted. In the recoating, the adhesion of paint between the first painting and the second painting sometimes causes an issue. When the bridging is incomplete in some part of the first paint film, it is easy to maintain good adhesion with the second paint film. Accordingly, such conditions that leave some incomplete bridging are often recommended. The temperature condition recommended in this case can be considered as based on the presumption of recoating. However, in order to satisfy the thread precision, dip coating in this development, the coating film is designed with one layer. It is therefore easily presumable that the upper limit of the film thickness target value will be exceeded if the coating film has two layers by recoating. That is, external appearance repair by recoating cannot be tolerated. From the above, it is considered that there is no need to leave the incomplete bridging portion for the purpose of securing the adhesion between the first layer and the second layer, and the baking conditions are changed.

Preparing bolts coated with the newly-developed paint, test pieces were produced by baking at various temperatures for 20 min. each. The test pieces were immersed in the brake fluid, and after that the appearance was checked. It has been confirmed from the tests that no deterioration of paint film such as melting occurs even when immersed in the heated brake fluid if the paint film is baked at 180°C for 20 min. as shown by Fig. 23. Accordingly the baking temperature was set at 180°C × 20 min. or more.

In the meantime, an excessively high baking temperature or long period of baking can cause oxidation of the plating, making the presumed corrosion resistance unattainable. It was therefore decided to seek conditions causing no deterioration of paint film even when baked for a long time at a high temperature. As the time period from loading up to

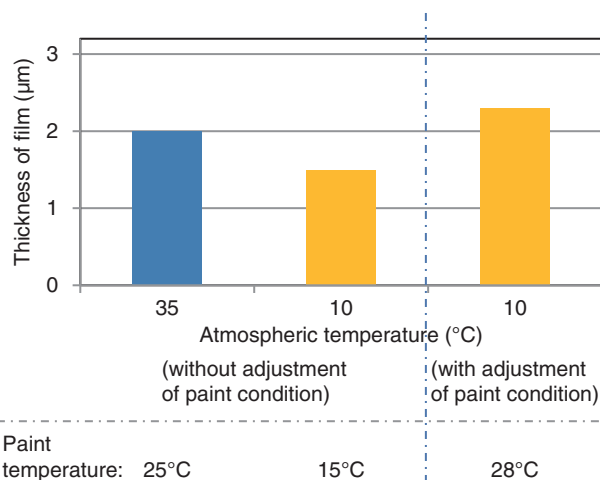


Fig. 22 Thickness of film under various seasons

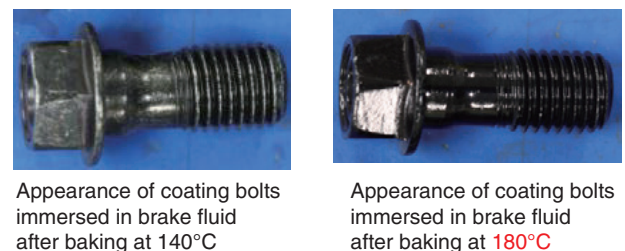


Fig. 23 Appearance of coating bolts immersed in brake fluid after baking at different temperatures

unloading is 60 min. in the baking oven used in this project, the baking period cannot be longer than that. As well as setting conditions within that range, confirmation tests were conducted up to 120 min., presuming an irregular stopping of the production line.

Increasing the temperature from 180°C by a 20°C increment, the paint film on the samples was baked at each temperature for various time periods, and corrosion resistance was measured. The test data are shown in Fig. 24.

It has been clarified from the tests that when baked at 240°C for 60 min., the corrosion resistance lowers significantly. Accordingly, the baking condition has been set at the temperature between 180°C and 220°C, and the time period between 20 min. and 60 min.

It should also be noted that in that temperature range, no immediate failure will occur even in the case of an unexpected line stopping.

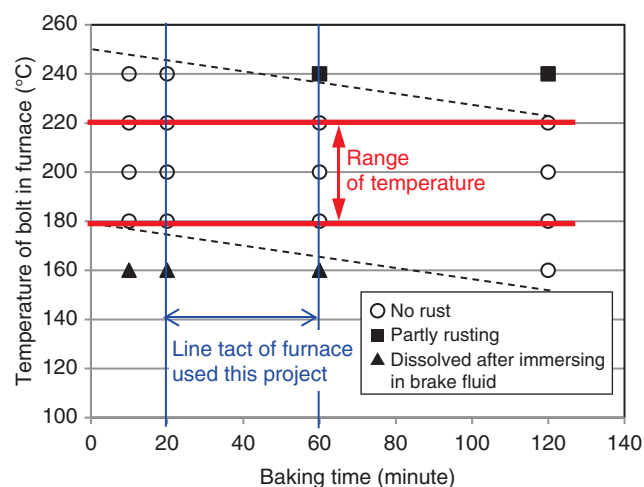


Fig. 24 Corrosion resistant confirmation result of baking temperature distinctiveness

4. Applications to Motorcycle Bolts and Benefits

4.1. Appearance

Figure 25 shows appearance of bolts having the newly-developed surface treatment actually applied.

With the black chemical layer provided as an undercoat, there is no unevenness of color. The L^* number of initial appearance is under 28, which means the appearance is as good or better than the black chromium plating.

The appearance after tightening was checked. The appearance of M6 bolt after being tightened to the specified torque is shown in Fig. 26.

4.2. Corrosion Resistance

Figure 27 shows the result of corrosion acceleration

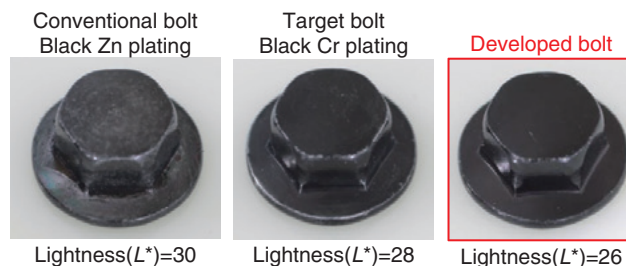


Fig. 25 Appearance of bolts

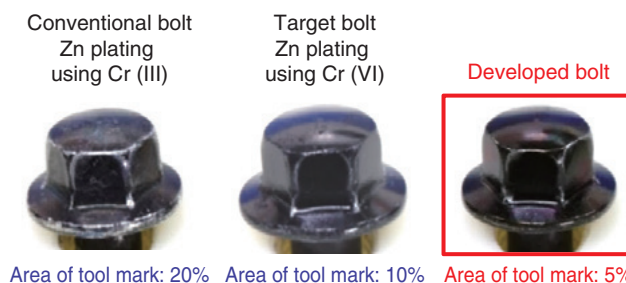


Fig. 26 Appearance of bolts after tightening

Count of test cycles		4	12
Bolt of handle holder	Appearance		
	Developed (Upper)	No rust	No rust
	Conventional (Lower)	WR: 3%	WR: 50%
Screw of master cylinder	Appearance		
	Developed (Right)	No rust	No rust
	Conventional (Left)	WR: 3%	WR: 100% RR: 5%
Oil bolt of caliper	Appearance		
	Developed (Upper)	No rust	WR: 1%
	Conventional (Lower)	WR: 1%	WR: 100%

WR: Area ratio of white rust
RR: Area ratio of red rust

Fig. 27 Appearance of bolt after corrosion test

test in the test mode assuming the actual use environment by attaching the bolts of the conventional product and the developed product to the test motorcycle. From these findings, an adequate corrosion resistance has been confirmed.

4.3. Weather Test

The color fade was measured after exposing in the outdoor environment basically as per JIS K5600-7-6 for 1.5 years. The color difference ΔE^*ab analyzed as per JIS Z8729 is shown in Fig. 28.

With the proper pigment selected for coloring, no apparent color fade is seen. Note that the discoloration of the conventional bolt was unmeasurable because of corrosion. It was concluded from these findings that substitution from current bolts was allowable because the discoloration including corrosion was less than that of current surface treatment.

4.4. Tightening Tests

Figure 29 shows comparison of friction coefficient on seating surfaces made of SP, A6061 and painted aluminum. In any seating surface material, the deviation of friction coefficient is smaller in the newly-developed surface treatment, falls within the range of conventional treatment.

While the large deviation in the conventional surface treatment can be considered attributable to the friction coefficient not intensively adjusted in the conventional surface treatment, we consider the deviation is small in the newly-developed surface treatment because the friction coefficient is intensively controlled by the friction modifier.

4.5. Film Thickness

Among the preset conditions, those under which the film thickness becomes the maximum are when

the spinning speed of the centrifuge is the lowest and the paint viscosity is the highest. In the meantime, the thickness becomes smallest when the spinning speed is the highest and the paint viscosity is the lowest. The thickness of paint film was measured from 10 pcs of the bolts treated under each of the above-mentioned two conditions. The average, maximum and minimum are shown in Fig. 30. Under either condition, the thickness falls within the target of 1 - 3 μm . It has thus been proven that the newly-developed surface treatment has no negatively effect on the fit of thread when tightening while maintaining an adequate blackness.

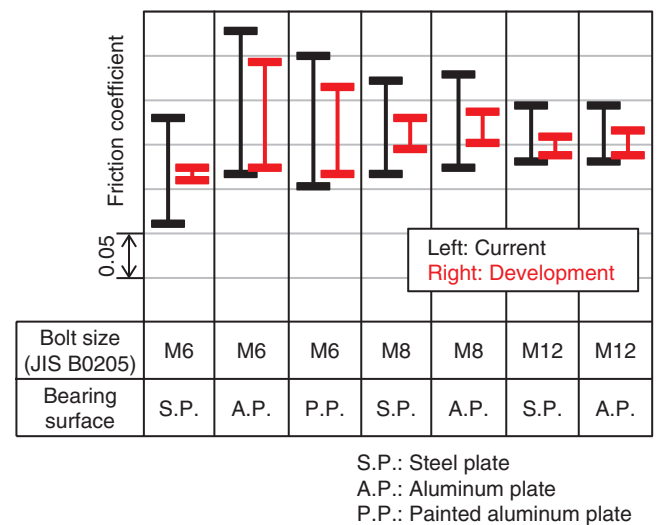


Fig. 29 Comparison of friction coefficient on various seating surfaces

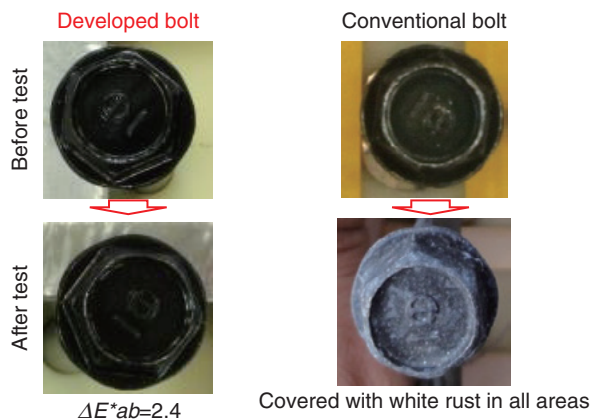


Fig. 28 Appearance before and after outdoor exposure test

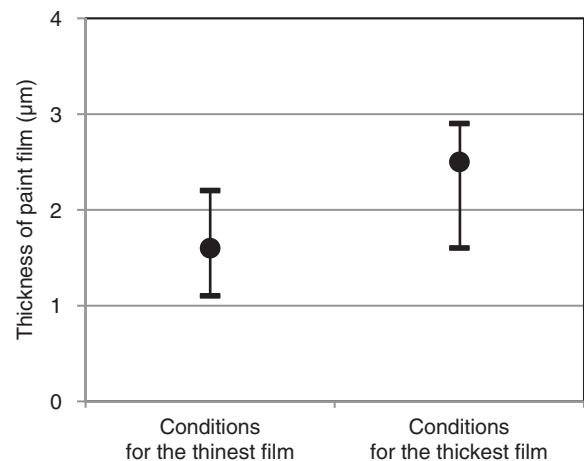


Fig. 30 Verification of film thickness deviations

5. Conclusion

The new surface treatment has been developed for black bolts that satisfy appearance and functional requirements of motorcycles by combining the black chemical coating and the dip coating. Given below is a summary of findings from this project.

- (1) The two-step coloring, i.e., the black painting overlaid on the chemically-produced black undercoat using the trivalent chromium, ensures uniform blackness of the bolt while maintaining thread precision.
- (2) With the clarification of how the chemical treatment solution containing the trivalent chromium deteriorates along with its limits, it is now possible to define the color of chemical conversion treatment film that serves as an undercoat of painting. Simultaneously, frequent changes of treatment solution requiring stopping of production equipment are no longer necessary, thus contributing to an enhancement of production efficiency.
- (3) The elimination of concealing treatment on the chemically-produced coating using the trivalent chromium contributes to the enhancement of adhesion and corrosion resistance. Also, the specifying of environmental conditions before the painting permits prevention of early corrosion of the chemically-produced undercoat using the trivalent chromium.
- (4) The addition of the friction modifier dispersible in the black paint permits a paint film having a required friction coefficient.
- (5) The clarification of the factors that affect paint film thickness in the dip coating helps to ensure consistent film thickness regardless of season.
- (6) The exclusion of recoat from the preconditions allows setting of paint baking conditions applicable to surfaces subjected to brake fluids.

The newly-developed surface treatment ensures blackness that can satisfy the requirements from motorcycles without using the environmentally hazardous material, and allows application of high-quality black bolts to motorcycles.

Note that the newly-developed surface treatment is referred to as HyD-Coat (BLK), which is a made word from Hybrid to mean the use of two kinds of material, Dual to mean the realization of appearance by two layers, Coat to mean a surface treatment, and BLK to mean a black color.

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Development of Direct Three-dimensional Shape Forming Technology of CF RTP by Film Stacking Method

Yoshihide YUZA*

ABSTRACT

Carbon fiber reinforced plastics greatly contribute to weight reduction of vehicles, but their application has been limited due to high manufacturing cost together with the cost of materials. In order to make this material widely available to motorcycles, we developed a technology that makes it possible to manufacture the parts at low cost by using carbon fiber reinforced thermoplastic as a material. For the molding, a manufacturing method was developed to directly form a three-dimensional shape without using prepregs while adopting a film stacking method in which a stack of thermoplastic resin films and carbon fiber woven fabrics is formed by hot pressing. When this manufacturing method was applied, issues on the exterior appearances of the part were revealed. We successfully solved the issues by devising the temperature settings and shapes of the molds and realized a product without irregularities of fibers while maintaining the required strength. The developed manufacturing method was applied to the parts of the CRF 450 Rally and the practicality of the method was proved.

1. Introduction

Carbon fiber reinforced plastics (CFRP), whose utilization is rapidly expanding in recent years, is a very lightweight and excellent strength material. Therefore, in the field of aerospace, it is used as a structural material replacing metals.

In addition, CFRP has also been demonstrating its features in racing vehicles of automobiles and motorcycles⁽¹⁾. CFRP, from its unique appearance, is a symbol of the superior performances of racing vehicles. Furthermore, it is anticipated that its use will be expanded aiming at weight reduction of the vehicle and the fuel economy enhancement by that⁽²⁾.

However, application of CFRP to mass-produced vehicles has been regarded as hard to achieve due to the high manufacturing cost beyond the price of the material.

The reasons for this includes that molding takes a long time, special equipment is required, and requirements for the storage conditions of materials are severe. In addition, the hurdles against recycling thermosetting resin, which is used as a base material, is also one other factor that makes the material not suitable for mass production.

To solve these problems, we have worked on the development of the technology that enables molding of

Carbon Fiber Reinforced Thermo-Plastic (CF RTP), in which thermoplastic resin is used as base material.

Furthermore, we intended to establish a manufacturing process to directly form deep and complicated three-dimensional shapes using the film stacking method, which is usually used for the forming of two dimensional shapes such as flat plates.

2. Examinations on Production Method and Base Matrix Materials

2.1. Examination on Production Methods

2.1.1. Conventional manufacturing method and associated issues with that

To begin with, we started with the examinations on manufacturing methods. CF RTP can be roughly categorized into two types depending on the length of carbon fibers and the continuous length without break when they are applied. One is a manufacturing method using continuous long fibers such as a woven fabric and the other is a manufacturing method using short discontinuous fibers made by cutting the fibers to a certain length.

The motorcycle part chosen as the subject of our investigation this time is a part that requires structural functionality and, in most of the cases, a superior exterior

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appearance as well. Therefore, in addition to its lightness and strength, the fine appearance featured by the weaves of carbon fibers is regarded as one of the important appealing factors. Therefore, a manufacturing method using a continuous fiber woven fabric having a fabric pattern was examined.

For CFRTP using a continuous fiber woven fabric, a method of press molding a thermoplastic prepreg is widely known. The outline of this production method is shown in Fig. 1. A thermoplastic prepreg, also called a stampable sheet, is a plate-like intermediate material impregnated, in advance, with a thermoplastic resin between multilayered fiber fabric sheets. The prepreg is heated, for example, by infrared heater to soften the resin impregnated in the fiber fabric, and press molding is performed. This method is a manufacturing method aiming at shortening the manufacturing cycle by separating the manufacturing process of the prepreg, in which a resin is impregnated in the fiber fabrics, and the molding process to form the final shape of the product.

There are several methods for producing thermoplastic prepreps, one of which is the film stacking method. The film stacking method is a method of impregnating fibers with a resin by superimposing film-like thermoplastic resin layers and fiber fabric layers in turn and pressing while heating.

The prepreg, in which the multilayered fiber fabric sheets are formed into the shape of a plate, is considerably hard, and the fiber fabric layers regulate the movement of each other. For this reason, the shape-imparting property is bad and it is not suitable for molding parts having complicated shapes often used for motorcycles. In addition, in order to make the surface of the product smooth, the fluidity of the resin must be increased. Therefore, it is necessary to heat the molds.

2.1.2. Direct molding of three-dimensional parts by film stacking method

In order to get better the shape-imparting property, it is desirable that each fiber layer freely moves independently. Therefore, our attention was paid to the material state

during the film stacking method is being applied.

As previously mentioned, in the film stacking method, each layer is independent because the material is in the state just simply laminated of resin layers and fiber fabric layers. In this state, even though a complicated shape with depth is to be molded, it is thought that the fiber fabric layers can be adequately shaped following the shape of the mold.

In addition, since it is unnecessary to prepare a prepreg, it is considered advantageous in terms of cost and thermal deterioration of the resin. Based on the above, we decided to pursue a method of forming a three-dimensional shape directly from the state of raw material being used in the film stacking method. Fig. 2 shows the outline of the process of the manufacturing method that was worked on this time.

First, in the same manner as in the ordinary film stacking method, a plurality of thermoplastic resin films and carbon fiber fabrics are laminated alternately.

Then, the laminated material is set on a heated mold and press molding is performed.

After applying pressure for a predetermined period of time, the mold is cooled, and when the shape is fixed, the product is taken out and molding is completed.

We named this forming process as the “Direct Film Stacking Method” on which we put the meaning that, in this manufacturing method, a three-dimensional shape can be directly formed.

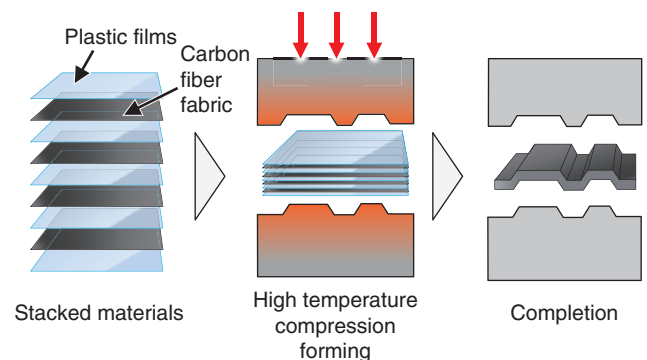


Fig. 2 Process of film stacking direct forming

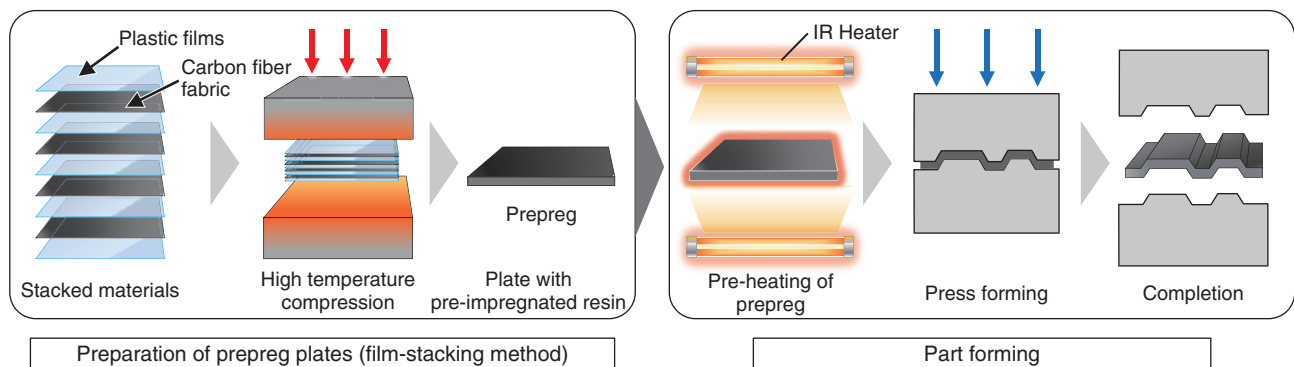


Fig. 1 Part forming using thermoplastic prepreg

Table 1 Comparison of base resins

	PMMA (Polymethyl methacrylate)	PC (Poly- carbonate)	PA6 (Polyamide 6)	PS (Polystyrene)	ABS (Acrylonitrile butadiene styrene)	PVC (Polyvinyl chloride)
Melting point (°C)	180	230	230	215	230	150
Heat deflection temperature (°C)	68	129	67	80	87	54
Flexural strength (MPa)	73	91	127	89	78	64
Tensile strength (MPa)	48	78	78	38	43	42
Stretch at break (%)	2	40	25	5	10	2

Numbers shown in the table are typical ones.

2.2. Selection of Base Matrix Resin

In the direct film stacking method, it is necessary for the thermoplastic resin serving as the base matrix material to take a film form.

For the selection of thermoplastic used as the matrix material, potential options of the material, which are generally available in the form of films, are shown in Table 1.

When applying a material to a vehicle part, it is better to have high physical properties in flexural strength, tensile strength and heat distortion temperature, etc. For elongation, that is, tensile elongation at break, about 5% is required. Therefore, polymethyl methacrylate (PMMA) and polyvinyl chloride (PVC) do not satisfy the requirements.

Furthermore, in addition to the physical properties shown in the table, weathering resistance and flame retardancy must also be considered.

In addition, as mentioned in Section 2.1.1, along with these physical properties, quality of appearance is very important. In order to show the texture of carbon fiber fabric, high transparency is required for the resin used as the base matrix material.

Based on the above considerations, polycarbonate was chosen as the base material. Polycarbonate has the maximum tensile strength of 78 MPa, as shown in the table, and the flexural strength is also the second highest after polyamide. Moreover, among the thermoplastic resins, the transparency is the highest next to polymethyl methacrylate. Furthermore, this material was selected because of one more advantage, which is the wide availability of the raw material in the form of thin films. This is another key condition for establishing a manufacturing method this time.

3. Molding Conditions

3.1. Verification of Molding Conditions using Flat Plate Shape Sample

In verifications of the molding conditions, the most important thing is the degree of resin impregnation. It can be said that the value of the flexural strength is higher when the resin is well impregnated into the fiber fabric. Accordingly, test pieces having a flat plate shape were

prepared and the applied load and the amounts of caused displacements were measured by the three-point flexure test, based on the test conditions defined in JIS K 7074, and the flexural strengths were calculated.

For carbon fiber woven fabric, CO6347B (T300B 3K, twill weave) manufactured by Toray Industries, Inc. is used, and four layers of this fiber fabric and five resin films are alternately laminated. A general pseudo-isotropic lamination of, from the top, 45°, 0/90°, -0/90°, and -45° was applied as the fiber directions. The laminated material is subjected to hot press molding with heated molds, and the degree of impregnation of the resin to the fiber fabrics is confirmed.

Three factors of temperature, pressure, and time are involved in impregnating the resin into the fiber fabrics, but in this paper, the measurement results are presented, specifically, for the molding temperature which affects the resin impregnation the most.

Fig. 3 shows the relationship between the temperature of the mold during molding and the flexural strength of the test piece serving as an index of resin impregnation. As the measurement conditions, the molding pressure was 3.6 MPa and the pressure holding time was 4 minutes.

Polycarbonate is an amorphous thermoplastic resin that does not have a clear melting point, but it is generally considered that its melting point is around 230°C. As the temperature rises above the melting point, the viscosity of the molten resin decreases.

From Fig. 3, it can be seen that the flexural strength is almost proportional to the temperature from 220°C to 280°C. It can be said that, as the molding temperature rises, the viscosity of the resin decreases and impregnation into the fiber fabrics gets better. In addition, it can be seen that there is a difference of two times or more in the flexural strength at the molding temperature of 220°C and 280°C, and that, at the low temperature, impregnation of the resin into the fibers is insufficient.

When observing the cross section of the test piece at this time, it is understood that the test piece formed at 280°C

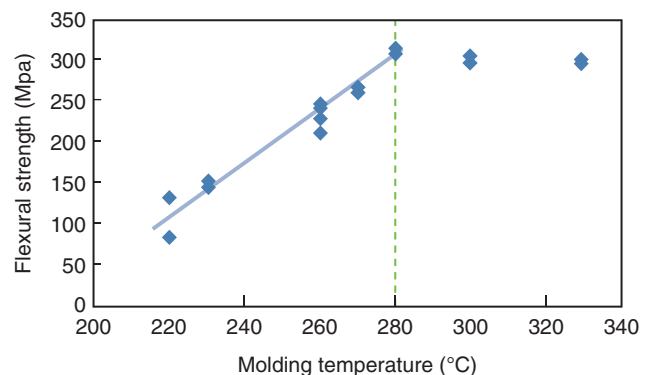


Fig. 3 Relationship between flexural strength and molding temperature

(Fig. 4) is impregnated with the resin deeply into the fiber fabric. In addition, the test piece (Fig. 5) molded at 230°C shows that the resin exists only on the surface of the fiber layer and is not impregnated therein, being left as empty spaces as a result. This is because the temperature of the resin is low and the viscosity is high, making the resin impossible to sufficiently impregnate.

Moreover, the flexural strength shows its peak value at 280°C and, thereafter, gradually decreases with increase of the molding temperature. Regarding the reason for showing this tendency, it is conceivable that the polycarbonate itself is deteriorated due to the heat during molding.

Based on the results shown above, the molding temperature was set at 280°C at which the resin can be sufficiently impregnated into the fiber fabric and the flexural strength becomes maximum.

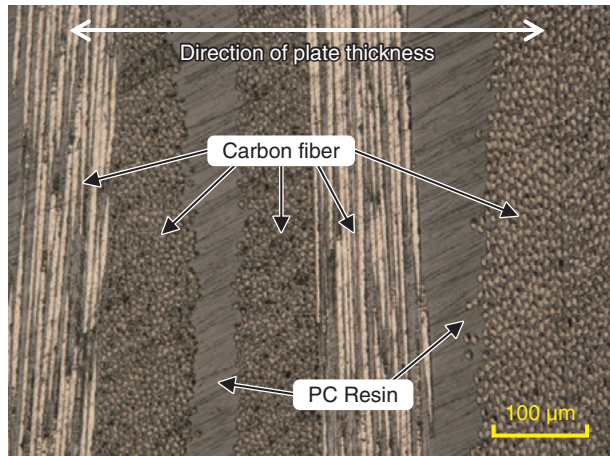


Fig. 4 Cross-sectional view of test piece with good impregnation condition of resin (TP processed at 280°C)

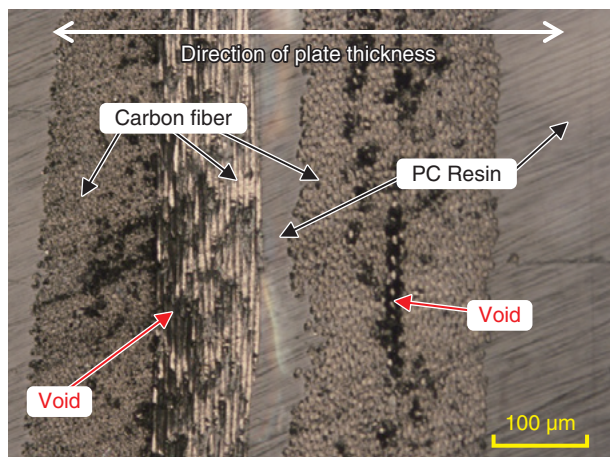


Fig. 5 Cross-sectional view of test piece with poor impregnation condition of resin (TP processed at 230°C)

4. Molding of Three-dimensional Shape

4.1. Three-dimensional Shape Forming

The part to be molded was the rear fender of the CRF 450 Rally, which is one of the motorcycles we produced. In the previous year's model of this vehicle, this part was manufactured using autoclave molding, and it is with the vertical and horizontal dimensions of 600 mm × 200 mm and the depth of about 120 mm. The part has almost vertical walls on the sides, and it also has complexly protruded or dented sections in the front part.

Based on the molding conditions obtained in the tests using test pieces, an actual molding was conducted and a satisfactory molded state was obtained for the horizontally-flat shape portion of the part. However, there were some flawed locations in almost vertical wall sections and in the sections with complicatedly placed protrusions and dents.

4.2. Defects due to Fiber Rupture and Exposure

Among the defects occurred in the molded part of the rear fender, the largest ones were ruptures of the fibers generated in the vertical wall portions on both sides.

Fig. 6 shows the state of the left side of the part. It was confirmed that the fibers in the surface layer were ruptured and the fibers inside were exposed, in the portion indicated by the yellow broken line in the figure. In addition, in the part indicated by the red broken line, it is seen that there are areas where the fiber is broken up throughout the entire layers, exposing the portions composed of only resin. In such a condition, generally anticipated strength as a composite material cannot be exhibited.

Furthermore, in the portion with protrusions and dents complicatedly situated as shown in Fig. 7, it can be seen where there is no surface resin, and the fibers are directly exposed.

In order to know in which step of the molding process the molding defects arises, the behaviors of the base material, when it is under the process of the closure of

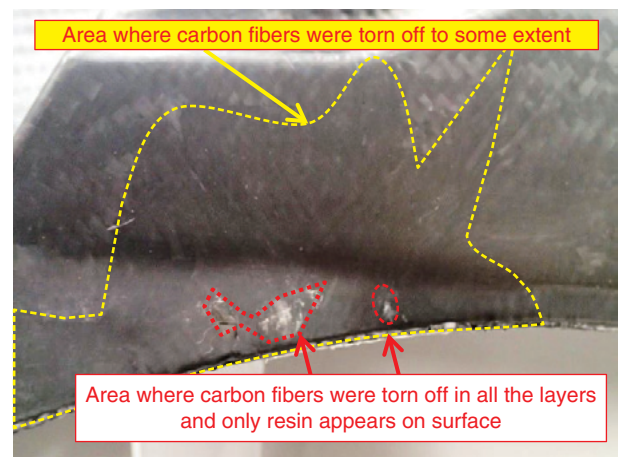


Fig. 6 Breaks of fibers appear on vertical wall section

the upper and the lower molds, were investigated. In this examination, the mold having protrusion is placed lower and the mold having dent is placed on the top. The observation was carried out by stopping the operation of the molds at the desired timing and by cooling down the mold thereafter.

Based on the results of the observation, the process shown below was estimated.

When the upper mold descends after the material is introduced, the resin film begins to melt from the part that touched the upper mold. In the flat part nearly horizontal, since the upper mold descends while contacting in the shape of roughly flat surface, the resin is impregnated into the fiber fabric and molding is performed fitting the mold shape.

On the other hand, in a portion where the inclination of the die wall is close to vertical, the clearance between the upper and lower dies becomes smaller than the thickness of the material at the earlier part of the molding process, and the corner portion of the upper mold touches the material first. As a result, the resin layer of the material surface is pierced by the corner of the die, and, it is considered that, the resin layer does not exist on the surface layer as shown in Fig. 7.

Furthermore, when molding a deep shape as shown in Fig. 6, the movement of the die continues even after the contact of the corner portion of the upper die, as described above, and the upper die further moves downward. Meanwhile, the molten resin has a high viscosity, and acts like an adhesive between the fiber fabrics, and between the fiber fabric and the die surface. Therefore, the fibers are stuck to the mold and torn as the die moves.

These processes are schematically shown in Fig. 8.

The cause of the molding defect is that the resin is melted before the composite layer, which is the raw material, is sufficiently fitted to the shape of the die. Unless the mold temperature is high, the resin film will not be melted to be ruptured. Furthermore, it can be said that the

fibers will not be torn unless the resin melts and sticks to the die.

Accordingly, in order to prevent the resin from melting and tear off before shaping, preliminary shaping with low temperature dies was also examined. However, the material before molding is about twice as thick as the clearance when the mold is closed. Therefore, it is almost impossible to press the material without applying any additional measures. Furthermore, scratches and press marks of fibers are left on the die surface.

By applying preliminary shaping using a plurality of dies, it is possible to realize a method capable of alleviating the above-described defects. However, in this development, we aimed at establishing a method that satisfies both conditions of shaping and resin impregnation with only one set of dies without using multiple dies.

In order to mold with a set of dies, it is necessary to impregnate the resin in one molding process and reduce the thickness of the material. In addition, in order to exhibit the strength as a composite material, it is necessary to realize a material state in which the resin is melted with the die heated to a high temperature and sufficiently impregnated into the fiber fabrics.

Although it is inadequate for the shaping process to set the mold temperature to high temperature, rising temperature is necessary for resin impregnation, and a method to satisfy these requirements simultaneously was investigated.

4.3. Enhancement of External Appearance by Differentiating Die Temperatures

We thought that we would be able to divide the two different processes of part shaping and resin impregnation and assign them individually to the upper and the lower dies.

Specifically, we examined a method of making a difference in temperature between the upper and the lower dies.

The temperature of the upper die is set to be equal to or more than the glass transition point of the resin, and less than the melting point.

By doing this, the resin film can be softened without

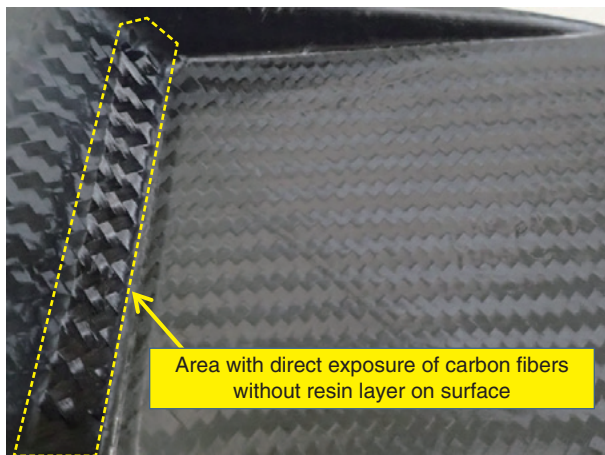


Fig. 7 Area on surface with direct fiber exposure

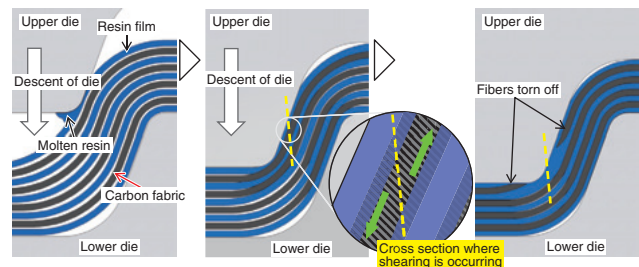


Fig. 8 Schematic views of cross sections of die, which show phenomena occurring while upper die is descending

melting and the base material can be shaped.

On the other hand, the temperature of the lower die is set to be equal to or higher than the melting point of the resin so that the resin film can be melted.

In the case in which those temperatures are set and molding is conducted, the movement of the die and those of layers of resin and fiber fabric can be described schematically as shown in Fig. 9.

The upper die descends while sliding on the surface layer of the resin film without melting it, and presses the material against the lower mold. The material pressed against the die melts from the side that has touched the lower die and is shaped along the die. Since the upper die descends while sliding on the surface of the material, the fibers are less prone to be torn. When the mold is closed, in the material, the resin is impregnated into the fiber fabrics with the heat delivered from the lower die.

The part molded by this method is shown in Fig. 10. No fiber breakage or disorder of weaving is observed in the appearance. Furthermore, it can be evaluated that the direction of the weave is uniform along the part surface shape and that it has an appearance close to that of the one in which the fiber fabrics are manually arranged.

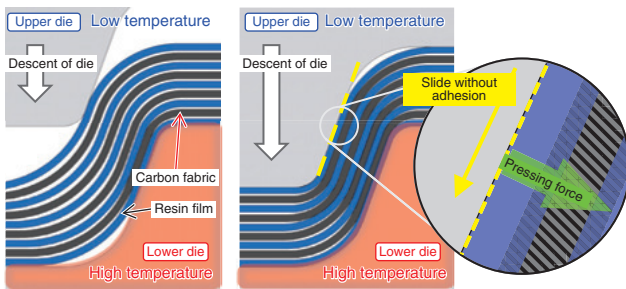


Fig. 9 Phenomena assumed to be happening between upper and lower molds while processing by developed method



Fig. 10 Appearance of vertical wall side surface when processed with developed method

From these results, it was verified that, by setting the upper die to a lower temperature at which the damage of the resin film can be suppressed, and setting the lower mold to a higher temperature at which sufficient resin impregnation to the fiber fabric is obtained, it is possible to eliminate the fiber breakages appearing on the vertical walls and improve the appearance of the product.

4.4. Investigation on Internal State of Material and Enhancement of Quality

To investigate the internal quality of the product molded by the method described in Section 4.3, the cross section was observed by cutting it in the same manner as the flat test plates. Figure 11 shows the cross section of the flat portion of the top surface of the part, and the cross section of the vertical wall portion is shown in Fig. 12.

As shown in Fig. 12, in the part, the resin penetrates deep into the fiber bundles. However, there are sections

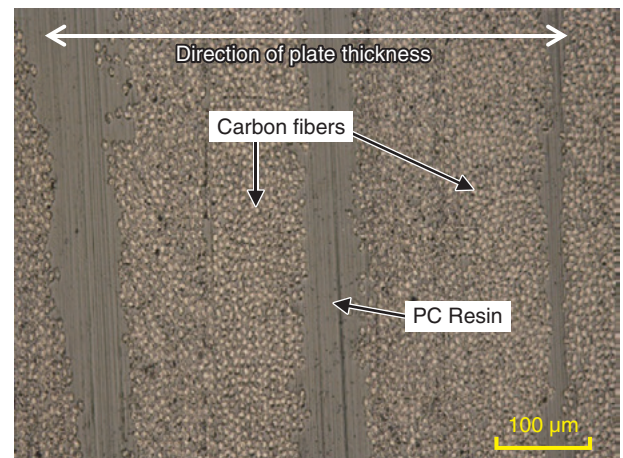


Fig. 11 Cross section of test piece at top flat part of product

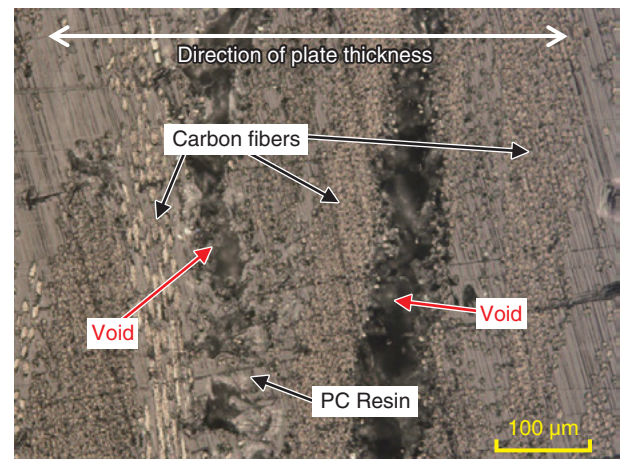


Fig. 12 Cross section of test piece at vertical wall part of product

where large voids are present in the fiber bundles.

It is considered that this was because the temperature of the resin was adequately high and the viscosity was low enough to sufficiently impregnate into the fiber fabric, but, despite of that, the process was stopped halfway.

Another possibility is that the impregnation of the resin had been distributed throughout the fiber bundles, but the material was in the state in which voids had occurred due to the volume reduction of the resin.

4.5. Quality Enhancement of Inner Part of Vertical Walls

Impregnation is a process of injecting the molten resin flows deep into the fiber bundles. In this manufacturing method, a force effective to make the resin flow is generated by the force in the vertical direction applied by the pressing machine. For this reason, to a horizontally flat plane, almost 100% of the force is applied, whereas only a component of the force with corresponding angle is applied to an inclined plane.

A method to take measures against this situation is conceivable in which the molding pressure is set extremely high anticipating the pressure drop due to the high inclination angle. However, even if such a method is schemed, it is not realistic to raise the molding pressure as sufficient as an enough force is generated to be applied to the wall portions substantially vertical.

There are also methods to resolve the issue by using partial dies⁽³⁾.

However, this technique involves an increase in processing time and cost, as compared with the case using a single set of dies, since the number of divisions of the die increases. In addition, when applying this method, there is a possible concern that molten resin enters the gap generated between the divided molds.

Here, we will reconsider the mechanism of causing insufficient impregnation of resin into fiber fabrics. In this method, trimmed portions, which are eventually not used as a finished part, are held in the areas outside the cavity. Therefore, it is impossible to make the space inside the cavity completely closed. In addition, the portions shown in Fig. 12 are located in the vertical wall part, particularly in the areas close to the trim line, in the whole shape of the product.

Therefore, we believed that impregnation into fibers can be promoted if the outflow of resin can be suppressed, and a scheme to narrow the clearance in the vicinity of the vertical wall portion trim line was studied. Specifically, the clearance between the upper and lower dies was narrowed down to the value obtained by summing up the thicknesses of the fiber fabric layers, and, when the upper die is descending, making it suppress the outflow of the resin during the die closure is in process (Fig. 13).

In order to confirm the effect of the scheme, shown in Fig. 13, and the pressure on the other surfaces, a pair of test dies having flat surfaces of different angles was produced. The test die was designed to include a total of five planes

having angles of 30°, 45°, 60°, 88.55° with respect to the horizontal direction, and the scheme shown in Fig. 13 was applied to the portions on the die corresponding to the plane of 88.55°. It is to be noted that, for the plane of 88.55°, the draft angle of 1.45° is secured with respect to 90°. The test part molded by this die had a shape as shown in Fig. 14. The sections shown in red were set so that the dies close completely, and the sections shown in green were set to be left not fully closed. The shape of each plane is rectangular, and it is 220 mm in length and 35 mm in width so that two specimens (100 mm × 30 mm) for flexure test could be cut out. A pressure sensor was placed in the center of each plane perpendicularly to the plane, and pressure changes in the cavity during molding at each plane were measured with the elapsed time. The purpose of the pressure measurement was to compare the pressure of the vertical wall plane with those of the other planes. Therefore, in addition to the vertical wall portion, the pressure at the horizontal plane

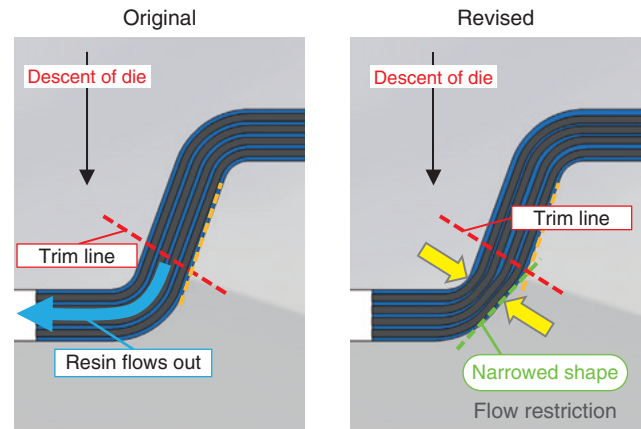


Fig. 13 Revised configuration of die with narrowed shape at resin outlet

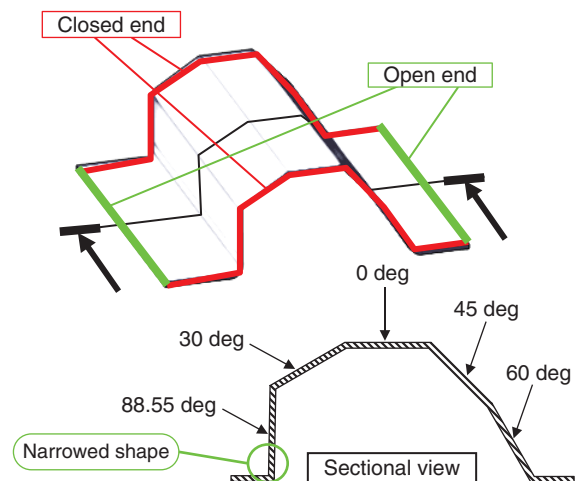


Fig. 14 Cross section of test piece for verification test of developed method

and the pressure at the 45° plane, which has middle angle thereof, was also measured.

Moreover, we also produced dies that do not apply the scheme of Fig. 13 to the plane of 88.55° and verified the effect of the scheme.

The conditions of temperature and pressure are the same as those described in the previous chapter. The changes in the measured pressure to the elapsed time are shown below. Fig. 15 shows the case where this scheme is not applied, and Fig. 16 shows the applied one.

Here, pressure is not detected for about the first 15 seconds because the substance inside is not in contact with the pressure sensor. Immediately thereafter, the sensor comes into contact with the resin which has not yet melted and detects a large pressure. The contacted resin melts according to the temperature of the mold and the pressure rapidly drops. Therefore, the evaluation of the in-cavity pressure was made for the period on and after around 20 seconds in the graph.

First, look at the diagram before applying the scheme (Fig. 15). Regarding the horizontal plane of 0°, with descending of the die, the pressure rises while showing a parabolic graph shape. Regarding the pressure on the

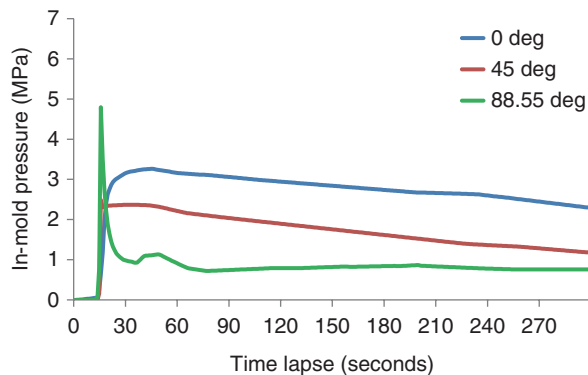


Fig. 15 Pressures in cavity to elapsed time without developed method

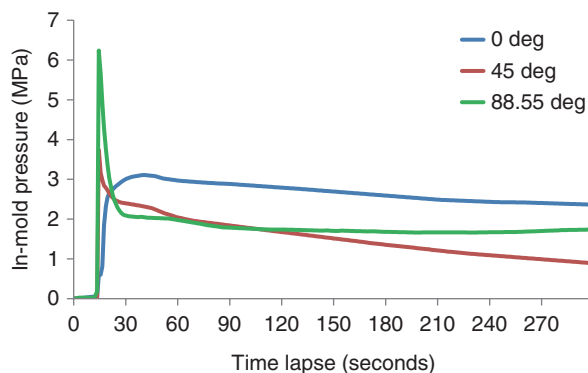


Fig. 16 Pressures in cavity to elapsed time with developed method

plane with the angle of 45°, it is changing at the value corresponding to a component of the force applied to the horizontal plane.

As can be seen in Fig. 15, the pressure in the vertical wall section is only about 1 MPa, after the pressure is stabilized. On the other hand, looking at Fig. 16 that shows the case in which a method was implemented to narrow the outlet of the resin, the pressure of the vertical wall section reaches 2 MPa at around the elapsed time of 30 seconds and that value is maintained thereafter. After about 100 seconds has elapsed, it is found that the pressure is higher than that on the 45° plane. It is considered that, on the 45° plane, the pressure gradually decreases as the outflow of resin progresses.

Further, specimens were cut out from the horizontal plane and the vertical plane of the molded part with the developed method, and flexure tests were carried following the same manner as shown in Section 3.1. The measurement result and section view of each specimen are shown in Fig. 17.

When comparing the flexural strengths of 0°, i.e. horizontal, and 88.55° planes, the difference is as small as 6 to 8 MPa. Moreover, from the state observed in the cross section, it was found that no void, as had been seen in Fig. 12, had occurred. As can be seen from the above results, by narrowing the clearance between the dies in the vicinity of the trim portion and suppressing outflow of the resin to maintain the pressure, impregnation of the resin is promoted, and the internal quality free of voids was able to be secured.

By applying this method in conjunction with the molding method that sets the temperature difference in the upper and lower molds described in Section 4.3, it was possible to realize excellent appearance together with good internal quality of the vertical wall part.

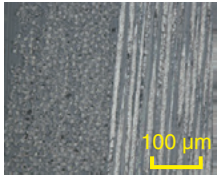
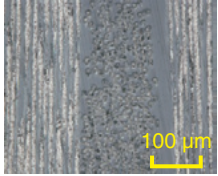
Plane angle (degree)	Number	Flexural strength (MPa)	Cross section
0	#1	313.60	
	#2	304.16	
88.55	#1	305.62	
	#2	298.17	

Fig. 17 Test results and cross sections of test pieces sampled from horizontal and nearly vertical walls

5. Application of the Developed Molding Method to Actual Vehicle Parts

Using this technology, the rear fender (Fig. 19) and the cover of electrical unit installed in the CRF 450 Rally (Fig. 18), which participated in the Dakar Rally in South America in 2016, were made. These parts demonstrated that they were fulfilling the performance and the durability required in the harsh rally of Dakar. These results proofed that the parts manufactured by the developed molding method are compatible even under the applied condition to actual vehicles.



Fig. 18 The CRF450 Rally



Fig. 19 Rear fender of the CRF450 made of CFRTP

6. Conclusions

We studied the molding method of carbon fiber reinforced plastic which can be applied to mass-produced motorcycles. As a result, direct film stacking method, which directly molds without using a prepreg, was established, and the following findings were obtained in the development process.

- (1) By molding having different settings in temperature between the upper and lower dies, it was made possible to shape the base matrix material along the die without breaking either fibers or resin, and, as a result, an excellent appearance was realized.
- (2) In order to increase the impregnation of the resin in the vertical wall, a mold structure with narrowed clearance between the molds of the resin outflow portion was applied. As a consequence, sufficient resin impregnation was realized also on the vertical plane, and the internal quality was enhanced as well.

It is expected that this technology will be widely applied to mass-produced motorcycles in the future. In addition, this method can be widely applied to parts other than of motorcycle, and the future possible deployment will be highly anticipated.

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■ Author ■



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Establishment and Experimental Demonstration of Distant Speech Recognition System for Communication Robot

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Naoaki SUMIDA**

Kazuhiro NAKADAI**

ABSTRACT

Distant speech recognition technology for a robot was implemented to communicate with humans at a natural distance. There were two issues to address. First, surrounding reverberation and noise act to reduce recognition performance. In an attempt to resolve this, dereverberation and sound source identification technology were introduced in addition to the existing developed technology. Second, speech frequency response characteristics and wording differ from person to person. To enhance recognition performance, a deep neural network was used in the acoustic model, in addition to class-based N-grams accounting for the properties of speech recognition tasks in the language model. These technologies were then integrated into a robot system to perform a themed experimental demonstration taking reception calls.

The demonstration achieved a reception success rate of 98.3% and, through analysis of the causes of erroneous speech recognition, clarified further issues to address for improving performance.

1. Introduction

Communication is a skill that robots require to coexist with humans and provide them services, and speech is the mode of communication most frequently used in daily interaction, as well as the most natural and direct^{(1), (2)}. As such, verbal communication using speech recognition will be the focus of this paper.

In terms of speech recognition, voice input interfaces based on use of close-talk microphones are now offered in practical applications, such as information retrieval on smartphones, and are gaining public acceptance⁽³⁾. Speech recognition is also a vital function with great application potential for robots required to communicate with humans⁽¹⁾.

However, verbal dialogue between humans and robots at a natural distance will require distant speech recognition, the ability to recognize speech from a distance with the microphone equipped on the robot. One issue to address with distant speech recognition is that noise and reverberations drop the signal-to-noise ratio much more than when using close-talk microphones, greatly reducing speech recognition performance^{(3), (4)}. Noise as addressed

in this paper will refer to all sounds other than the target speaker's voice. As noises by this definition are input when using speech recognition in everyday settings, responding correctly requires the system to distinguish between the target speaker's voice and all other sounds⁽⁵⁾. This issue is particularly important with distant speech recognition, given the high frequency of input from noises and sounds other than the target speaker's voice. In addition, distant speech recognition must address the general issues facing speech recognition: handling individual differences in terms of voice type and wording⁽³⁾.

The individual core technologies of distant speech recognition have been the subject of numerous research studies. There is also the CHiME Challenge, a contest for distant speech recognition using common benchmarks⁽⁶⁾. This contest focuses on handling noise and reverberation, the issues to address for distant speech recognition.

Meanwhile, using ASIMO⁽⁷⁾, our humanoid robot, we at Honda have taken on an application for voice interaction with humans as a theme, aiming to achieve a practical level of distant speech recognition technology. Achieving distant speech recognition with a robot requires not only resolving the various issues facing distant speech recognition, but

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also integrating the underlying core technologies into robot systems.

Furthermore, extended use of these systems and analysis of the data will be important in evaluating performance of the application and unearthing those issues that only occur when used in the field by actual customers. As such studies are almost nonexistent elsewhere, the data collected and results from the demonstration should contribute greatly to future research and development. This paper will consist of reports on the distant speech recognition technology implemented and the results of the experimental demonstration conducted to verify its effectiveness.

2. Research Goals

The goals of this research are to improve the performance of practical level distant speech recognition and to clarify through actual use the issues to address when using distant speech recognition in a total system.

As detailed in the previous section, the issues to achieving distant speech recognition are numerous. Of these, this paper will be an attempt to improve performance by resolving the following four issues:

- (1) Reduced performance of speech recognition due to reverberation;
- (2) Erroneous speech recognition of non-target sounds;
- (3) Reduced performance of speech recognition due to individual differences in voice type; and
- (4) Reduced performance of speech recognition due to freedom in user wording.

For (1), speech recognition performance deteriorates significantly when reverberation time exceeds the speech recognition processing time unit (25 ms for this system)⁽⁸⁾. In public facilities, one of our targets, reverberation time is expected to exceed this time. Furthermore, compared to close-talk microphones, distant microphones are more affected by reverberation. As observed direct sounds are less powerful, the reverberation component power is almost unchanged. Thus, the dereverberation method proposed by Gomez et al.⁽⁸⁾ was introduced in order to eliminate the reverberation component.

For (2), as erroneous speech recognition processing of noise degrades performance, sound source identification using a Gaussian mixture model (GMM) was introduced as a pre-processing step to speech recognition to differentiate between target speech and non-target sounds⁽⁵⁾.

For (3), the model for speech phonemes (hereinafter, the “acoustic model”) must reflect the characteristics of as many people as possible. Conventionally, the GMM-based Hidden Markov Model (GMM-HMM) has been used for this model⁽⁹⁾, but research⁽¹⁰⁾ has recently increased using deep learning, which offers the potential for more precise modeling. Therefore, in this research, a deep neural network-based Hidden Markov Model (DNN-HMM)⁽¹⁰⁾ was introduced.

For (4), consider the scenario of calling for a worker at

company reception. One person may ask the receptionist, “Mr. Nakadai, please,” while another may say, “Yamamoto here to see Mr. Sumida.” Thus, speech recognition must be able to recognize the varied wording of the user, restricting the applications in which it is used. In light of this, a class-based N-gram language model was introduced⁽¹¹⁾.

In order to make the technology practical, instead of simply evaluating the above technologies individually, we thought it important to integrate them as a robot system and confirm their effectiveness when used by actual customers. Doing so will improve performance by identifying the real issues to address and furthering technology development.

Some examples of robot system demonstrations using distant speech recognition do exist, such as airport guidance using Hitachi, Ltd.’s EMIEW3⁽¹²⁾ and the Haneda Robotics Lab guide robot⁽¹³⁾, but as of April 2017, all such demonstrations have been over shorter terms of approximately one week, and the results, including analysis, remain closed. Therefore, for approximately two months, we demonstrated with the theme of reception calls and analyzed the data in order to clarify the issues to address.

3. Achievement Methods

This section explains the individual technologies used in order to resolve the issues.

3.1. Dereverberation

3.1.1. Dereverberation based on spectral subtraction

This sub-section is a description of the new algorithm used to enable online processing for the spectral subtraction-based dereverberation approach⁽⁸⁾. This approach achieves dereverberation by treating the reverberation component of input speech as noise, and then suppressing this noise with spectral subtraction.

Reverberation components are generally handled separately for early reflections and late reverberations due to the differences in their properties. This approach estimates the late reverberation component and suppresses it through spectral subtraction. The approach only suppresses late reverberation; it does not suppress early reflection. The majority of early reflection, characterized as reflected sounds that arrive relatively quickly after direct sound arrives, falls within the window length that is processing time unit for the latter part of speech recognition. Thus, early reflection can be suppressed with feature normalization techniques, such as cepstral mean normalization (CMN) and spectral mean normalization (SMN).

Late reverberation is estimated from $X(f, t)$, a short-term Fourier transform (STFT) of the input speech, and $H_L(f)$, a transfer function of the late reverberation. Given that the time window of $X(f, t)$ overlaps with the STFT of the past D frame, the amplitude spectrum for late reverberation $\hat{X}_L(f, t)$ at frequency-bin f and time t is approximated by:

$$|\hat{X}_L(f, t)| = \left\{ \frac{1}{D+1} \sum_{d=0}^D |X(f, t-d)H_L(f)|^\gamma \right\}^{\frac{1}{\gamma}} \quad (1)$$

Here, γ is a parameter set to a value of no more than 2, meant to keep the estimate of late reverberation from growing too large. For this research, $\gamma = 1.5$. Disassembling the STFT into frames and using past frames in this fashion allows for online processing with little lag.

The power spectrum $|X_E(f, t)|^2$, which includes the direct sound and early reflection, is calculated by spectral subtraction using the estimated late reverberation as:

$$|\hat{X}_E(f, t)|^2 = \begin{cases} |X(f, t)|^2 - \delta(f) |\hat{X}_L(f, t)|^2 & (> 0) \\ \beta |X(f, t)|^2 & (\text{else}) \end{cases} \quad (2)$$

Here, the β parameter functions to keep the power spectrum from resulting in a negative value. Using the pre-measured impulse response, $\delta(f)$ is calculated by standard optimization of the minimum mean square error (MMSE) from the late reverberation component estimate $\delta(f) \hat{X}_L(f, t)$ and actual value $X_L(f, t)$.

Using phase for input $X(f, t)$, output spectrum $\hat{X}_E(f, t)$ is calculated as:

$$\hat{X}_E(f, t) = \sqrt{|\hat{X}_E(f, t)|^2} e^{j\phi_X(f, t)} \quad (3)$$

Here, $\phi_X(f, t)$ expresses the phase of $X(f, t)$.

3.1.2. Evaluation testing

In order to confirm the effect of dereverberation, word accuracy for the trained DNN-HMM acoustic model was benchmarked, comparing results with and without dereverberation applied. For more details on learning by the DNN-HMM acoustic model and training data, refer to Sub-section 3.3. For evaluation benchmark data, reception call activity was recorded using the robot at reception with a reverberation time of 1.02 seconds with the reverberation time 20 (RT20) method. A sample utterance would be: “Yamamoto of Nakadai Holdings here to see Mr. Sumida.” In total, there were 258 instances of voice activity by 26 people, with 5,629 words recorded. Evaluations are based on word accuracy. The mean for all words and results by class (name of visitor or staff, organization name of visitor, affiliation name of staff; hereinafter collectively the “required vocabulary for reception”) for each voice activity that appeared are given in Fig. 1. Between evaluations with and without dereverberation, the mean word accuracy significantly increased by 2 points, and the level of significance was 5% by binomial test⁽¹⁴⁾. Looking at word accuracy for each class shows that the effect of dereverberation is particularly high for name of visitor or staff and organization name of visitor. As with mean word accuracy, the difference is significant for these

two parameters. Of the classes, name of visitor or staff and organization name of visitor contain many words and are not easy areas for speech recognition to analyze. Presumably, this could explain the greater improvement in recognition rates with dereverberation.

3.2. Sound Source Identification

3.2.1. Sound source identification model

In sound source identification, the input speech for each speech segment is identified as target speech or non-target sound, again referring to noise and sounds other than target speech. Its purpose is to identify target speech with high recall and allow for subsequent noise to be rejected. Target speech and noise were modeled with GMM for use in identification, using 27 dimensions⁽¹⁵⁾ for mel-scale log spectrum (MSLS) features extracted from the input speech. With margins at the start and end of the input speech segment to prevent any speech from being missed, the start and end of segments are unnecessary for sound source identification. Thus, as the power is lower at the start and end of segments than in the target portion, only features for times greater than the average power for the input speech segment were used for sound source identification (Fig. 2).

Next is the GMM model for target speech and non-target sounds. Expressing input features for time t as x_t , the class m (target or non-target) probability density function $p_m(x_t)$ can be expressed as:

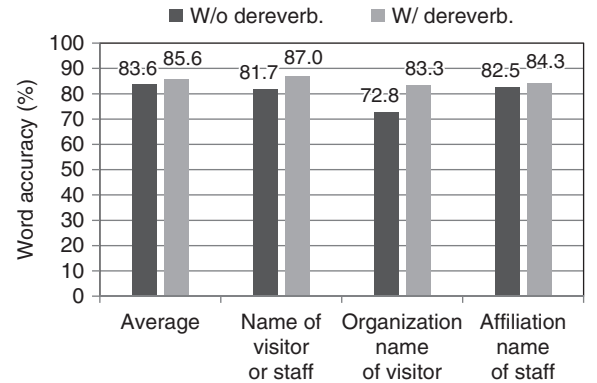


Fig. 1 Advance of word accuracy by using dereverberation

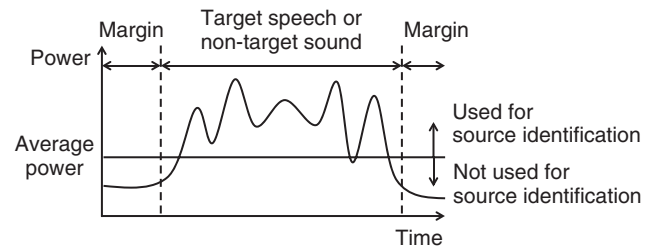


Fig. 2 Frames used for source identification

$$p_m(x_t) = \sum_{k=1}^K \lambda_{mk} N(x_t; \mu_{mk}, \sigma_{mk}^2) \quad (4)$$

In this probability density function, K is the number of mixtures, λ_{mk} is the mixture weight, and $N(x; \mu, \sigma^2)$ is the normal distribution of mean μ and dispersion σ^2 . Parameters λ_{mk} , μ_{mk} , and σ_{mk}^2 are estimated by EM algorithm with the training data.

During sound source identification, a vote is cast for class m with the highest likelihood for each time, using likelihood $p_m(x_t)$ for times of powers greater than average power P_{avg} in the input speech. The overall tally is normalized to arrive at a score, with highest scoring class m identified as the sound source for that voice activity segment. Score S_m is calculated as:

$$S_m = \frac{1}{|T_p|} \sum_{t \in T_p} Presence_m(x_t) \quad (5)$$

$$Presence_m(x_t) = \begin{cases} 1, & m = \operatorname{argmax}_i p_i(x_t) \\ 0, & \text{otherwise} \end{cases} \quad (6)$$

Where $P(t)$ expresses the power of input speech at time t , it is defined as $T_p = \{t | P(t) > P_{avg}\}$, expressing the collection of times of powers greater than the average power for input speech.

3.2.2. Training data

For the training data for the target speech and non-target sound GMMs, the speech spoken by subjects to the robot and surrounding noise in the reception call usage environment were put through sound source localization, voice activity detection, and sound source separation. Training datasets for each class consisted of target speech from 104 speakers, with 26,164 voice activity segments and 1,577 non-target sounds. Correct labels were assigned to target speech and non-target sounds for each sound separated from the sound source.

3.2.3. Evaluation testing

In evaluation testing for the sound source identification approach of the system, two evaluation sets were used for the recorded speech as spoken by subjects to the robot in the reception call usage environment. The first set was the aforementioned evaluation benchmark data for reception calls with 26 speakers. The second set was the actual data from customers who used the system in the reception call demonstration to be detailed below. Breakdowns of the target speech and non-target sounds for each evaluation set are given in Table 1.

Performance for sound source identification was evaluated as the recall and precision for voice activity units. Here recall refers to the percentage of voice activity where actual target speech (or non-target sound) is predicted as target speech (or non-target sound). Meanwhile, precision

Table 1 Evaluation set for source identification

Evaluation set	Class	Number of sounds
Benchmark	Target speech	1,006
	Non-target sound	239
Reception experiment	Target speech	829
	Non-target sound	7,978

Table 2 Evaluation results of source identification

Evaluation set	Class	Recall (%)	Precision (%)
Benchmark	Target speech	96.5	91.1
	Non-target sound	94.5	80.5
Reception experiment	Target speech	87.1	34.7
	Non-target sound	95.7	98.4

refers to the percentage of voice activity where predicted target speech (or non-target sound) is actual target speech (or non-target sound). The resulting recall and precision for sound source identification in each evaluation set are given in Table 2.

A high recall is important for target speech in reception calls, and high recall was achieved for each evaluation set. However, recall for target speech in reception call usage is lower than the benchmark. Given the many sounds detected as surrounding noise when no speaker was present, due to the demonstration being over a longer term, the recall results are attributed to the high percentage of non-target sounds in the reception call demonstration evaluation set. The high number of noises were successfully identified as non-target sound and rejected at a high recall rate of 95.7%.

3.3. Speech Recognition: Acoustic Model

The approach applied for distant speech recognition in the robot hardware was DNN-HMM, an approach based on DNN reported to dramatically improve speech recognition rates. The following issues arise in DNN-HMM application of distant speech recognition for robot hardware:

- (1) Requires large training dataset; and
- (2) Mismatching between input speech and acoustic model.

Given that deep learning generally requires large training datasets, DNN-HMM applications for distant speech recognition in robots will also presumably require a large training dataset. Conventionally, we use a corpus with 82 hours of read-out speech to train the acoustic model with GMM-HMM. In application of the DNN-HMM, however, we collected a corpus of 904 hours of speech for use in training.

Also, in distant speech recognition using a robot-mounted microphone array, the signal-to-noise ratio of the input speech is decreased by surrounding noise, noise from the robot, and reverberation. Even pre-processing such as noise reduction and dereverberation is unable to

eliminate all noise and reverberation from the input speech. Further, mismatches in the input speech and acoustic model also reduce the rate of speech recognition. Ideally, the acoustic model and input speech will be matched by recording speech using the robot's microphone array in the environment where speech recognition will be used (hereinafter, "actual machine recording"). Preparing the large training dataset in this fashion is no simple task, however. Therefore, in addition to actual machine recording speech, we also used for training data speech simulating input speech during speech recognition usage by using pre-measured impulse response and robot noise, then synthesizing from clean speech and processing with sound source separation and dereverberation (hereinafter, "synthesized speech").

3.3.1. Deep neural network acoustic model

For training and decoding the DNN-HMM acoustic model, the open source software speech recognition toolkit Kaldi⁽¹⁶⁾ was used. The input features were made 297 dimensional, joining the 27-dimension MSLS feature with the 5 frames before and after it. For output, a fully connected DNN with 6 hidden layers of 2,048 units was used to set output as each of the triphone HMM states. State-level minimum Bayes risk was used for the DNN training criteria.

3.3.2. Performance verification through training data volume

In order to confirm performance of the acoustic model created in this research, word accuracy was compared whenever the training data increased. As shown in Table 3, 904 total hours of training data was used. Here "reception speech corpus" and "reception speech corpus recorded with ASIMO" are speech corpora collected for expected reception call tasks. The reception speech corpus comprises task voice activity recorded from expected reception call task scenarios read aloud and using the Wizard of Oz method. In recording task voice activity, speech close to that during system usage can be recorded by giving the speaker a task but leaving wording up to the speaker to recreate conversations between speaker and system. The reception speech corpus recorded with ASIMO is actual machine recordings of expected reception call task scenarios read aloud. For evaluation, the aforementioned evaluation benchmark data was used to evaluate word accuracy of 5,629 words in total. Word accuracy for the training datasets is given in Fig. 3.

A word accuracy of 88.9% was achieved for the 904 hours of training data, representing a vast improvement in performance. For comparison, word accuracy was 29.2% for the evaluation benchmark data when evaluated with the conventional GMM-HMM acoustic model.

3.4. Speech Recognition: Language Model

Language model requirements to be met for the

Table 3 Training data of our acoustic model

Speech corpus	Style	Speech	Hours
Commercially available speech corpus	Reading	Synthesized	329
Reception speech corpus	Reading and spontaneous speech	Synthesized	453
Reception speech corpus recorded with ASIMO	Reading	Recorded with ASIMO	122
Total			904

reception calls were set as follows:

- (1) Allow speakers to speak freely;
- (2) Completely cover all names of staff and affiliation names of staff; and
- (3) Ability to register additional visitor names and organization names of visitors at any time from data collected during the demonstration.

To meet these requirements, a class-based N-gram language model was used. To allow speakers to speak freely in wording, the class-based N-gram language model was trained with a language corpus collected from variously worded reception calls. Next, names of staff, names of visitors, and other headings were grouped into classes, allowing them to be covered completely and simplifying addition of new visitor names or other headings. There are seven classes in total: name of staff, affiliated company name of staff, affiliated office name of staff, affiliated department name of staff, affiliated block name of staff, name of visitor, and organization name of visitor.

The reception call language model as created had a vocabulary of 1,586 words at the start of the demonstration. This expanded to 1,681 words by the end of the demonstration, adding new visitor names and other vocabulary.

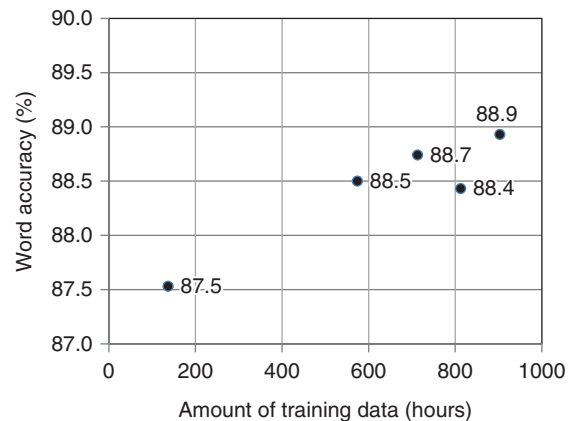


Fig. 3 Advance of word accuracy with increased training data

4. Experimental Demonstration

The technologies from the previous section were integrated with the robot, then used by regular customers and evaluated for performance.

4.1. Target Configuration

In actual performance evaluation, tasks were clearly defined, and then system usage by regular customers was evaluated. Our thinking was that having actual regular people use the system would help in determining current performance for practical use, and that analysis would further clarify the issues to address. Here the target task was set as taking calls at company reception. Customers coming to reception were made to talk to the robot in order to call an associate (person in charge, or PIC), and the robot made the actual call to the PIC. The speech-activated reception call flow is given in Fig. 4. Note here that the demonstration was approved by the Honda R&D Bioethics Committee prior to being conducted.

4.2. Demonstration Environment

For the test, the robot was positioned at reception for the R&D Center X (formerly the Fundamental Technology Research Center). Actual customers visiting the center spoke to the robot, and the robot called the PIC.

4.3. System Configuration

The system configuration used in the demonstration is given in Fig. 5. The areas outlined in dotted lines are the topic technologies treated in this research. In the demonstration, the aforementioned algorithms and data were applied for the dereverberation, sound source identification, acoustic model, and language model.

For the later language understanding step, the vocabulary needed for calling was extracted on a rule basis.

Distant speech recognition systems used in conversations with the robot must be able to respond quickly and process

input speech from multiple sources simultaneously. In order to speed up response times, processing from speech input at the microphone array to speech recognition was moved online. So that the speech recognition system could recognize and process input speech from multiple sources simultaneously, the system was built to track orientation of the multiple sound sources, then assign and manage an ID unique (sound source ID) to each sound source.

Processing from speech input to feature extraction was moved online by using HARK⁽¹⁷⁾, the open source software system for robot audition. For the dereverberation method in particular, as the algorithm required speech input to be analyzed in voice activity units, the algorithm was modified to allow online processing as outlined in sub-section 3.1.1. To create a speech recognition system, the aforementioned

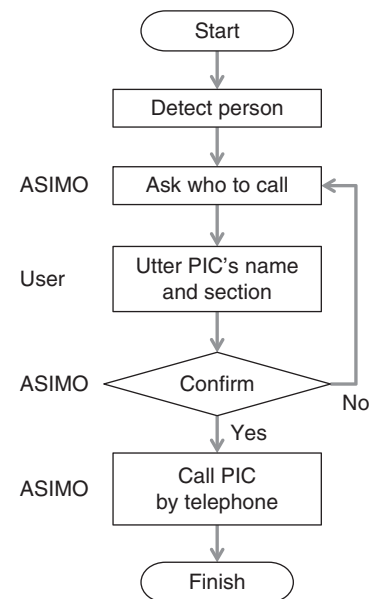


Fig. 4 Reception task flow

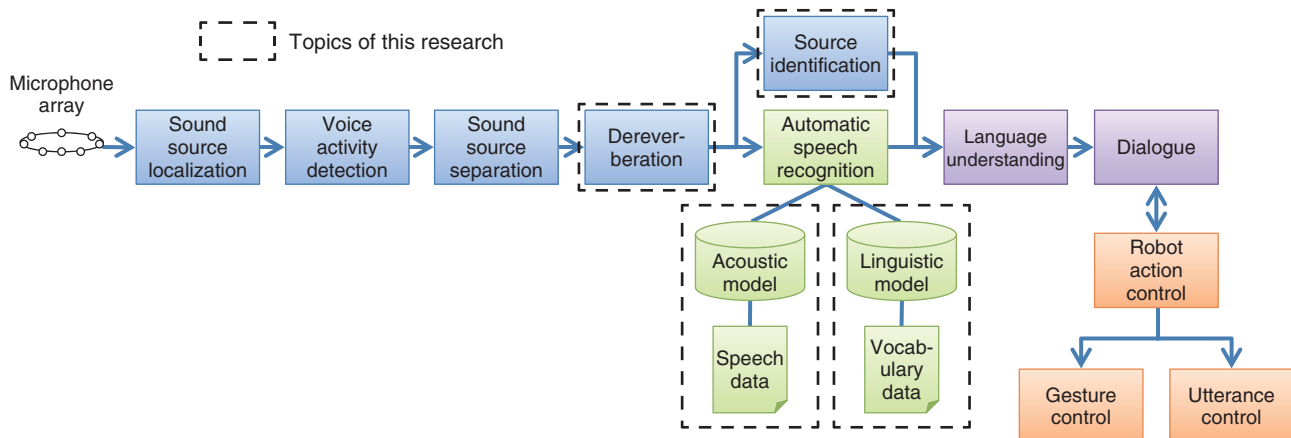


Fig. 5 Receptionist system

Kaldi was used to calculate acoustic likelihoods using a DNN acoustic model and to search word string candidates using a weighted finite state transducer. Newly implemented in this research were sequential processing for input features and simultaneous processing for multiple sound sources with threads. In order to speed up response and simultaneously process multiple sound sources, the package is capable of sequentially processing features input in 10-ms increments only, dividing each pair of input sound source IDs and feature strings into threads, and simultaneously processing the threads.

4.4. Demonstration Scenarios

Demonstration scenarios were built based on the flow given in Fig. 4. For the demonstration, the system was allowed to re-listen three times. Reception was considered successful when the correct PIC was called and unsuccessful in any other case the scenario did not advance, due to erroneous speech recognition or other causes.

4.5. Results

The demonstrations at reception took place over 37 days from January to February 2016. A total of 303 requests by actual speech were received at reception. A total of 4,881 words in actual customer voice activity were used to evaluate speech recognition. Speech recognition was evaluated based on word accuracy and the rate at which the correct PIC was actually called (reception success rate). Overall word accuracy was 66.8%. Of the 303 reception instances, 298 were successful for a reception success rate of 98.3%.

4.6. Discussion

Analyzing the causes for the five unsuccessful reception calls, two were erroneously recognized due to substitution error, and three were due to erroneous sound source identification (target speech discarded as non-target sound). In the substitution errors, the system erroneously recognized a name similar to that of the actual PIC. Regarding the sound source identification errors, an approach with a different model may be needed as the GMM may not fully describe the model to separate target speech with non-target sounds.

In terms of speech recognition, word accuracy dropped from 88.9% in benchmarking to 66.8% in the demonstration. The causes of error in recognition in the demonstration are grouped as given in Table 4. Of these error causes, three represent issues to be addressed in practical application. First, while specific to reception calls, erroneous recognition increases due to first-time visitors' names and company names being unknown words. Second, erroneous recognition increases with regular customers due to increased incidence of phenomena peculiar to spontaneous voice activity, such as filler words and misspeaking. Third, erroneous recognition increases when voice activity is overlapped with robot speech, which

Table 4 Cause of error in reception experiments

Cause of error	Word error rate (%)
Unknown words	10.9
Spontaneous speech	8.8
Non-target sound and VAD	5.7
Lack of training data	4.5
Overlapping speech	3.3
Total	33.2

results from the user not knowing the timing for robot voice activity and other causes. While the robot can recognize overlapping speech, in many cases the person will stop speaking when overlapping occurs, resulting in erroneous recognition. This presumably happens as it can be hard to read when the robot will start speaking.

Most cases of erroneous recognition, however, were not fatal to completing the reception task. The system was able to recognize with high accuracy the most important information, the PIC name, and affiliation name, thus achieving a high reception success rate. Performing tasks more complex than reception calls with voice interaction in the future will require automatic addition of unknown words, support for phenomena peculiar to natural voice activity, and turn-taking that is easier for the user to read.

5. Conclusion

Distant speech recognition technology was created for communicating with humans at a natural distance.

The dereverberation, sound source identification, and acoustic model proposed for the research were evaluated with evaluation benchmark data, and the implemented technology was confirmed to improve performance. In particular, the DNN acoustic model was confirmed to improve performance to 88.9% when trained with 904 hours of data. The proposed approach was integrated into the robot, achieving an overall word accuracy of 66.8% and reception success rate of 98.3% when used by actual customers at reception.

Analysis of the demonstration data revealed the following issues to address in order to further improve performance:

- (1) Support for unknown words;
- (2) Support for speech phenomena peculiar to spontaneous voice activity; and
- (3) Turn-taking and other robot expression.

With continuous daily use by actual customers, this demonstration, which gathered, analyzed, and verified data, should serve as a test case in further experimental demonstrations.

While the research theme of reception took place in a relatively quiet environment, it will be important in the future to also provide support for crowd noise, overhead announcements, and loud noise as found in public facilities and other places where people congregate.

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Lap Time Simulation Technology for Performance Design during Production Car Development

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ABSTRACT

A lap-time simulation technology for circuit driving compatible with performance design technologies employed during the development of production vehicles has been developed. The method creates vehicle models using data employed in the model-based development of production vehicles, and by combining these with models of driving and road surface conditions, reduces the computation time necessary for lap time simulation. The ability to define two models using the circular arc and whole curve transition methods makes it possible to apply the method in the performance design of production vehicles using all drive types. The method enables treatment of lap times during circuit driving as one item in the study of specifications during performance design in the development of production vehicles. The application of the method in the study of specifications during the development of the new NSX and the CIVIC TYPE R demonstrated the validity of the concept and the effectiveness of the method.

1. Introduction

Model-based development is an effective means of increasing the efficiency of the automotive development process at a time when the complexity of systems is rapidly increasing⁽¹⁾. Model-based development is also a means of reducing the time necessary for performance design, and the application of these technologies not only reduces development time, but also allows examination of new performance factors. One such representative performance factor is lap time during circuit driving.

Lap time simulations have conventionally been employed in the development of racing vehicles. Because lap time simulations have been created mainly for the purpose of calculating and predicting lap times as a substitute for conducting measurements in actual vehicle tests, the major focus has been on minimizing error in an attempt to help ensure that calculation results conform closely to values measured in driving tests. As a result, it is necessary to use not only highly detailed vehicle data, but also a high volume of vehicle-related peripheral data, such as data concerning the course that is the subject of the simulation, detailed vehicle aerodynamic characteristics, changes in temperature, and the specific characteristics of the driver's vehicle operation. The complexity of these

simulation models results in long computation times, and it has therefore not been an easy matter to use lap time simulations in performance design during the development of production vehicles^{(2), (3)}.

While it is possible to consider model-free development based exclusively on the results of lap time measurements conducted during driving tests, in order to help ensure safety, this necessitates the possession of an exclusive test circuit, and the use of drivers with high levels of skill. The frequent use of tests involving so many restrictions would affect the development of other production vehicles, and is therefore impractical. As a result, lap time has not been employed as a focus item in performance design for production vehicles other than in the case of special models based on a concept of appealing to a high level of dynamic performance.

However, the ability to treat lap time as a performance factor in performance design during the development of production vehicles would be beneficial from the perspective of the efficient development of high-performance vehicles. Doing so would require taking a different perspective to conventional lap time simulations, and output calculation results in a short period based on limited data. The application of the technologies of model-based development was therefore considered as a response to this necessity.

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2. Aims for Developed Technology

Employment of lap time simulations in the development of production vehicles would require conducting calculations based on easily obtainable data, as well as studying specifications within a limited period of time. General applicability making it possible to employ the method for all production vehicle types would also be necessary. Taking these demands into consideration, the following four items were set as development targets:

- (1) Ability to generate vehicle models using data employed in model-based development of production vehicles;
- (2) Reduction of the computation time necessary for output of results, enabling use of the method for the performance design during the development of production vehicles;
- (3) Realization of the ability to use the method for performance design of the three types of standard production vehicles, i.e. front-wheel, rear-wheel, and four-wheel drive; and
- (4) Ability to output, in addition to lap time results, results for other indices of dynamic performance including maximum acceleration, maximum lateral acceleration, maximum deceleration, and maximum speed.

3. Mechanism for Lap Time Simulation

Because standard vehicle dynamics simulations run models on horizontal planes without specifying a course, the only elements necessary for the simulations are those related to vehicle conditions. By contrast, for lap time simulations it is necessary to define three main elements in the model: in addition to elements related to vehicle conditions, these are elements related to driving conditions and elements related to the state of the road surface.

3.1. Elements related to Vehicle Conditions

In this paper, elements related to vehicle conditions refer to basic elements of vehicle dynamic performance, specifically driving (acceleration performance), turning (cornering performance), and stopping (braking performance)⁽⁴⁾. The representative indices that express these basic elements of performance are acceleration, lateral acceleration, and deceleration, the respective maximum values of which are termed maximum acceleration, maximum lateral acceleration, and maximum deceleration.

To study acceleration performance, maximum acceleration is calculated using models of the powertrain system created using elements including the weight of the vehicle, the torque characteristic of the engine or motor, the gear ratio, and the diameter of the tires. At the same time, maximum acceleration is also calculated using a chassis system model created using the weight of the vehicle, the vehicle's center of gravity, the front-rear force characteristic of the tires, and the front and rear distribution of drive force.

Actual acceleration at any point is calculated by comparing the results of the two, and subtracting the driving resistance component (air resistance, rolling resistance, etc.) from the lowest.

With regard to cornering performance, maximum lateral acceleration is determined based on the weight of the vehicle, the vehicle's center of gravity, the cornering characteristic of the tires, the distribution of roll stiffness, suspension stiffness, the suspension alignment characteristic, and downforce. Actual maximum lateral acceleration at any point is calculated by subtracting driving resistance including air resistance and rolling resistance from the results.

In the case of deceleration performance, maximum deceleration is calculated based on the weight of the vehicle, the vehicle's center of gravity, the front-rear distribution of braking force, and the front and rear force characteristic of the tires. As in the calculation of acceleration performance, actual deceleration at any point is calculated by subtracting driving resistance including air resistance and rolling resistance from the results.

The discussion above has provided an overview of the elements related to vehicle conditions necessary for lap time simulations. The details are identical to those for the Level 1 and Level 2 simulations defined in a previous paper⁽¹⁾.

3.2. Elements related to Driving Conditions

Driving conditions are conditions that specify what locus the vehicle traces on the circuit course (termed the "driving locus" below), the timing of acceleration, and the timing of deceleration. Driving locus models affect the results of lap time simulations, and a variety of methods of creating the models have therefore been proposed. Regardless of which method is used, however, if an ideal driving locus is determined based on calculations alone, in the absence of reference data, it becomes necessary to separately create an optimization logic, increasing the computational burden and necessitating an extended period of time⁽⁵⁾⁻⁽⁷⁾. In the present case, the use of a high volume of driving locus data obtained from actual measurements as reference data and the definition in advance of driving loci derived statistically using specific rules, in order to reduce computation time, was effective in reducing the computational burden.

The driving locus on any circuit can be classified into two domains: straight sections and corner sections. The definition of driving loci in the corner sections is of particular importance, because it has a significant effect on the results of lap time calculations. Conventionally, the driving locus models employed in lap time simulations have been limited to a single type, and the rules employed have become very complex when they are applied to all circuits and the performance design of all vehicles in development. In order to address this issue, the present research defined two types of driving locus model, and employed either

model in response to specific circumstances. The methods of generating these two types of model have been termed the circular arc method and the whole transition curve method.

3.2.1. Circular arc method

The circular arc method is a method of specifying the entire driving locus by approximating the driving locus on straight sections as a straight line and the driving locus on corner sections as an arc. Figure 1 shows the radius of curvature of the driving locus specified by the circular arc method as a graph. In the straight sections, the radius of curvature becomes infinitely large, and its value cannot be defined. In the corner sections, the radius of curvature takes a fixed value, and is shown as an arc. The advantage of this method is that acceleration and deceleration can be completed on the straight sections, and lateral acceleration is constant on the corner sections. This makes it easy to understand the effect of vehicle characteristics in the straight sections and the corner sections. In addition, the models are simple, and the computational burden is low.

3.2.2. Whole transition curve method

In the whole transition curve method, the driving locus on the straight sections is approximated by a straight line, as in the circular arc method, but the driving locus on the corner sections is not specified using arcs, but rather using particular curves. Here, these curves are termed transition curves. Transition curves are determined statistically from past measurement data; optimum paths are determined in order to help ensure that no discontinuities occur in the

radius of curvature^{(5), (8)}. Figure 2 shows an example of the radius of curvature of a driving locus specified using the whole transition curve method expressed as a graph. The radius of curvature of the transition curve from the straight to the apex of the corner decreases monotonically, and after the apex of the corner increases monotonically towards the next straight section. The advantage of this method is that it is possible to gradually change the radius of curvature when connecting the straight and corner sections, producing a driving locus that is closer to reality than the circular arc method. Computation results generated by this method correspond particularly well with the results of actual driving tests in situations involving the frequent occurrence of scenarios in which lateral acceleration gradually increases as deceleration gradually decreases, or in which acceleration gradually increases as lateral acceleration gradually decreases. In addition, calculations for the entire corner section are able to consider the tire friction circle⁽⁹⁾ characteristic, and the method is therefore suited to use in cases in which braking force and side force are simultaneously produced on the tires (Tire slip conditions: Combined). However, the whole transition curve method uses a higher volume of data than the circular arc method, and the computational burden is therefore higher. In addition, because the method does not distinguish between a state in which the vehicle is braking and driving in a straight line and a state in which the vehicle is performing a steady-state turn, it is not easy to clearly distinguish the effect of vehicle characteristics in relation to straight sections and corner sections in studies of specifications for performance design.

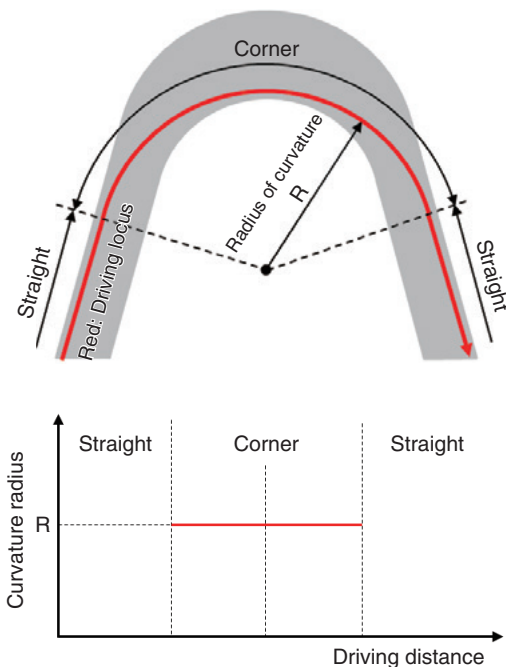


Fig. 1 Circular arc method

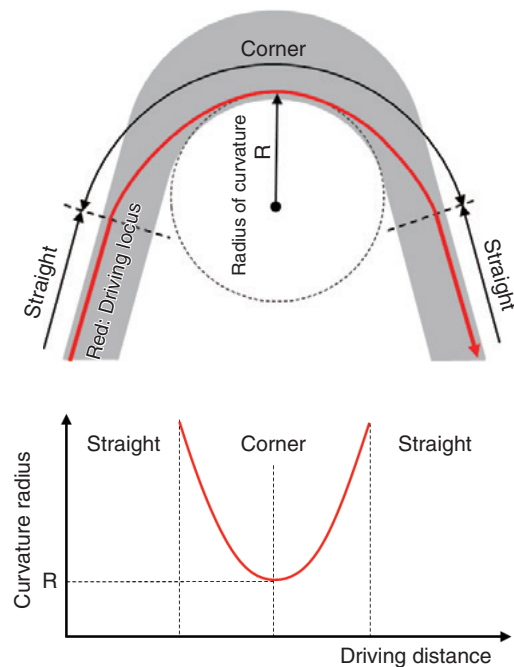


Fig. 2 Whole transition curve method

Table 1 Characteristics of two methods

Method	Definition of corner	Tire slip conditions	Characteristics
A	Circle	Pure	Contribution of straights and corners to lap time is clear
B	Transition curves	Combined	Radius of curvature is continuous (Locus is close to actual drive)

A: Circular arc method
B: Whole transition curve method

Table 1 summarizes the specific characteristics of each method, as discussed above.

3.2.3. Specification of driving loci for simulations

Actual driving loci can be considered as comprising straight lines, arcs, and transition curves connected in complex ways. In principle, the use of the two methods described above enables comprehensively expressing all driving loci. The circular arc method offers considerable advantages in that the method simplifies understanding of the effect of vehicle characteristics in relation to straight sections and corner sections, and the computational burden is low. This is why lap time simulations employed in performance design generally use the circular arc method. However, in the case of front-wheel drive vehicles fitted with high-power engines and high-performance brakes, in corner sections powerful forces act simultaneously on the front wheels in the longitudinal and lateral directions, and if calculations are conducted without consideration of the

friction circle characteristic, the level of divergence from the actual state becomes greater and error cannot be ignored. This issue can be addressed by using the whole transition curve method for simulations in these cases. The use of the two methods therefore makes it possible to conduct lap time simulations for all vehicles.

With regard to driving conditions, in addition to specifying the driving locus, it is necessary to specify the timing of deceleration, cornering, and acceleration. In the simulations under consideration, which divide the driving locus into straight sections and corner sections, the point at which deceleration ends corresponds to the point at which lateral acceleration occurs, and the point at which acceleration begins corresponds to the point at which lateral acceleration is 0. With the vehicle speed at these points as a reference, in the corner sections, the circular arc method defines a cornering motion with the vehicle's speed fixed at the maximum lateral acceleration. Figure 3 shows lateral acceleration and vehicle speed output during cornering under the conditions of the circular arc and whole transition curve methods as graphs. Beneath the graphs, the figure shows images of the directions of the forces generated within the tire friction circles.

With regard to vehicle speed on the straight sections, from the point at which the vehicle leaves the corner section and lateral acceleration becomes 0, vehicle speed is increased by maximum acceleration, and at the point at which lateral acceleration increases at the next corner

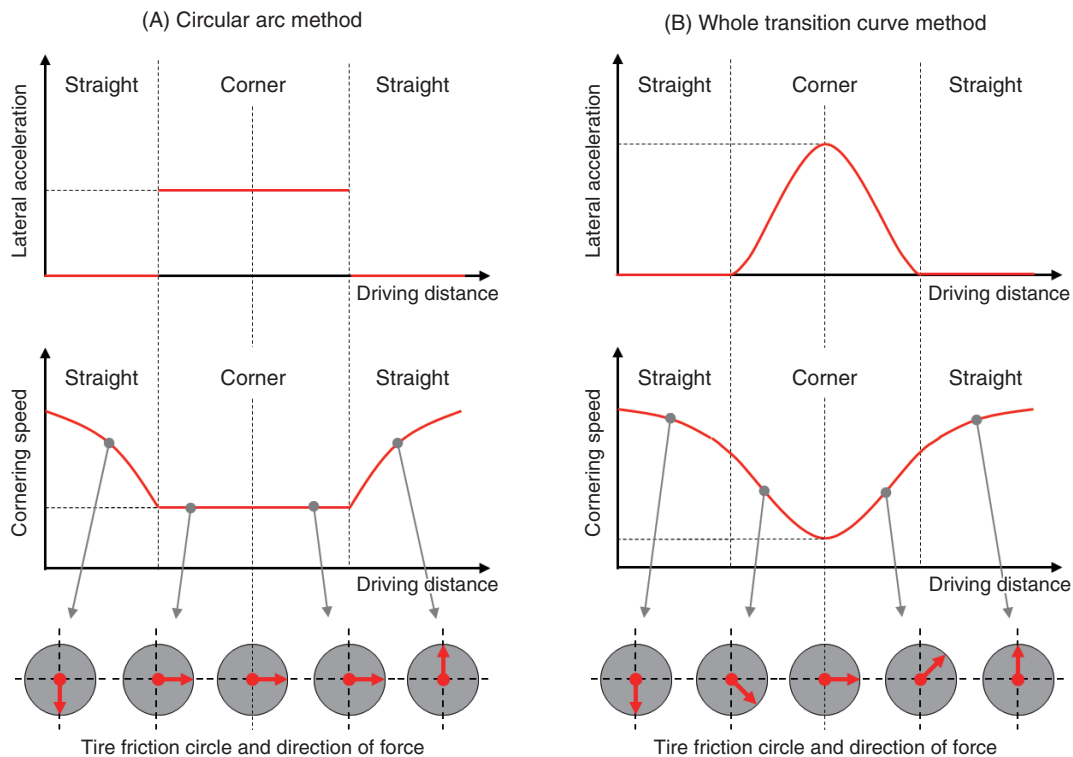


Fig. 3 Comparison of two methods

section, vehicle speed is reduced by maximum deceleration in order to realize the maximum cornering speed. Figure 4 shows changes in speed between straight sections for the circular arc method. This figure shows that the driving locus calculated by increasing vehicle speed by maximum acceleration with point x1 (commencement of acceleration) as the reference, and the driving locus calculated by reducing vehicle speed by maximum deceleration with point x2 (completion of deceleration) as the reference, cross at point x3. The concept is the same for the whole transition curve method.

The specification of driving conditions as discussed above makes it possible to specify the driving locus at any point of a circuit lap as shown in Fig. 5. Because vehicle speed can be continuously calculated, lap time can also be calculated simultaneously. This makes it possible to reduce the simulation computation time without the use of optimization logic or other methods, and to specify driving

loci able to be employed in effective lap time simulations for use in the performance design of production vehicles.

3.3. Elements related to the Shape of the Road Surface

The shape of the road surface is made up of slope (the gradient in the direction in which the vehicle is proceeding), undulation, and cant (the gradient in the lateral direction of the vehicle). The slope of the road surface affects acceleration and deceleration, and cant affects maximum lateral acceleration.

The left-hand side of Fig. 6 shows the slope of the road surface. This image shows the gradient of the road surface in relation to the direction in which the vehicle is proceeding. Acceleration and deceleration when the vehicle is advancing or braking are affected by gravitational acceleration in response to the degree of the slope, and

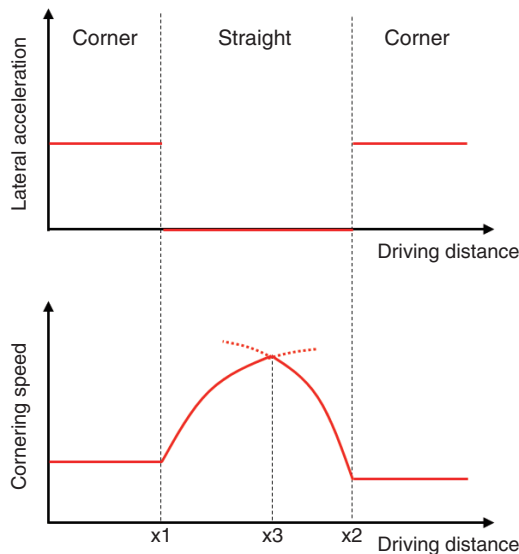


Fig. 4 Speed on straight

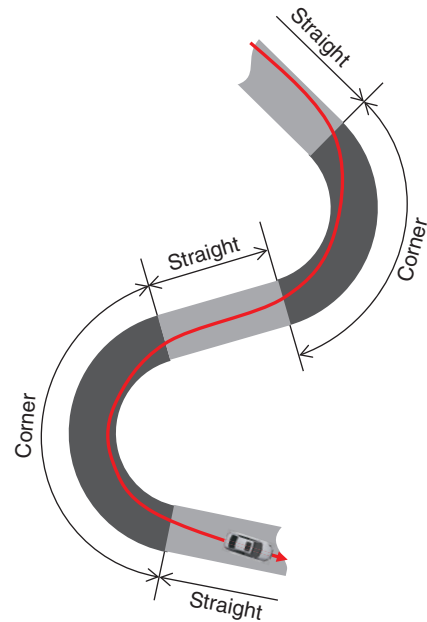


Fig. 5 Straights and corners

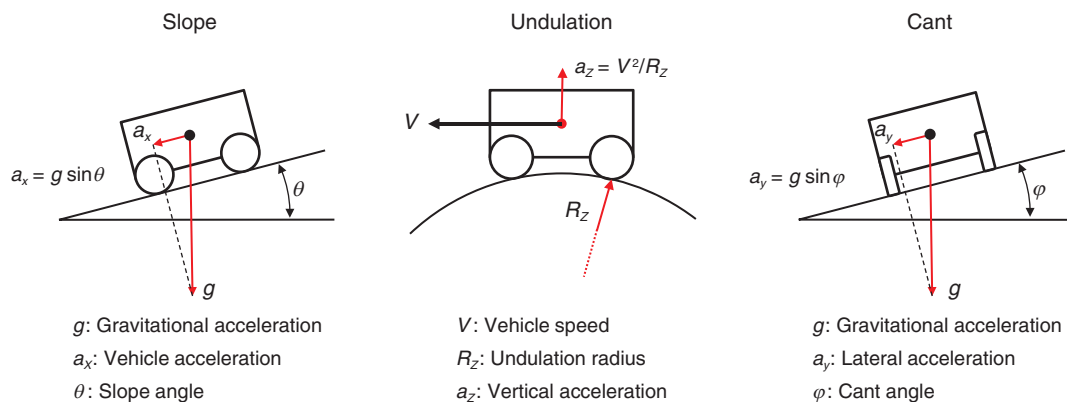


Fig. 6 Elements related to road surface shape

change as a result. The image in the middle of Fig. 6 shows the undulation of the road surface. When a vehicle is driving on an undulating road of this type, when the vehicle is proceeding on a convex section, a force acts in the upwards direction to lift the vehicle; when a vehicle is proceeding on a concave section, a force acts in the downward direction, as if pressing the vehicle against the road surface. When the lifting force in the upwards direction is acting on the vehicle, the friction circles of the tires are reduced; when the pressing force in the downwards direction is acting on the vehicle, the friction circles of the tires increase. As a result, maximum acceleration and deceleration as well as maximum lateral acceleration are affected. The right-hand side of Fig. 6 shows cant. Cant is a left-right inclination of the road surface in relation to the direction in which the vehicle is proceeding. As in the case of slope, when the vehicle is cornering, lateral acceleration is affected by the degree of cant and changes as a result.

4. Verification of Effectiveness and Examples of Application

This section will discuss the development of two models featuring significantly different drive types and specifications to provide examples of the use of lap time simulations in vehicle studies. The first of these was the new model NSX. This was a high-performance four-wheel drive vehicle, with high loads generated on the rear wheels. The second was the 2015 model CIVIC TYPE R. This was a high-performance front-wheel drive vehicle, with high loads generated on the front wheels (Table 2). Lap time simulations will be discussed for two circuits: the Tsukuba Circuit, on which large numbers of lap time measurements have been conducted during the development of past production vehicles; and the Nürburgring Circuit, which is frequently used to provide benchmarks during vehicle development. MATLAB was employed for the simulations.

4.1. NSX Development

The NSX is Honda's representative high-performance super sports car, and was developed with the aim of realizing the world's highest level of dynamic performance. Targets were set for the top level not only in lap time, but also in all other indicators of dynamic performance, including maximum acceleration, maximum deceleration, maximum lateral acceleration, and maximum speed.

Figure 7 shows the results of a lap time simulation and actual lap time measurement data presented graphically as a driving history, both for the Tsukuba Circuit. The red solid line shows calculation results, and the blue broken line shows actual measurement data. The graph indicates that the results of the developed lap time simulation conform closely to the results of actual driving tests.

Lap time, maximum speed, maximum acceleration, maximum deceleration, and maximum lateral acceleration can be derived from the driving history produced using

Table 2 Specifications of NSX and CIVIC TYPE R

	NSX	CIVIC TYPE R
External dimensions L × W × H (m)	4.490 × 1.940 × 1.215	4.390 × 1.880 × 1.460
Wheelbase (m)	2.630	2.600
Weight (kg)	1800	1380
Drive type	Engine and Motor/AWD	Engine/FWD
Maximum power (Engine/Motor) (kW)	373/200 System maximum power: 427	228
Maximum torque (Engine/Motor) (Nm)	556/366 System maximum torque: 646	400

calculation results. From driving history data, it is possible to consider factors such as the characteristics of the circuit, including the speed ranges used overall, the frequency of straights and corners, and the degree of acceleration and deceleration.

Figure 8 shows a graph produced from a lap time simulation for the Tsukuba Circuit, with lap time and maximum speed used as respective indicators on the horizontal and vertical axes. The graph plots results for six different specifications, based on calculations conducted

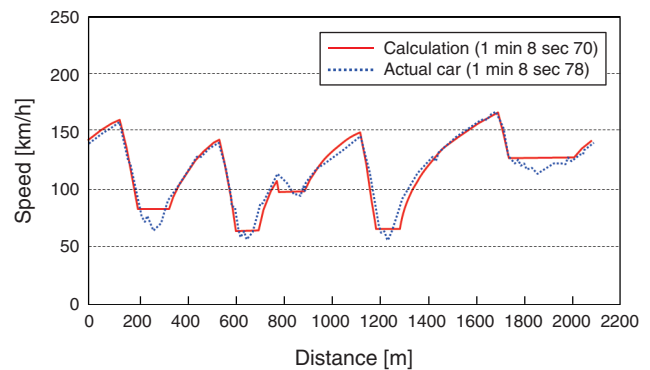


Fig. 7 Driving history

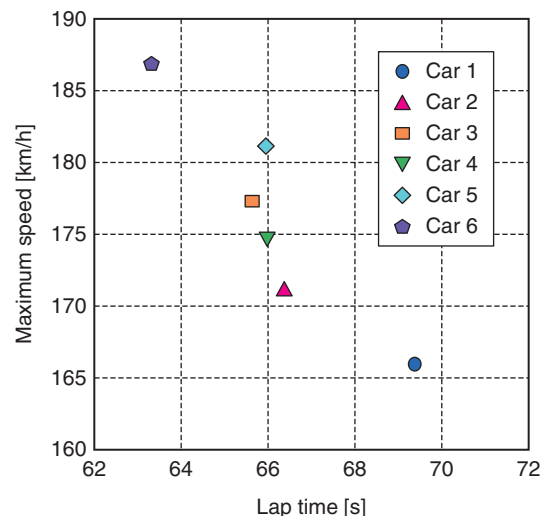


Fig. 8 Lap time and maximum speed

for Cars 1 to 6, representing different combinations of tire size, aerodynamic characteristics, and weight distribution conditions. Because shorter lap time and higher maximum speed results are preferred, the results for Car 6 plotted in the upper left of the graph indicate that this car displays the highest level of performance.

Figure 9 shows results for maximum lateral acceleration expressed as a bar graph. Higher maximum lateral acceleration can be considered to produce higher performance, and higher results are therefore preferred in this bar graph.

The horizontal axis of Fig. 10 shows maximum deceleration determined by the chassis and tires with the brake elements removed, and the vertical axis shows maximum acceleration determined by the chassis and tires with the engine elements removed. This makes it possible to compare the effect of the chassis and tires on acceleration and deceleration performance. For both indicators, higher values show higher performance, with the chassis whose results are plotted in the upper right of the graph displaying the highest potential.

The results shown in Figs. 8 to 10 discussed above are representative results output by lap time simulations. During performance design in the initial stage of the development of the NSX, these graphs were compared while conducting performance design for a variety of specifications. The characteristics of each component, including engine power, cornering of the tires, air resistance and downforce, suspension alignment, and battery layout were studied, and specifications that satisfied target performance on the Tsukuba Circuit were determined.

Turning to examples of performance design using the Nürburgring Circuit, Fig. 11 shows total times for straights and corner sections presented as a graph, with the different sections classified by color. Results for total time for the straights are shown in green, and results for the total time

for the corners are shown in red. Cars 1 to 4 show the results of analyses of the driving loci of four representative sports car models manufactured by competitors. These results indicate whether it is more effective to apply measures for the straights or for the corners. The graph suggests which component it would be most effective to apply measures to in order to reduce lap time. For example, if the vehicle were driving on a circuit made up exclusively of corners, the ranges in the corner sections would be the most frequent, and it would be possible to effectively reduce lap time through measures that increase speed during cornering. The study of specifications for the NSX was based on

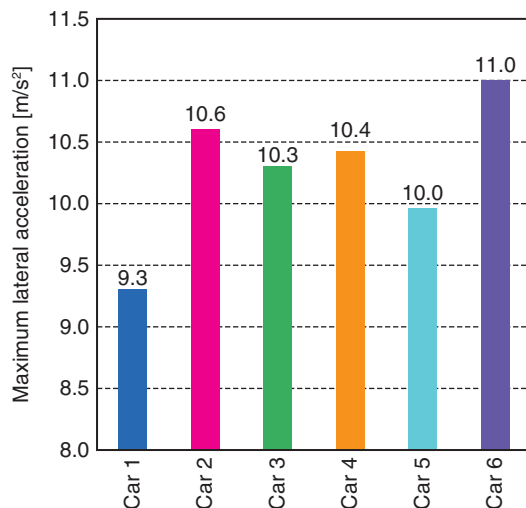


Fig. 9 Maximum lateral acceleration

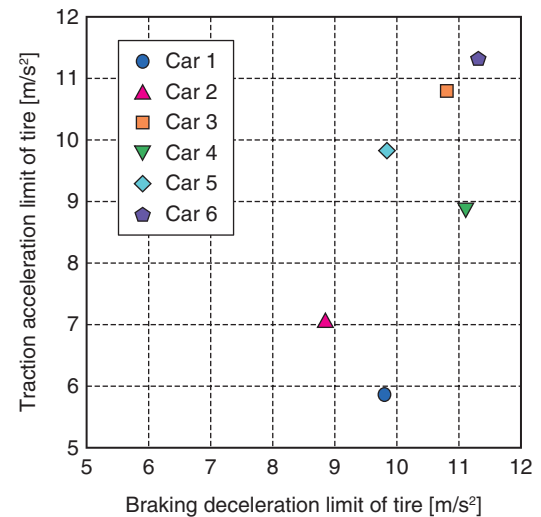


Fig. 10 Tire traction and deceleration limits

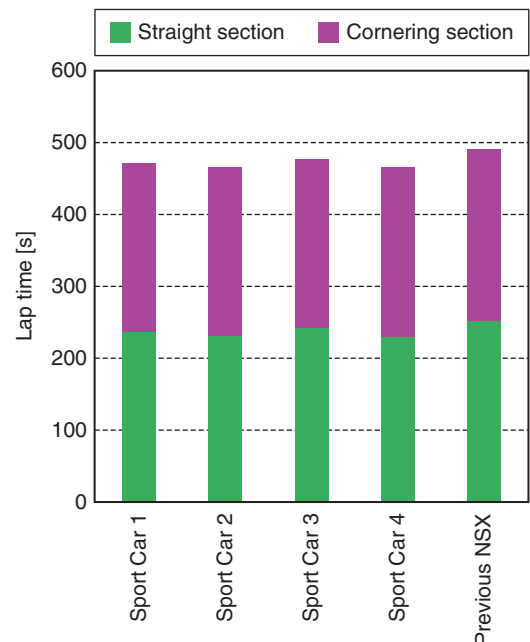


Fig. 11 Time for straight and corner

considerations of this type, and optimal specifications were pursued based on a variety of perspectives before the ultimate specifications were determined.

Figure 12 shows the results of a study conducted for performance design in corner sections. The graph shows the effect of the battery layout for the hybrid motor, the use of aerodynamic devices such as spoilers, and of tire size. Studies of this type made it possible to obtain potential achievement of 234 sec or below set as the total target time in the corner sections.

In the actual development process, respective specifications were determined on the basis of these simulation results, and a prototype vehicle was created. This prototype was able to achieve the target time in actual driving tests. Figure 13 shows a graph of results for various powerplant specifications studied during performance design, and the effect of the specifications applied in order to realize the targets for lap time and maximum speed.

4.2. Development of CIVIC TYPE R

The CIVIC TYPE R is a representative Honda high-performance front-wheel-drive vehicle. The concept for the vehicle was to achieve the fastest lap time for a front-wheel drive vehicle on the Nürburgring Circuit. In practical terms, this meant a lap time of within 7 min 50 sec (470 sec). The process of performance design in relation to the lap time of the CIVIC TYPE R was basically the same as that for the NSX, but while the NSX was a four-wheel-drive vehicle, the CIVIC TYPE R employed front-wheel drive. The front wheels therefore supported both cornering side force and braking and drive force in the corner sections, making the way in which the front tire friction circles were used an important factor. The use of the whole transition

curve method employing friction circle models for lap time simulations therefore generated values closer to actual vehicle measurements for the CIVIC TYPE R. The vehicle therefore provides a representative example of a case in which performance design employed both lap time simulations using the circular arc method and those using the whole transition curve method.

Figure 14 shows a graph of forces produced by a tire contact patch, measured in order to specify the tire friction circles for the whole transition curve method.

Figure 15 compares lap times for the CIVIC TYPE R on the Tsukuba Circuit calculated using the circular arc method (red solid lines), calculated using the whole transition curve method (red broken lines), and actually measured lap times (blue broken lines). This graph shows that the whole transition curve method produces calculation

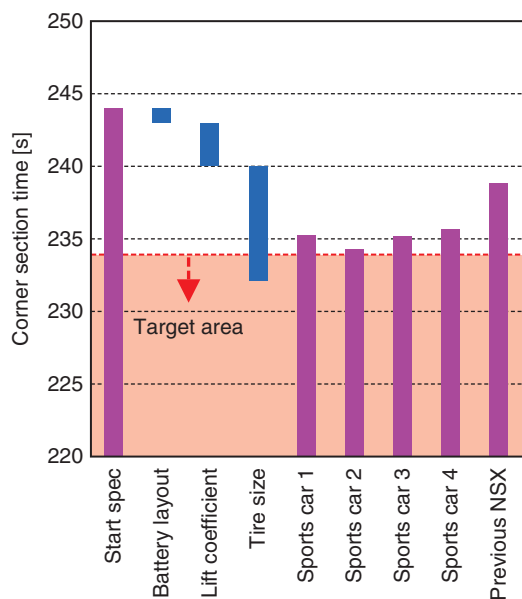


Fig. 12 Results of study of specifications for NSX

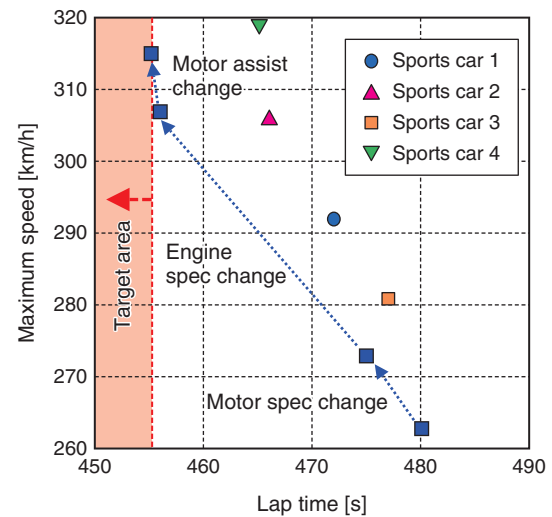


Fig. 13 Lap time and maximum speed

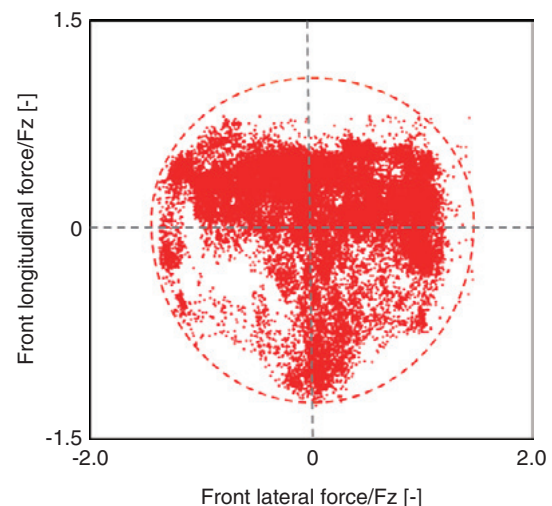


Fig. 14 Force generated on road surface

results closer to the results of actual measurements than the circular arc method. Calculation results produced by the circular arc method tend to diverge from actually measured values especially in the case of powerful front-wheel-drive vehicles like the CIVIC TYPE R. In such cases, it is possible to study the effects of performance design with the necessary accuracy by creating calculation models using the whole transition curve method.

Figure 16 shows a graph of the effect allotted to each component in realizing the target lap time for the CIVIC TYPE R on the Nürburgring Circuit. This graph indicates

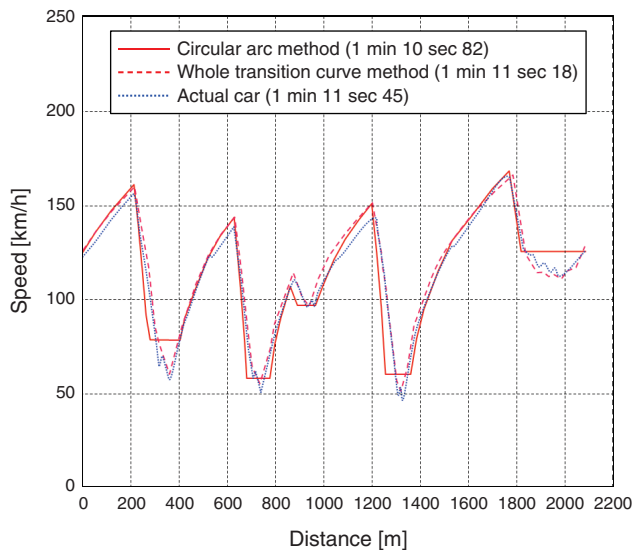


Fig. 15 Comparison of results of two methods and actually measured values

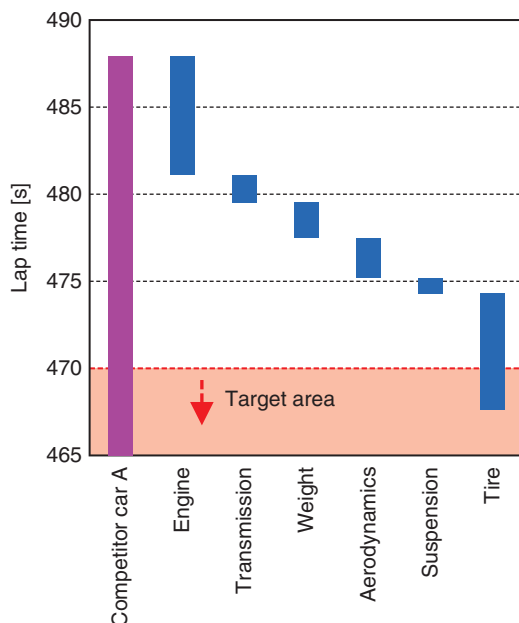


Fig. 16 Deployment of system for CIVIC TYPE R

that applying measures in the areas of engine power, the transmission gear ratio, vehicle weight, the aerodynamic characteristic, the suspension specifications, and the tire size, enabled the potential realization of the target lap time. As this demonstrates, the use of lap time simulation made it possible to allot performance elements to each component at the stage of performance design.

5. Conclusion

This paper has presented two examples of the use of lap time simulations for the Tsukuba and Nürburgring Circuits in the development of production vehicles. These examples have demonstrated the validity of the authors' concept of lap time simulation models and the effectiveness of the simulation technologies.

The research discussed in the paper can be summarized as follows:

- (1) A lap time simulation tool using conditions defined during the model-based development of production vehicles has been created.
- (2) The specification of elements related to driving conditions and to road surface conditions has reduced computation time, making it possible to apply lap time simulations to performance design in the development of production vehicles.
- (3) The generation of two models using the circular arc and whole curve transition methods enables creation of lap time simulation environments able to respond to all vehicle drive types.
- (4) In addition to lap times, the method is able to output values for other performance indicators, including maximum acceleration, maximum lateral acceleration, maximum deceleration, and maximum speed.

The developed tool is able not only to predict lap times as a substitute for vehicle tests, but also to allocate performance demands for the characteristics of each component based on lap time targets, and thus to proceed effectively with system design, demonstrating that the tool can be applied in the development of production vehicles.

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Construction of Model to Predict Wear Amount on Exhaust Valve Seats for Gasoline Engines

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ABSTRACT

A technique has been created to predict the amount of wear on exhaust valve seats for gasoline engines. Through bench and rig wear tests, a prediction model was constructed with multiple factors as variables. Through these tests, the controllable factors were categorized, and sensitivity for each factor was determined from the measured wear data. The model was also applied to valve seats of different materials, confirming its versatility. By using the model to predict the amount of wear on valve seats in the cylinder head design phase, a cylinder head structure was quickly devised to increase valve seat wear resistance, shortening the development period and reducing development cost.

1. Introduction

In addition to the demands for greater performances, higher output, and a better fuel economy, today's automotive engines also face a demand for reduced CO₂ emissions to lower their environmental impacts. In response to this demand, Honda has been developing downsizing turbocharged engines⁽¹⁾. In turbocharged engines, gas is combusted at higher temperatures and pressures than in naturally aspirated engines. Thus, great attention should be given to wear on the valve seats, a factor which greatly affects engine performance.

Valve seats come in contact with intake and exhaust valves during the compression stroke, and they should be airtight to seal the compressed air-fuel mixture and the gas in the combustion stroke. Worn valve seat will reduce sealing performance with the valves, in turn degrading airtightness. The intake valve seats for gasoline engines are cooled by latent heat from vaporization during the intake stroke. Meanwhile, the exhaust valve seats are exposed to hot, high-pressured exhaust gases during the exhaust stroke, making them hotter than the intake valve seats. Thus, valve seat wear for gasoline engines is greater and needs more attention on the exhaust valve seats than on the intake valve seats⁽²⁾. To date, new materials have been developed to increase wear resistance for individual valve

seats⁽³⁾⁻⁽⁶⁾. However, as actual engine conditions for valve seats cannot be reproduced in stand-alone testing, valve seat wear resistance for actual engines should be confirmed with bench tests or road tests. If the tests show wear resistance to be low, the cylinder head structure should be redesigned and retested, in turn extending the development period and raising development costs. If the cylinder head structure is to be altered to increase valve seat wear resistance at the initial design phase, the amount of wear should first be predicted with testing. To date, however, valve seat wear has not been able to be predicted. The factor sensitivity to the numerous factors generating valve seat wear in testing could not be determined, and so no mathematical model has been constructed to predict wear.

Thus, in this research, the factor sensitivity for valve seat wear was determined for various tests, and a model was constructed to predict wear for exhaust valve seats in gasoline engines. The findings are as reported below.

2. Research Goals and Model Construction

The goal for the research was to build a model for predicting exhaust valve seat wear in bench test and road test for gasoline engines. The model was built by testing valve seat wear, and then using the response surface methodology from the wear data obtained in testing.

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Response surface methodology is a technique which uses test data to construct mathematical and statistical models to derive the optimum solution for the target variable(s). It is suited to constructing models from limited sets of test data. The factors resulting in valve seat wear are input into the model as variables to predict the amount of valve seat wear. The following steps were taken to build the model:

- Step 1: Identify wear factors for valve seats and sort by test
- Step 2: Construct a model for the air-fuel ratio, surface pressure on the valve seat face, and surface temperature on the valve seat face
- Step 3: Reflect deformation of the valve seat face into the model
- Step 4: Reflect combustion pressure and temperature into the model
- Step 5: Verify model accuracy and examine model versatility

3. Identifying Wear Factors for Valve Seats and Sorting by Test

A diagram of the main causes and factors in valve seat wear is shown in Fig. 1. There are 2 main causes in valve seat wear on actual engines: frictional force and the relative slip between the valve and valve seat. When a valve closes, it is impacted by the valve spring and seated on the valve seat. Then, the valve is pressed against the valve seat by combustion pressure, generating frictional force and causing the valve face to slip slightly. As the valve seat is also deformed by the combustion temperature and pressure, it makes non-uniform contact with the valve, generating a non-uniform frictional force. This generates various other phenomena⁽³⁾ as well, such as an adhesion of combustion products due to the change in air-fuel ratio, and change in friction coefficient and adhesion resistance due to the change in surface temperature on the valve seat face. The identified factors are:

Factor 1: Air-fuel ratio

Factor 2: Surface pressure on the valve seat face

Factor 3: Surface temperature on the valve seat face

Factor 4: Deformation of the valve seat face

Factor 5: Combustion pressure

Factor 6: Combustion temperature

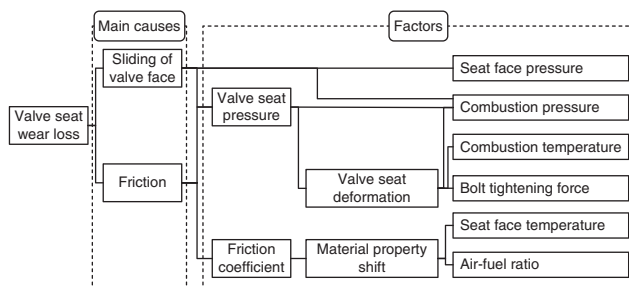


Fig. 1 Factor system diagram

Based on the identified factors, the authors proceeded to measure the amount of valve seat wear and construct a model, controlling for air-fuel ratio, and surface pressure, surface temperature, and the deformation of the valve seat face for the rig tests, as well as for combustion pressure and temperature for bench tests.

4. Constructing a Model for the Air-fuel Ratio, Valve Seat Face Pressure, and Valve Seat Face Temperature

4.1. Overview of Test Rig

The test rig used in testing is shown in Fig. 2. To get closer to an actual engine for the bench tests, the test rig was built with the following parts: actual engine valves, actual engine valve seats of ferrous sintered alloy comprising Cr-Mo-Co hard particles, and a setting plate fabricated from the cylinder head material used in the actual engine.

Various test conditions were adjusted. The valve seat face pressure with the valve seated was adjusted through valve lift with the cam mechanism. The air-fuel ratio was also adjusted through a mixture of LP gas and air, supplied to a burner. Finally, valve seat face temperature was adjusted by changing the height of the burner.

4.2. Determining Factor Sensitivity

The rig tests were performed within the driving condition range of bench tests to measure the amount of valve seat wear. An L18 orthogonal table of the test conditions is given in Table 1. The factorial effects from the L18 test results are given in Fig. 3. From the factorial effects, sensitivity was determined to be highest for valve seat face temperature. Meanwhile, sensitivity for the air-fuel ratio was determined to be the same as that for valve seat face pressure.

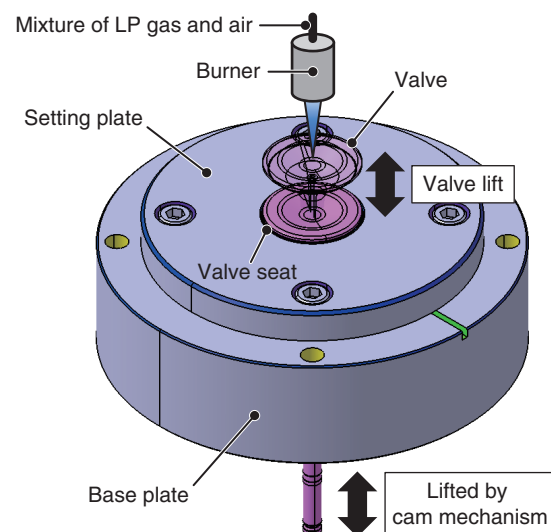


Fig. 2 Valve seat testing machine

Table 1 L18 orthogonal table

No.	Air-fuel ratio [-]	Seat face pressure [MPa]	Seat face temperature [deg C]	Cam rotation speed [r/min]	Valve rotation speed [r/min]	Test duration time [hour]
1	11.9	12.1	240	3000	20	6
2	11.9	10.1	240			
3	10.7	12.1	280			
4	10.7	10.1	280			
5	13.1	8.1	200			
6	13.1	8.1	280			
7	14.3	10.1	200			
8	14.3	8.1	200			
9	14.3	12.1	240			
10	13.1	12.1	240			
11	11.9	8.1	280			
12	11.9	12.1	320			
13	13.1	10.1	200			
14	13.1	10.1	280			
15	14.3	10.1	240			
16	14.3	12.1	320			
17	14.3	12.1	200			
18	10.7	12.1	200			

4.3. Constructing the Model

Using the valve seat wear measurements from the L18 tests, a model was constructed with valve seat face pressure and temperature and air-fuel ratio as the input parameters.

For the response surface methodology, a radial basis function network (RBF network)⁽⁷⁾ was used given as they are more compatible with objective function distributions than polynomial models over the entire design space. RBF networks approximate the objective function distribution as a summation of basis functions. The RBF network approximated objective function $f(x)$ as given in Eq. (1), using distance $\|x - x_i\|$ from measuring point i , radial basis function $\phi(r)$, coefficient a_i , and scaling parameter c .

$$f(x) = \sum_{i=1}^N a_i \phi\left(\frac{\|x - x_i\|}{c}\right) \quad (1)$$

Hardy Multiquadric Eq. (2) was used as the basis function:

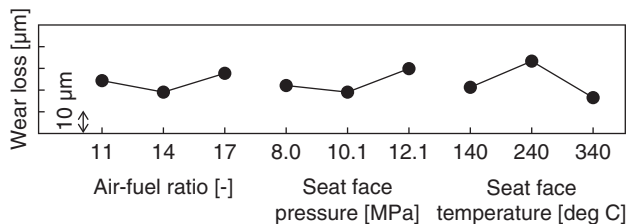


Fig. 3 Factorial effects on L18 test

$$\phi(r) = (1 + r^2)^{1/2} \quad (2)$$

The IDAJ optimization tool modeFRONTIER[®] was used to create the model. Valve seat wear W_0 can be expressed with the model given by Eq. (3):

$$W_0 = f(AF, P_s, T_s) \quad (3)$$

In Eq. (3), AF is the air-fuel ratio, P_s is the seat face pressure, and T_s is the seat face temperature.

4.4. Verifying Accuracy of Model Predictions

Prediction accuracy using the constructed model was verified by entering the rig test conditions (air-fuel ratio, valve seat face pressure and temperature) into the model and comparing the predicted valve seat wear to the test results. The compared results are given in Fig. 4. The constructed model was able to predict valve seat wear at a high accuracy of $R^2 = 1.00$.

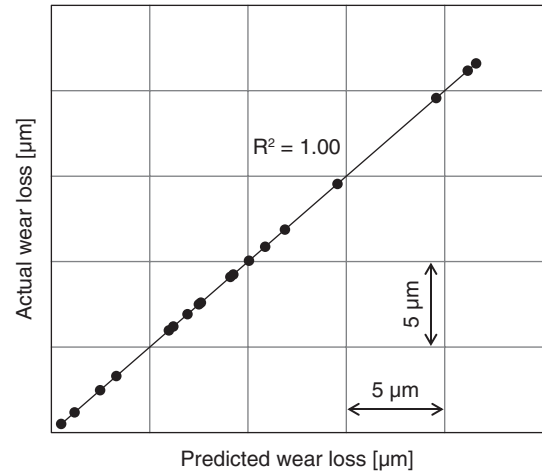


Fig. 4 Comparison between predicted wear loss and actual wear loss

5. Reflecting Valve Seat Face Deformation into the Model

5.1. Test Overview and Measuring Method for Valve Seat Face Deformation

The test rig was the same as that shown in Fig. 2. The methodology for valve seat face deformation is illustrated in Fig. 5. Valve seat face deformation, equivalent to that in the actual engine, was recreated by pinching shim plates between the setting plate and base plate, then forcing deformation of the setting plate. The valve seat was measured before testing with a three-dimensional measuring machine, confirming deformation to be equivalent to that in an actual engine. Specifications for the three-dimensional measuring machine used in measurement are given in Table 2, and the appearance of the measured valve seat

Table 2 Measuring machine specifications

Manufacturer		TOKYO SEIMITSU ACCRETECH
Product name		SVA Fusion
Accuracy	MPE _E	1.9 + 4 L/1000 μm
	MPE _p	1.9 μm
	MPE _{THP}	2.8 μm

is shown in Fig. 6. Deformation was measured with the following steps:

Step 1: Press fit the valve seats into the setting plate

Step 2: Form a contact surface with the valves

Step 3: Measure the contact surface after forming

Step 4: Pinch the shim plates and tighten the plates

Step 5: Measure the contact surface after tightening

Thus, valve seat face deformation was calculated based on these steps by superimposing measurements from after forming (Step 3) and measurements from after tightening (Step 5) to compare the data. A sample calculation is given in Fig. 7. The data was compared in the valve lift axial direction; results were taken as positive when the measuring plane, after tightening, was displaced in the valve lift direction, and negative when displaced in the opposite direction.

Figure 8 shows three-dimensional measurements of the valve seat face deformation as reproduced in this test and valve seat face deformation results from an actual engine as calculated with computer-aided engineering (CAE). The CAE results are calculated with the cylinder heads attached in ambient temperature. The three-dimensional measurements show similar amplitude and cycle of valve seat face deformation as the CAE results, meaning that this approach reproduced valve seat face deformation equivalent to that in actual engines. Hereinafter, the amplitude of

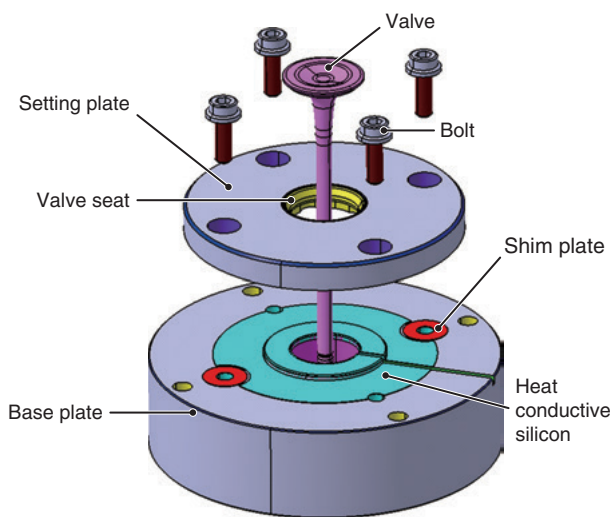


Fig. 5 Methodology of valve seat face deformation

deformation for the valve seat will be treated as valve seat face deformation.

5.2. Test Conditions and Determining Sensitivity

In this test, wear was measured when a valve seat was deformed and when none were deformed, taking air-fuel ratio, valve seat face pressure, and valve seat face temperature as constant. The measurement results are given in Fig. 9. Under the same conditions, wear increased by deforming the valve seats, indicating sensitivity to wear.

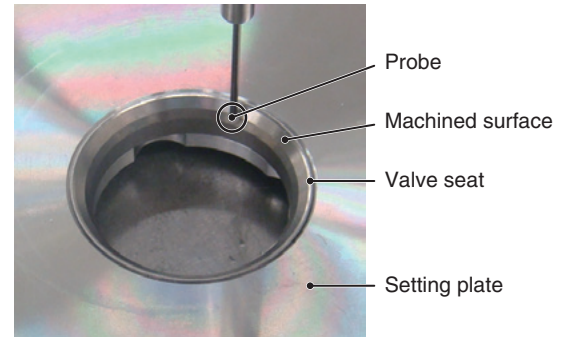


Fig. 6 Appearance of measured valve seat

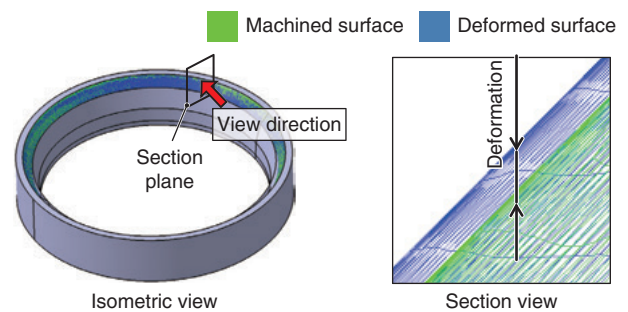


Fig. 7 Calculations for valve seat face deformation

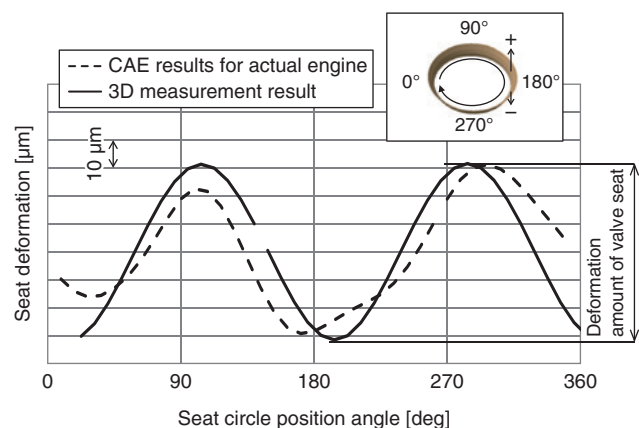


Fig. 8 Valve seat face deformation

5.3. Reflecting into the Model

Valve seat face deformation is reflected into the model. Inputting the air-fuel ratio, valve seat face pressure, and valve seat face temperature, wear W_ε for this test was predicted from predicted wear W_0 , valve seat face deformation $\Delta\varepsilon$, and coefficient B using Eq. (4).

$$W_\varepsilon = (B * \Delta\varepsilon + 1) W_0 \quad (4)$$

The wear prediction model was constructed by inputting air-fuel ratio, valve seat face pressure, valve seat face temperature, and valve seat face deformation as the parameters for Eq. (4).

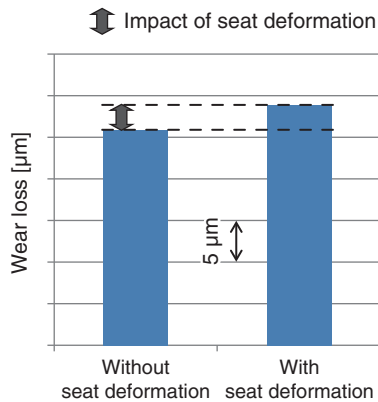


Fig. 9 Impact of seat wear loss on seat deformation

6. Reflecting Combustion Pressure and Temperature into the Model

6.1. Bench Test Conditions and Wear Measurements

The engine specifications used for this test are shown in Table 3. Valve seat wear was measured using radiation wear measurement. Radiation wear measurement is a method of measuring valve seat wear by activating the valve seat to be measured and then measuring the radiological dosage emitted by the valve seat⁽⁸⁾. An image of the radiation detection machine is given in Fig. 10, and the engine bench test conditions are given in Table 4.

6.2. Reflecting Test Results into the Response Surface Model

The change in wear loss ratio with change in combustion pressure is shown in Fig. 11. Wear loss ratio increases with combustion pressure. Combustion temperature also rises with combustion pressure. This wear loss ratio increase was attributed to a valve micro slip due to the increase in combustion pressure and temperature.

Based on this attribution, valve seat face pressure due to valve micro slip from combustion pressure and temperature was calculated with CAE and reflected into the model to compensate for combustion pressure and temperature.

Table 3 Engine specifications

Type of engine	L4 DOHC i-VTEC Turbo	
Bore × Stroke (mm)	86.0 × 85.9	
Displacement (cm ³)	1996	
Compression ratio	9.8	
Number of valves	Intake	2
	Exhaust	2
Valve head dia./ Stem dia. (mm)	Intake	35.0/34.5
	Exhaust	29.0/28.5
Valve seat width (mm)	1.6	
Valve seat base hard particles	Cr-Mo-Co hard particles	
Maximum power (kW/rpm)	228/6500	
Maximum torque (Nm/rpm)	400/2500-4000	
Fuel type	Petrol	

Table 4 Engine bench test conditions

No.	Engine speed [r/min]	Intake air pressure [hPa]	Engine power [kW]	Test duration time [hour]
1	2750	750	27	116.3
2	4500	2300	169	8.0
3	5700	1175	115	30.5
4	5700	1480	145	65.0
5	5700	1950	182	6.5
6	6500	1480	126	20.0

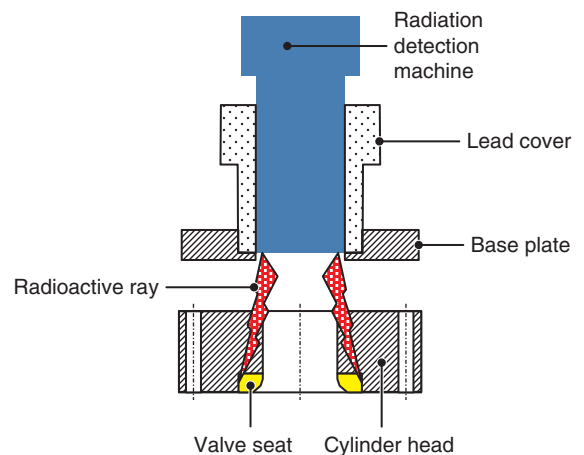


Fig. 10 Wear loss measured with radioactive rays

Equation (5) was derived to predict wear amount W_{total} for the test from valve seat wear W_e as predicted by the model accounting for valve seat face deformation, valve seat face pressure P_v due to valve micro slip, and coefficients D and E .

$$W_{total} = D \cdot \exp(E \cdot P_v) \cdot W_e \quad (5)$$

Thus, a model to account for combustion pressure and temperature during bench test was constructed from Eq. (5) by inputting the air-fuel ratio and the pressure, temperature, deformation, and pressure due to the valve micro slip of the valve seat face.

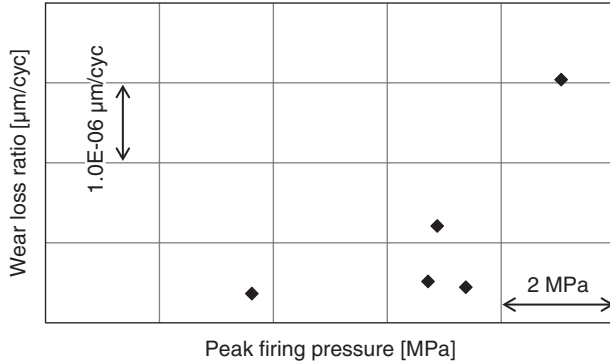


Fig. 11 Wear loss ratio and combustion pressure

7. Verifying Model Accuracy and Examining Model Versatility

7.1. Verifying Model Accuracy

Valve seat wear as predicted with the model for bench test and road endurance test are given in Fig. 12. The model was able to predict valve seat wear for bench test and road endurance test at a high accuracy of $R^2 = 0.9105$.

7.2. Examining Model Versatility

Model versatility was investigated based on application of the model when using a different valve seat material. The valve seat material considered was ferrous sintered alloy, comprising Cr-Co-Fe-Ni hard particles. This differs from a ferrous sintered alloy comprising Cr-Mo-Co hard particles. Model application and versatility when using the different valve seat material was investigated by taking the following steps:

- Step 1: Build a test rig as presented in Section 4.1., using the actual engine valves and valve seats
- Step 2: With the test rig from Step 1, select one of the test conditions from the L18 orthogonal table, given in Table 1 in Section 4.2. and measure valve seat wear
- Step 3: Using the test condition selected in Step 2, compare the valve seat wear as measured in Section 4.2. with that measured in Step 2, then calculate the wear correction value for the model
- Step 4: Correct the model using the wear correction value

calculated in Step 3

The model, as corrected by following these steps, was used to predict valve seat wear for bench test with the different valve seat material. The predictions are given in Fig. 13. The results accurately predicted valve seat wear in the bench test, meaning the model is highly versatile.

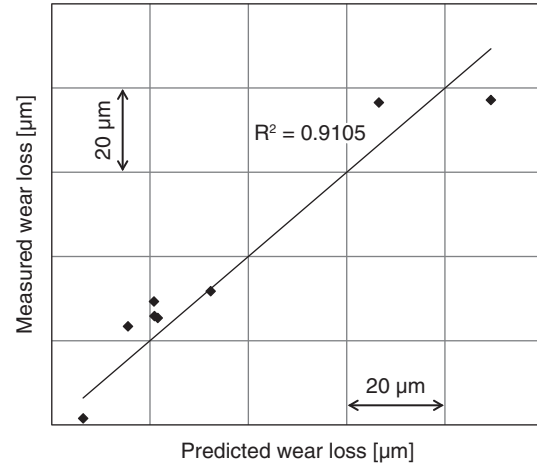


Fig. 12 Wear loss predicted with response surface model and actual road tests

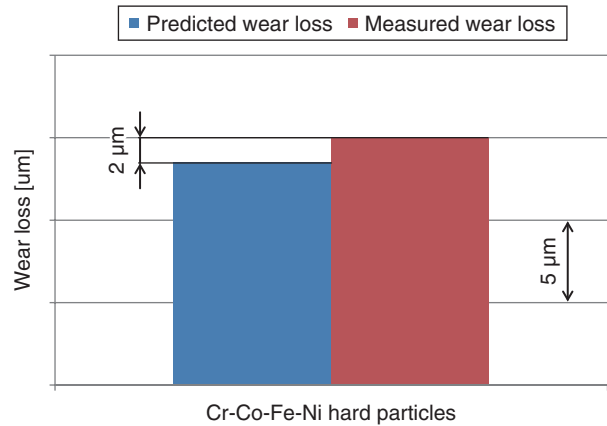


Fig. 13 Predicted results for engine with different materials

8. Conclusion

Through this research, the following findings were made and a model was successfully constructed for predicting exhaust valve seat wear in gasoline engines. By doing so, a method has been devised to reduce wear for various tests while building the cylinder head at the initial design phase of engine development to help increase valve seat wear resistance. This has reduced redesigns and retesting, in turn shortening the development period and reducing development costs.

- (1) By determining the factor sensitivity for wear, sensitivity was found to be highest for valve seat face temperature, making it a factor to keep note of.
- (2) Valve seat face deformation was found to be sensitive to wear.
- (3) By measuring valve seat wear for bench test using radiation wear measurement, it was determined that the wear loss ratio increases with combustion pressure.
- (4) Valve seat wear was also predicted when using different valve seat material, showing that the model constructed is highly versatile.

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Enhancement of Accuracy of Tire Wear Prediction Method by Reflection of Material Temperature Characteristics

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ABSTRACT

In order to increase the prediction accuracy of tire wear, prediction error has been decreased by setting differing temperature characteristics for each rib in the tread rubber viscosity, characteristic of a prediction model. In addition, though previously challenging, calculation of the wear degree for each rib has increased the accuracy of uneven wear prediction, such as center wear in the front tires of front wheel drive vehicles and wear on the outer shoulders of rear tires. This prediction model will make it possible to predict the degree of wear, including uneven wear, from the initial stage of vehicle development in addition to studying rolling resistance and wet braking performances, which will contribute to increased vehicle development efficiency. By reducing the necessity of conducting wear evaluation tests using real vehicles, the model will also contribute to reducing the person-hours involved in testing.

1. Introduction

Automakers are reducing the rolling resistance of tires in order to increase fuel efficiency as a response to global environmental issues. Normally, when tread rubber with low hysteresis loss is employed to reduce tire rolling resistance, wet braking performance also declines. The use of silica as an additive in addition to conventional carbon black reduces hysteresis loss and boosts wet braking performance, but the wear life of the tire declines. It is necessary to balance these antagonistic tire performance demands with a combined variety of other design elements, such as the tire tread pattern, the internal structure of the tire, and the tire compound composition. These performance demands have a significant effect on vehicle performance design, and the ability to make accurate predictions at the initial stage of development would be a major contribution in raising the efficiency of the vehicle development process as a whole.

However, making predictions is not an easy task because wear life is affected by a large number of factors and design elements, including loads, slip velocity, the physical properties and temperature characteristics of the rubber used, road surfaces, and driving conditions. This means that

studies necessitate extended periods of driving tests, and this has a significant developmental effect.

Previously proposed methods of evaluating wear can be broadly divided into evaluation using driving tests, and evaluation on the bench.

In wear evaluation using driving tests, benchmark tires and the tires under evaluation are fitted to vehicles, allowing for conditions to be close to actual use environments. However, it is not easy to hold factors in the test environment constant, such as road surface conditions, vehicle operation, external temperatures, and sunshine. Relative wear evaluations are therefore mainly used in the later stages of vehicle development, and rarely applied in the initial stages.

Wear evaluation on the bench involves a combined evaluation of the form of wear, using a unit tire wear test apparatus, and the distribution of wear energy on the surface of the rolling tire, using a wear energy test apparatus^{(1), (2)}. These evaluation methods make it possible to hold the test environment constant, and because they do not use an actual vehicle, they can be readily employed for studies in the initial stage of development. However, the test apparatus road surface differs from an actual road. In the case of a drum test apparatus, the shortening of

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the tire's contact patch length produces differences in the condition of the tire contact patch, and at times it is not possible to reproduce wear in actual use environments. Kobayashi, et al proposed a prediction method based on Scallamach's theory, combining wear energy with an index expressing the wear resistance of the rubber⁽³⁾. Excepting the shoulders of the tire, the predictions made using this method corresponded well with data from actual use environments.

In a previous paper⁽⁴⁾, the authors proposed a prediction model based on a wear volume formula for polymer abrasion⁽⁵⁾, using the physical properties of tread rubber and contact patch data to accurately predict the wear life of the front wheels on a front wheel drive (FF) vehicle. However, issues remained in relation to the prediction of uneven wear of the front tires and the accuracy of prediction of wear life in the rear tires.

This paper discusses the correction of this prediction model to make it possible to reflect different temperature characteristics for each rib in the tread rubber viscosity characteristic employed in the new model, based on the finding of Hirayama, et al⁽⁶⁾, that the wear life of tire tread rubber displays a strong correlation with the properties of the rubber at lower temperatures, rather than road surface temperatures. It was verified that the prediction of wear life using the new model, including wear in the rear tires and uneven wear, displayed sufficient accuracy for use in vehicle development.

2. Tire Wear Life Prediction Formula

The authors' previous paper proposed a model for the prediction of tire wear life employing a wear volume formula for polymer abrasion (Eq. (1) below).

$$V = k \frac{\mu WL}{H\sigma\varepsilon} \quad (1)$$

V : Wear volume [mm³]
 k : Constant [-]
 μ : Coefficient of friction [-]
 W : Load [N]
 L : Slip distance [mm]
 H : Rubber hardness [°]
 σ : Breaking strength [MPa]
 ε : Breaking strain [%]

This model expressed the wear life of groove i , shown in Fig. 1, L_{ti} , as Eq. (2), using wear speed for each rib, V'_j ,

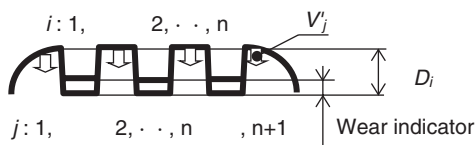


Fig. 1 Tread rib wear speed and groove depth

the groove depth at i , D_i , and a wear indicator height of 1.6 mm.

$$L_{ti} = \frac{2 \times (D_i - 1.6)}{V'_j + V'_{j+1}} \quad (2)$$

L_{ti} : Wear life [km]
 i : Groove position No.
 j : Rib position No.
 D_i : Groove depth at i [mm]
 V'_j : Wear speed at j [mm/km]

The wear coefficient in Eq. (1), μ , can be expressed as a function of the storage elastic modulus, E' , and $\tan \delta$, which both display temperature characteristics. In this paper, μ is expanded with consideration of the temperature characteristic as shown in Eq. (3), based on findings reported in a paper by Kawakami, et al⁽⁷⁾.

$$\mu(T) = f[\tan \delta(T), E'(T)] \quad (3)$$

$\mu(T)$: Coefficient of friction at T (°C) [-]
 T : Temperature [°C]
 $\tan \delta(T)$: Loss factor at T (°C) [-]
 $E'(T)$: Storage modulus at T (°C) [-]

The distribution of both contact patch stress and tire surface temperature in a tire fitted to an actual vehicle, is affected by tire deformation and the heat generated by friction with the road surface. Due to this, wear in each rib is dependent on the shape of the contact patch, as well as alignment factors such as toe and camber, and can therefore be considered to differ for each rib. The wear volume formula for each rib, Eq. (4), can therefore be defined by substituting μ in Eq. (1) with the coefficient of friction in Eq. (3), $\mu(T)$.

$$V_j = k_j \frac{\mu_j(T) W_j L_j}{H\sigma\varepsilon} \quad (4)$$

V_j : Wear volume at j [mm³]
 k_j : Constant at j [-]
 $\mu_j(T)$: Coefficient of friction at j [-]
 W_j : Contact patch pressure at j [MPa]
 L_j : Slip distance at j [mm]

This makes it possible to express the wear speed for each rib, V'_j , as Eq. (5).

$$V'_j = k_j f(W_{aj}, W_{bj}, S_j, E'_j(T), \tan \delta(T), H, \sigma, \varepsilon) \quad (5)$$

W_{aj} : Average pressure [kg/mm²]
 W_{bj} : Maximum pressure [kg/mm²]
 S_j : Slip distance (calculation) [mm]

As H , σ , and ε in Eq. (4) are materials terms, in this paper they are considered constant, irrespective of the rib position. In addition, because the load term, W , and the slip

distance term, L , are affected by alignment, W_j and L_j have been employed.

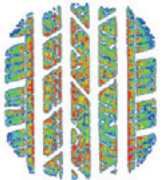
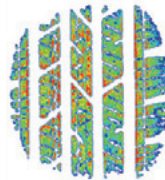
3. Tire Contact Patch

W_j , L_j , and $\mu_j(T)$ in Eq. (4) are determined for each rib in order to reflect the differences in the mechanism of wear for each rib in the contact patch and the differing wear conditions for the front and rear tires in the prediction model.

In most cases, the front tires on an FF vehicle tend to display center wear due to acceleration and deceleration, while rear tires tend to display shoulder wear as a result of initial alignment. It can therefore be hypothesized that differences in the stress distribution and heat balance of the contact patch affect wear life. Contact patch pressure was measured for front and rear tires in order to verify this hypothesis. The distribution of shear force in the contact patch during acceleration and deceleration, a factor in center wear in front tires, was also measured. In the case of the shoulder wear in rear tires, toe and camber angles were imparted to tires, and the temperature of the contact patch when the tire was rolling was measured, and the distribution of wear energy in the contact patch was studied.

3.1. Contact Patch Pressure for Each Rib

Contact patch pressure was measured and the load term, W , was determined in order to study the effect of load on the front and rear tires, as well as their toe and camber angles on the load on each rib. Figure 2 shows a sample of the measurement results (215/50R16 100S). The figure shows measured values for average contact patch pressure, W_a , maximum contact patch pressure, W_b , and the ratio of W_a and W_b for each rib when the center rib contact patch pressure is 1.

	Front					Rear				
Foot print										
Rib No.	#1 (out)	#2	#3*	#4	#5 (in)	#1 (out)	#2	#3*	#4	#5 (in)
Load [kN]	4.82					3.55				
Toe [°]	0					0.09 (in)				
Camber [°]	0					1.00 (negative)				
W_a [MPa] (%)	0.36 (94)	0.36 (96)	0.38 (100)	0.37 (98)	0.36 (94)	0.37 (97)	0.36 (95)	0.38 (100)	0.37 (97)	0.36 (95)
W_b [MPa] (%)	1.44 (160)	1.10 (122)	0.90 (100)	0.93 (103)	1.44 (160)	1.43 (130)	0.90 (82)	1.10 (100)	1.19 (108)	1.43 (130)

* Reference for maximum and average pressure

Fig. 2 Maximum and average pressure of contact patch

Table 1 Calculation results for slip distance

	Front					Rear				
Rib No.	#1 (out)	#2	#3	#4	#5 (in)	#1 (out)	#2	#3	#4	#5 (in)
Slip distance [mm]	4.43	5.26	5.49	5.22	4.61	10.14	7.21	4.13	0.74	3.03

Figure 2 shows that W_a is highest for the center of the tire and W_b is highest for the shoulders of the tire for both front and rear tires. In addition, it was considered that due to factors such as the load on the front and rear tires, as well as differences in alignment, the effect of W on wear differs for each rib. It was further considered that the accuracy of wear prediction could be increased by setting W_a and W_b for each rib.

3.2. Calculated Values of Slip Distance for Each Rib

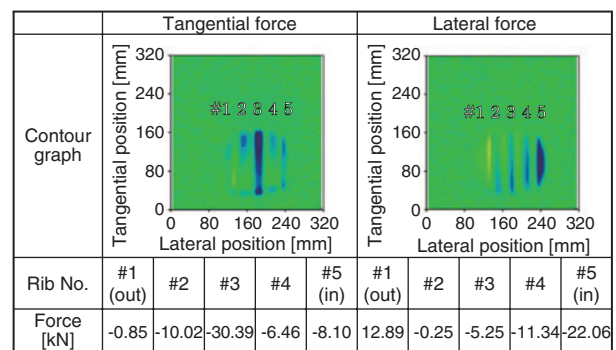
Because it is not easy to directly measure the slip distance term, L , as in the authors' previous paper, this term was calculated for each rib using a geometrical method. Table 1 shows the calculation results.

The results in Table 1 show that for the front tires, the slip distance tends to become higher the closer the rib is to the center of the tire, while in the rear tires, slip distance tends to become higher the closer the rib is to the outer side of the tire. This matches the tendency of the front tires to display center wear and the rear tires to display shoulder wear.

3.3. Factor Analysis of Tire Wear

A force matrix sensor manufactured by A&D Company, Limited, was employed to measure the shear force of the contact patch in front tires while fitted to a vehicle and rolling. Figures 3 and 4 respectively show an example of the results for acceleration and deceleration.

The measurement results shown in Figs. 3 and 4 indicate that a large shear force is produced on the center rib during acceleration and that shear force is distributed



Load: 4.3 [kN] Temperature: 25 [°C] V = 34.3 [km/h]

Fig. 3 Contact patch shear force during vehicle acceleration

uniformly on each rib during deceleration.

These results conform with the tendency of the calculation results for slip distance shown in Table 1, and also match the empirical observation that the front tires in FF vehicles display center wear.

Next, the temperature of the surface of the tire tread when rolling was measured using a flat-belt tire-test machine in order to determine the effect of the rear tire toe and camber angles on the contact patch's temperature. Figure 5 shows temperature measurement results for each rib, and Fig. 6 shows measurement results for the temperature distribution in the tread cross-section.

The results shown in Fig. 5 indicate that the temperature of the outer rib is 1.9°C lower than the temperature of the inner rib.

The results in Fig. 6 show that temperature is lower on the outer side of the tire for the entire tread cross-section as well.

The energy budget of the tire surface is a balance between dynamic energy generated by the deformation of the rubber due to slip and heat energy generated by internal hysteresis⁽⁸⁾, as shown in Eq. (6), and the amount

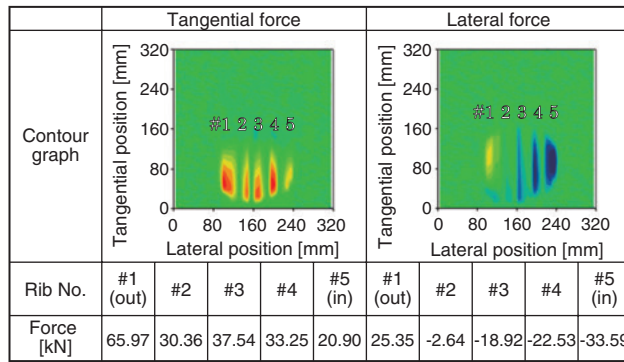


Fig. 4 Contact patch shear force during vehicle deceleration

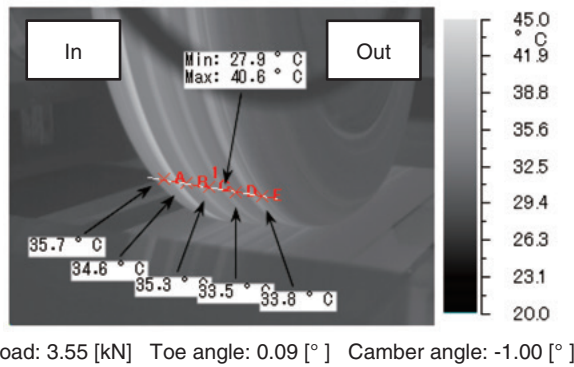


Fig. 5 Measurement of tire surface temperature on flat track

of energy that is dissipated. It is considered that because of this, internal heat generation is controlled and the surface temperature is lower in sections of the tire with a high-slip distance.

In addition, wear advances more rapidly the lower the temperature of the tire tread rubber is. Due to this, wear is swifter to appear in the outer section of the tire, where slip distance is high and temperature is low. These results indicated that it would be possible to realize a more accurate wear prediction by employing the proposed method and using a temperature-dependent coefficient as the $\mu(T)$ term for each rib.

$$W_l = \int_0^{\frac{2\pi}{\omega}} \sigma \dot{\epsilon} dt = \pi \epsilon_0^2 E'' = \pi \epsilon_0^2 E' \tan \delta \quad (6)$$

W_l : Strain energy [J]

σ : Internal stress [MPa]

ϵ : Strain [mm]

ϵ_0 : Maximum strain [mm]

3.4. Calculation of Wear Prediction Model Coefficients

In their previous paper, the authors used the value at $T = 25$ [°C] for the $\mu_j(T)$ term in Eq. (4). In this paper, experimentally determined optimal values will be employed for each rib. Wear speed in Eq. (2), V_j is calculated using Eq. (7).

$$\log V_j' = C_{waj} \times W_{aj} + C_{wbj} \times W_{bj} + C_{sj} \times S_j + C_{s2j} \times S_j^2 + C_{c(E')j} \times E_j'(T) + C_{c(\tan\delta)j} \times \tan\delta(T) + C_{c(H)j} \times H + C_{c(\sigma)j} \times \sigma + C_{c(\epsilon)j} \times \epsilon + k_j \quad (7)$$

C_{waj} : Coefficient of average pressure

C_{wbj} : Coefficient of maximum pressure

C_{sj} : Coefficient of slip distance

C_{s2j} : Coefficient of slip distance (square member)

$C_{c(E')j}, C_{c(\tan\delta)j}, C_{c(H)j}, C_{c(\sigma)j}, C_{c(\epsilon)j}$: Coefficient of rubber

In order to calculate optimal values, $\tan \delta$ and E' for each rib of the front and rear tires were varied within a range

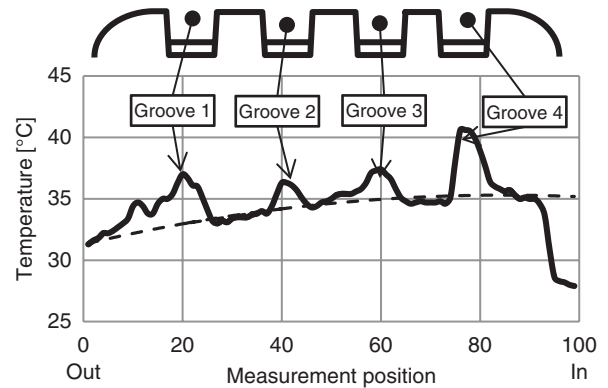


Fig. 6 Tire surface temperature distribution on flat track

Table 2 Maximum correlation coefficient and temperature

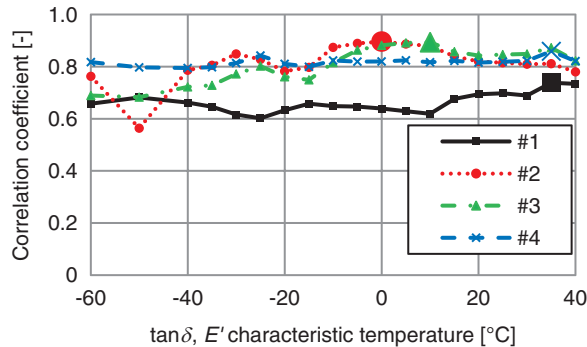
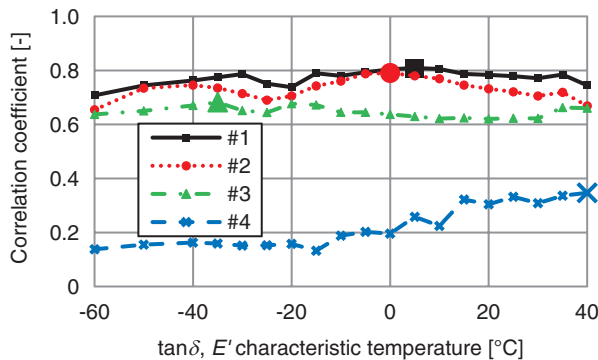
Groove position			#1 (out)	#2	#3	#4 (in)
Correlation coefficient [-] at temperature [°C]	Front	Current	0.766 (at 25)	0.802 (at 25)	0.800 (at 25)	0.844 (at 25)
		Proposed	0.738 (at 35)	0.896 (at 0)	0.893 (at 10)	0.859 (at 35)
	Rear	Current	0.793 (at 25)	0.311 (at 25)	0.403 (at 25)	0.145 (at 25)
		Proposed	0.809 (at 5)	0.791 (at 0)	0.683 (at -35)	0.347 (at 40)

between -60°C and 40°C , and a multiple regression analysis was conducted. The temperatures at which the correlation coefficients, between the results of predictions using the model and the results of driving tests for $\tan\delta$ and E' , were at their highest were determined by this analysis. Figures 7 and 8 show graphs of the temperatures for $\tan\delta$ and E' employed in calculations and the correlation coefficients, while Table 2 shows the maximum correlation coefficients and the temperature at that time.

Table 3 shows the coefficients employed in Eq. (8), obtained from Table 2. Using these it was possible to set wear speed formulas for each rib.

Table 3 Results for multiple regression model coefficients

Groove position		Front				Rear			
		$i=1$ (out)	2	3	4 (in)	$i=1$ (out)	2	3	4 (in)
Load factor (Ave.)	W_a	0.20	-0.05	-0.05	-0.25	-0.38	-0.64	-0.63	-0.21
Load factor (Max)	W_b	0.06	-0.02	-0.02	0.02	0.04	-0.05	-0.06	-0.04
Slip distance	S	8.51	6.12	6.12	-2.23	1.78	1.33	1.17	-2.03
Slip distance (Square)	S^2	-7.22	-4.67	-4.67	12.59	-0.80	-0.97	-0.83	1.57
Material property	C_c ($\tan\delta$)	0.00	-0.35	-0.35	0.01	-0.30	-0.13	0.10	0.22
	C_c (H)	0.62	-0.25	-0.25	-0.94	-0.63	-0.15	-0.14	-0.15
	C_c (ε)	0.33	-0.20	-0.20	-0.52	-0.15	-0.04	-0.06	0.07
	C_c (σ)	-0.21	1.02	1.02	0.61	0.50	0.39	0.48	-0.16
	C_c (E')	-2.02	0.66	0.66	2.73	0.63	0.05	0.00	-0.79
Constant	k	-3.93	1.92	1.92	6.22	5.43	4.50	3.47	4.04

Fig. 7 Relationship between $\tan\delta$, E' and correlation coefficient for front tireFig. 8 Relationship between $\tan\delta$, E' and correlation coefficient for rear tire

4. Accuracy Verification

In order to verify the accuracy of the proposed tire wear prediction model, passenger vehicles in categories B to D, and SUV, were employed to conduct driving tests of 15 types of tires, and the accuracy of predictions made using the models proposed in the authors' previous paper, and those models proposed in this paper, were then compared.

4.1. Results of Wear Life Prediction

Tables 4 and 5 show wear life measured in driving tests and wear life predicted using the current and proposed models for the front and rear tires.

Using these results, the predictive accuracy of each model in relation to wear life in driving tests was studied. Figures 9 and 10 respectively show results for the front tires and the rear tires.

As Fig. 9 shows, the average error of values estimated using the prediction model in relation to the results of front tire wear tests using actual vehicles was 15.7% for the previous model, but 12.5% for the proposed model, representing a 3.2-point reduction in error. In the case of the rear tires, a 2.4-point reduction was realized, from 16.2% to 13.8%, as shown in Fig. 10.

The correlation coefficients between wear life measured in driving tests and wear life predicted by each model were also studied. Figure 11 shows results for the front tires, and

Table 4 Front tire wear life

	Wear life [1000 km]														
Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Measurement	34.1	30.3	29.2	32.3	33.2	36.8	34.7	31.1	25.6	28.2	28.5	23.0	21.1	20.8	20.8
Current	32.4	35.1	29.8	37.3	39.7	37.1	32.9	32.9	33.3	32.7	30.6	29.9	24.9	24.6	27.1
Proposed	31.4	35.1	29.9	33.3	36.7	36.5	34.1	34.0	32.0	30.7	30.1	26.7	25.9	25.1	28.6

Table 5 Rear tire wear life

	Wear life [1000 km]														
Test No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Measurement	58.9	77.6	54.9	85.2	47.3	75.2	52.0	45.2	54.5	47.7	40.1	40.3	57.6	45.9	35.7
Current	44.1	67.2	49.3	73.8	53.1	68.5	49.3	53.1	68.7	54.1	46.1	51.1	49.0	39.8	46.6
Proposed	46.3	72.3	46.2	67.8	52.8	65.3	48.4	46.8	67.4	45.7	45.7	47.8	53.3	40.6	45.4

Fig. 12 shows results for the rear tires.

The correlation coefficient for the front tires has increased from 0.821 to 0.866, and the correlation coefficient for the rear tires has increased from 0.760 to 0.809.

This verifies that consideration of the temperature characteristic of the tires has increased the accuracy of prediction. It is considered that the application of this prediction model in the tire development process for new vehicles will reduce the need for tire verification tests in the case of tires for which the previously reported model was

not able to determine whether an actual vehicle verification test was necessary or not.

4.2. Results of Uneven Wear Prediction

As Table 2 showed, consideration of the temperature characteristic in relation to μ made it possible to increase the correlation coefficients for grooves #2 through #4 for the front and rear tires.

It was considered that this would increase the accuracy of uneven wear prediction, and the results of driving tests and wear life predictions using each of the models were therefore compared for each groove in the front and rear tires. Figure 13 shows the results of Test No. 10, as an example of the results.

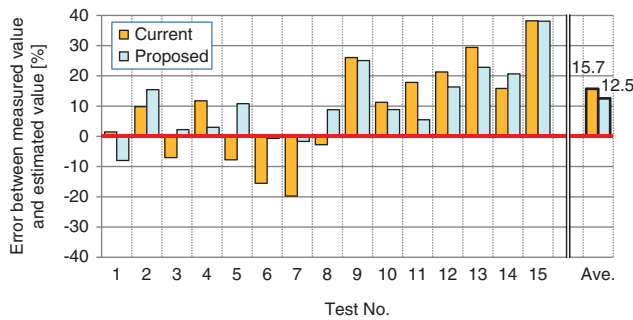


Fig. 9 Accuracy of prediction of front tire wear life for current and proposed method

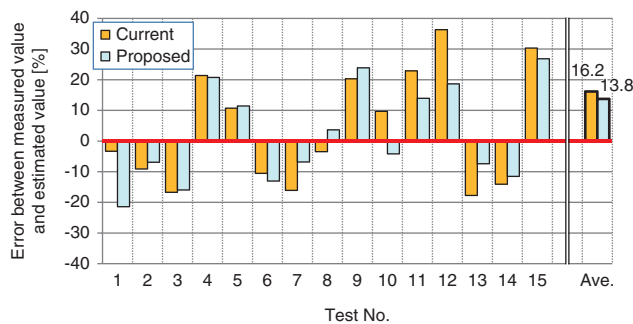


Fig. 10 Accuracy of prediction of rear tire wear life for current and proposed method

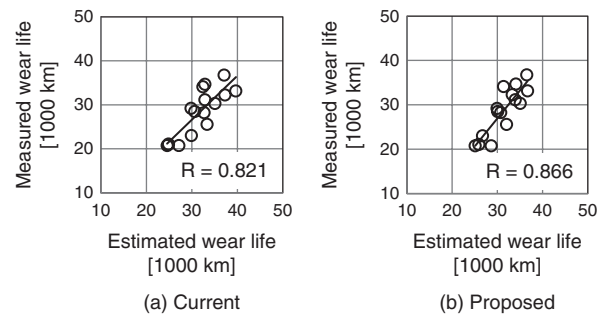


Fig. 11 Estimation and measurement of front tire wear life

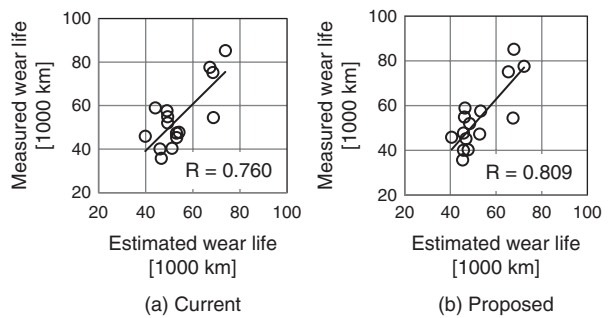


Fig. 12 Estimation and measurement of rear tire wear life

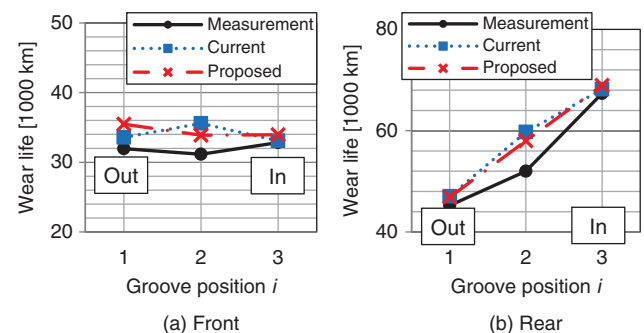


Fig. 13 Estimation and measurement of uneven wear

The use of the proposed model made it possible to predict the tendency of center wear for the front tires, which was calculated as shoulder wear inaccurately using the previous model. With regard to wear in the rear tires, the model was also able to accurately predict the tendency of wear in the shoulders of the tire, and the values predicted for wear in each groove were close to the results of driving tests. These results indicated that the proposed model increased the prediction accuracy of uneven wear.

5. Conclusion

A method of increasing the accuracy of a tire wear life prediction model was proposed, and its effectiveness was studied.

It was verified that taking the differing temperature characteristics of each rib from the front and rear tires into consideration for the wear coefficient, μ , employed in the wear life prediction model increased the accuracy of wear prediction and also increased the correlation coefficient between the results of predictions and driving tests. In addition, the accuracy of prediction of uneven wear was also increased. These results demonstrated that the proposed model was able to predict wear including differences in the form of uneven wear.

The application of this model in the new tire development process will make it possible to study performance during the initial stages of vehicle development, contributing to increased development efficiency. In addition, by reducing the necessity for wear evaluations in driving tests involving actual vehicles, the application of the model will also contribute to reducing the development time period.

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Study of Curing Behavior of Urethane Clear for Short Baking

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ABSTRACT

Curing behavior required for polishing repair of the clearcoat has been studied with the aim of shortening the baking time for reducing CO₂ emissions in the coating process. The authors also studied curing behavior that enables the transition of Isocyanate to the basecoat from the clearcoat.

As a result, it was found that polishing reparability is enhanced by increasing the storage modulus of the clearcoat at the end of baking. Furthermore, it was found that there is a correlation between the time until the storage modulus rises and transition amount of isocyanate to the basecoat. The curing behavior required for a shorter baking time and directivity in resin design were determined from these results.

1. Introduction

At Honda, development into reducing volatile organic compounds and dechlorination has been conducted for the purpose of decreasing the amount of environmentally hazardous substances used in automobile coating⁽¹⁾. In recent years, amidst a strong demand for the reduction of greenhouse gas emissions that are said to cause climate change, the reduction of CO₂ emitted in automobile manufacturing processes has become an important issue.

In the body coating process at automobile manufacturers, a 3-coat 2-bake coating system with shorter processes has been developed for reducing CO₂ emissions⁽²⁾⁻⁽¹⁰⁾. On the other hand, although a 3-coat 1-bake coating system is being introduced in bumper coating ahead of body coating, further reduction of CO₂ emissions is required.

Shortening of the baking time is effective for reducing CO₂ emissions that are generated in the bumper coating baking process. During the baking process, it is important that coating performance, such as mechanical strength and chemical durability, is contributed to by crosslinking of the clearcoat and control of transition of curing components between coats. Conventional methods where crosslinking of coats after baking is analyzed is limited to qualitatively ascertaining curing behavior during the baking process, and quantitative analysis of coating performance was not possible. For this reason it is considered that, by quantitatively analyzing curing behavior in the baking process to clarify the correlation with coating performance,

the optimum curing behavior can be established to further shorten the baking time.

This paper describes the results of analyzing the relationship between curing behavior and coating performance in the clearcoat baking process that is required to achieve a shorter baking time.

2. Issues in Shortening the Baking Time

Clearcoat that is used on resin parts including bumpers is a two-portion-type urethane resin made up of hydroxy-containing acryl and a hexamethylene diisocyanate trimer (isocyanurate trimer) on the curing component. In the coating process, this coat is a low-viscosity fluid that can be easily handled, whereas in the baking process, the coat is a thermosetting resin material that becomes a rigid coated film as a result of a three-dimensional crosslinking structure that forms due to a crosslinking reaction. To shorten the baking time, it is important that polishing reparability after baking and coating adhesion in the user's operating environment be satisfied after having promoted the crosslinking reaction between the acrylic resin and isocyanate.

The coat structure on the bumper is as follows. A clearcoat is a multilayer film formed on the basecoat by recoating as shown in Fig. 1, and the bumper coat has a mechanism where a crosslinking reaction occurs on the basecoat during baking by isocyanate transiting to the basecoat from the clearcoat after coating clearcoat and, as a result, coat strength is enhanced and film adhesion

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properties are expressed.

A coated film that satisfies coating performance, such as polishing reparability and film adhesion properties can be obtained by performing baking of this coat at 80°C for 20 minutes.

A common method for shortening the baking time is to add a curing-acceleration catalyst such as dibutyltin dilaurate (DBTDL) to the clearcoat to promote the reaction⁽¹¹⁾. It is known that polishing reparability during baking is enhanced by promoting the crosslinking reaction of the clearcoat by this method. On the other hand, because the crosslinking reaction of the clearcoat is promoted, the transition amount of isocyanate to the basecoat decreases, raising the issue that adhesion will drop. For this reason, the clarification of the relationship between curing behavior and coated film performance in the baking process and the setting of an optimum curing behavior become issues.

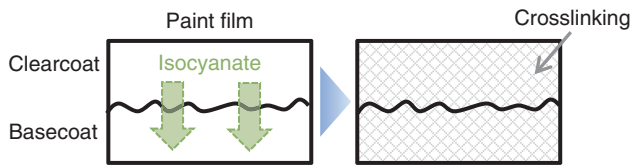


Fig. 1 Film structure of automotive bumper paint

3. Approach to Ascertaining Curing Behavior

With the crosslinking reaction in the baking process, it is presumed that functional groups that should react are already in pairs as shown in Fig. 2 and will not react by a typical 2-component reaction, and that these are connected as a stochastic process. It is considered that a pair of specific functional groups is formed because the crosslinking structure restricts motion⁽¹²⁾.

In the reaction shown in Fig. 2, in which specific functional groups AB react to link together, the formation speed of reaction product AB is expressed as $k \text{AB}$ (where, k is the reaction rate constant). Loss of AB is proportional to time t , and the 1st-order reaction rate equation in Eq. (1) is derived if the product after all AB pairs react is taken to be $AB(\infty)$ and the start time of the 1st-order reaction is taken to be td .

$$AB = AB(\infty)\{1 - \exp[-k(t - td)]\} \quad (1)$$

To ascertain the curing behavior in the baking process, measurement of changes in the crosslink density during curing is necessary. The crosslink density is reflected as the storage modulus since, in almost all cases, the coat state during curing is in the rubber elastic region⁽¹³⁾. For this reason, the curing behavior in the baking process can be ascertained by measurement of changes in the storage

modulus during curing.

A rigid-body pendulum-type physical properties testing instrument (RPT-3000W made by A&D Company Limited) as shown in Fig. 3 was used to track changes in the storage modulus during the baking process. This instrument allows a pendulum supported on its knife-edge as its reference point to freely swing in contact with a coating film, and calculates changes in the storage modulus of the coating film from the measured cycle. The swing cycle of the pendulum changes due to changes in dynamic properties when a clearcoat is present between the substrate and knife-edge in the state as shown in Fig. 3. Relative storage modulus $E'r$ can be found as Eq. (2) from the swing cycle of the pendulum⁽¹⁴⁾.

$$E'r = (1/T^2 - 1/T_0^2)/(1/T_1^2 - 1/T_0^2) \quad (2)$$

T_0 : Swing cycle without coating film

T_1 : Swing cycle at reference point

T : Swing cycle with coating film

If Eq. (1) is applied to changes in $E'r$, Eq. (1) can be considered to conform with the test equation that is equivalent to the 1st-order reaction rate equation shown in Eq. (3) from the time that the gelation reaction concludes onwards.

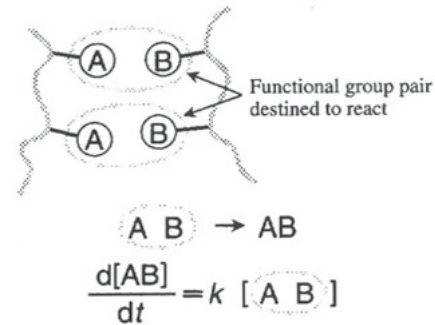


Fig. 2 Hypothetical 1st order reaction. Concentration of reaction product $[AB]$ increases in exponential function.

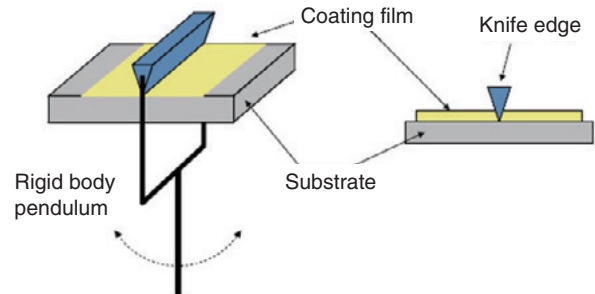


Fig. 3 Rheological measurement apparatus

$$E'r = E'r(\infty)\{1 - \exp[-k(t - td)]\} \quad (3)$$

t : time [min]

$E'r(\infty)$, k , td : constant

It was confirmed that, in curing processing, $E'r$ is proportional to the crosslink density within the limits of changes in $E'r$ that conform to the 1st-order reaction equation⁽¹⁵⁾.

In this study, verification of the correlation with the 1st-order reaction equation will be performed to confirm whether the curing behavior of the coating film can also be tracked by using $E'r$ in bumper coating. The purpose of this study is to clarify the relationship between curing behavior and coating performance, as well as to construct a curing behavior concept with a view to shortening the baking time.

4. Test Methods

4.1. Specimen Preparation Method

The sample for measuring curing behavior was prepared by coating a 0.5 mm-thick stainless steel substrate with clearcoat to a film thickness of 30 μm after baking. The temperature rise curve was set so that temperature rose from 25°C to 80°C in 15 minutes after which the baking temperature was maintained at 80°C or 90°C at 10 or 20 minutes.

The sample for confirmation of polishing reparability and film adhesion properties was prepared by coating priming paint on a polypropylene substrate and further applying a black basecoat, on top of which was applied a prepared clearcoat, and then baking for 10 or 20 minutes at 80°C.

The sample for verification of the transition amount of isocyanate was prepared by coating a black basecoat on a polypropylene substrate, then a prepared clearcoat, baking for 10 or 20 minutes at 80°C, and then peeling off the coated film from the polypropylene substrate to isolate the coated films.

4.2. Polishing Reparability Test Method

Testing of the polishing repair was performed 10 minutes after baking and removal of the sample prepared in Section 4.1. above. After polishing for 15 seconds with 2500 grade sandpaper with a load of 600 g applied, it was confirmed that polishing reparability was possible without any occurrence of white blurs as shown in Fig. 4.

4.3. Film Adhesion Properties Test Method

Film adhesion properties were tested according to a cross-cut test method (JIS K5600)⁽¹⁶⁾ in which a test piece is immersed in 40°C water for a specified period of time and then removed, and the test piece then checked for occurrence of swelling, peeling, etc. of the coated film.

4.4. Transition Amount of Isocyanate Verification Method

The rear surface of the basecoat of the coated film was

measured by a Fourier transform infrared spectrophotometer (Nicolet iS10 FT-IR made by Thermo SCIENTIFIC), and the ratio between the peak intensities of nurate ring derived from isocyanate (1690 cm^{-1}) and ester derived from acrylic resin in the basecoat (1730 cm^{-1}) was measured based on the chart shown in Fig. 5. The calibration curve of the nurate ring/ester peak intensity ratio (1690 cm^{-1} /1730 cm^{-1}) against the amount of isocyanate blended in the basecoat was used to calculate the amount of isocyanate contained in 1 cm^3 of basecoat resin component according to Eq. (4).

$$\begin{aligned} \text{Transition amount} &= \frac{\text{Isocyanate transferred (cm}^3\text{)}}{\text{Resin component added with transferred isocyanate (cm}^3\text{)}} \\ \text{of isocyanate (cm}^3\text{/Resin cm}^3\text{)} & \quad (4) \end{aligned}$$

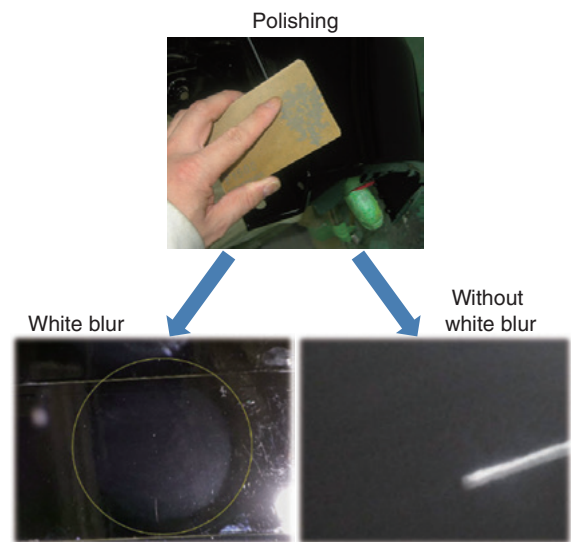


Fig. 4 Schematic diagram of repairability test

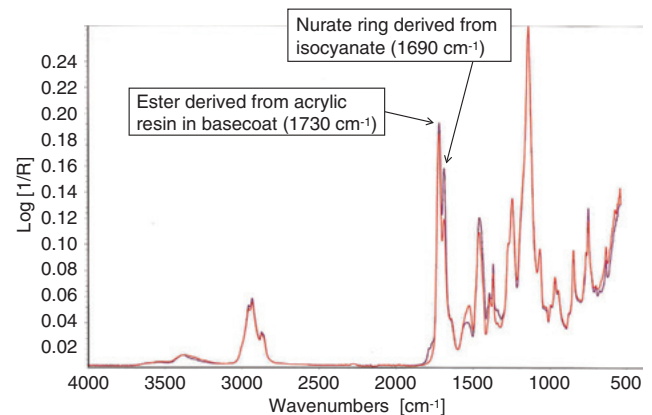


Fig. 5 FT-IR chart of basecoat film

5. Testing and Verification of Curing Behavior and Observations

5.1. Relationship Between Curing Behavior of $E'r$ in Curing Processing and 1st-order Reaction Rate Equation

Figure 6 shows the result of evaluating the relationship between change in behavior of $E'r$ in the baking process and the 1st-order reaction rate Eq. (3) by using 80°C baking-type clearcoat that forms a urethane bond made up of hydroxy-containing acrylic resin that is used in bumpers and isocyanate.

$E'r$ resulted in approaching a coefficient of multiple correlation of 0.999 with respect to the 1st-order reaction rate Eq. (3) within a baking time of 25 to 60 minutes. From this fact, it was confirmed that even with the 80°C baking-type clearcoat that was used in this study, $E'r$ indicates changes in the storage modulus in the curing process, and that use of $E'r$ enables tracking of the curing behavior.

5.2. Result of Influence of Increase in Catalyst Amount on Polishing Repairability and Film Adhesion

Table 1 shows the result of having verified polishing repairability and adhesion properties by conventional clearcoat and by a model clearcoat whose catalyst amount has been increased to twice the conventional amount. When the baking time was reduced simply with a conventional clearcoat, the crosslinking reaction of the clearcoat would not progress sufficiently, resulting in both polishing repairability and film adhesion properties being lowered. When the amount of catalyst added to the clearcoat is excessively increased, however, it was found that the crosslinking reaction progresses at the same rate as in the current reaction and polishing repairability is enhanced although adhesion deteriorates.

Figure 7 shows the result of the transition amount of isocyanate at this time. A decrease in the transition amount

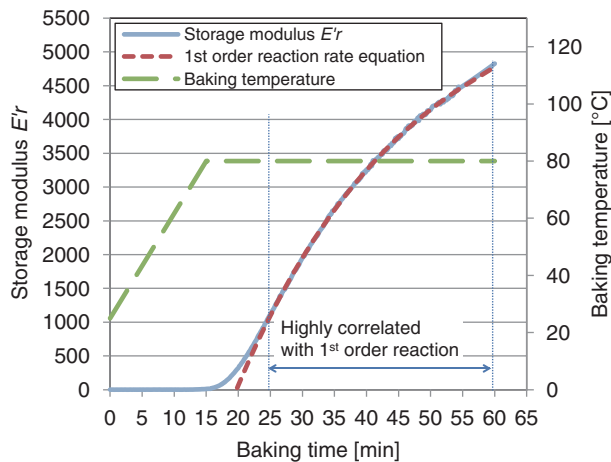


Fig. 6 Storage modulus behavior and 1st order reaction rate equation in baking process

Table 1 Result of spot repair and adhesion property

	Baking condition	Polish	Adhesion	Test number
Current clearcoat	Standard 80°C 20 min	Good	Good	(1)
	Shortened 80°C 10 min	Poor	Poor	–
Current clearcoat with double catalyst		Good	Poor	(2)

of isocyanate to the rear side of the basecoat could be confirmed by doubling the conventional amount of catalyst used.

Whereas the crosslinking reaction of the clearcoat was promoted by an increase in the amount of catalyst added to the clearcoat, and polishing repairability was enhanced as anticipated, it is considered that promotion of the crosslinking reaction in the clearcoat suppresses the transition of isocyanate to the basecoat, resulting in peeling of the coated film.

From these results, it was considered to be important to clarify the curing behavior at the end of baking of the clearcoat that is required for satisfying polishing repairability as well as to clarify the curing behavior of the baking process that is required in transition of isocyanate to the basecoat.

5.3. Verification Result of Polishing Repairability and $E'r$ at Completion of Baking

Figure 8 shows the results of verifying the relationship between polishing repairability and $E'r$ after baking has elapsed by using a conventional clearcoat and a clearcoat

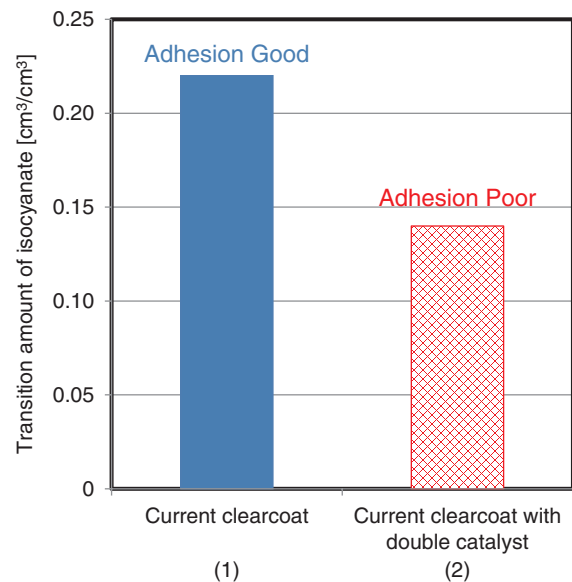


Fig. 7 Transition amount of isocyanate at increasing amount of catalyst

whose catalyst amount has been increased to twice the conventional amount.

The value immediately after baking ends at fixed baking conditions is used for $E'r$ at the completion of baking.

It was found that all coats satisfy polishing repairability at an $E'r$ of 2500 or higher. It is considered that, along with lengthening of the baking time, each of the functional groups of hydroxy-containing acrylic resin and isocyanate form a sufficient crosslink, and that the storage modulus of the coated film increases, which results in formation of a clearcoat having satisfactory polishing repairability. Generally, it is considered that the apparent crosslink density at the end of baking can be increased by increasing molecular weight, glass transition temperature, and the amount of functional groups as coating resin properties.

5.4. Verification Results of Transition Amount of Isocyanate and $E'r$ Rise Start Time

Figure 9 shows the results of having prepared a model clearcoat whose curing catalyst amount has been increased from 0.5 times to twice the amount, and having verified the relationship between the transition amount of isocyanate to the basecoat and the $E'r$ rise start time and coating adhesion. The time from start of baking until $E'r$ reaches 5 is used for the $E'r$ rise start time to clarify the time it takes for the affect of measurement noise to be eliminated and for temperature rise to begin.

It was found that the transition amount of isocyanate to the basecoat increases and adhesion is enhanced by delaying the time until $E'r$ rises.

It was also found that the time until $E'r$ rises speeds up and, at the same time, the transition amount of isocyanate increases by baking at 90°C compared with baking at 80°C. It is considered that solvent volatility was promoted the higher the baking temperature became, the time until $E'r$ rises increased, and, at the same time, the drop in the

coated film melting viscosity due to the rise in coated film temperature promoted the transition of isocyanate to the basecoat. Although increasing the baking temperature to 90°C cannot be considered as a countermeasure for CO₂ emissions since this increase leads to an increase in CO₂ emissions, which is contrary to the original purpose of this study, it became clear that the same trend was present even at different temperatures. Generally, it is considered that initial curing of baking can be delayed by lowering molecular weight, glass transition temperature, and the amount of functional groups as coating resin properties.

5.5. Observations Intended for Shortening Baking Time

Figure 10 shows the concept behind shortening the baking process based on the above results. To satisfy

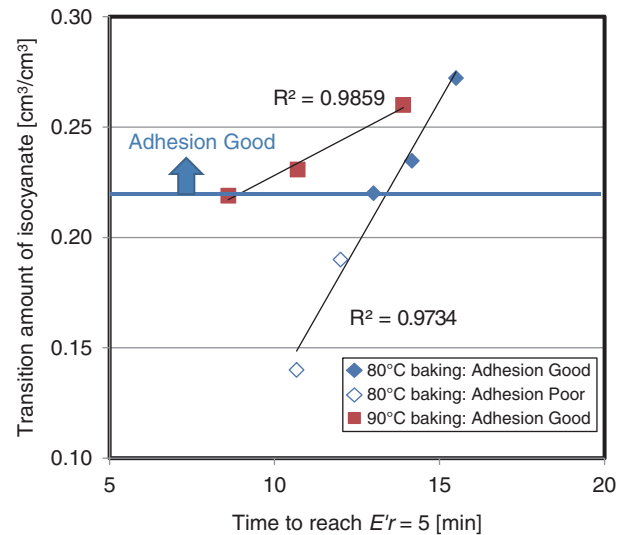


Fig. 9 Relationship between time to reach $E'r = 5$ and transition amount of isocyanate

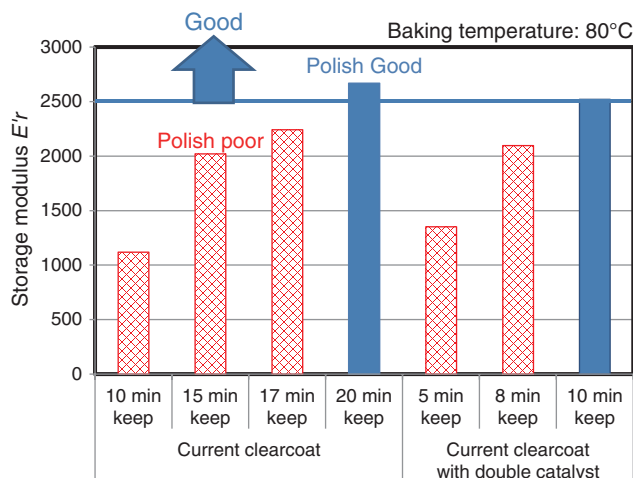


Fig. 8 Relationship between sharpness and storage modulus

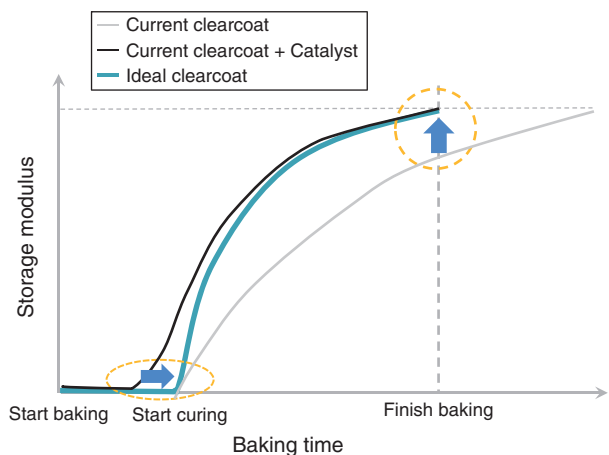


Fig. 10 Concept of storage modulus for short baking clearcoat

polishing repairability, it was considered that increasing E' at the end of baking was necessary for increasing the storage modulus by the crosslinking reaction caused by baking. On the other hand, to satisfy film adhesion, it was considered that delaying the time until E' starts to rise was necessary for maintaining required isocyanate transition. These are considered attainable by altering curing properties in the initial and later stages of baking by combining resins having slow and fast curing speeds by the design of molecular weight, glass transition temperature, and the amount of functional groups as coating resin properties.

6. Conclusion

Regarding the curing behavior during baking of clearcoat that is required to shorten the baking process, our study focused on the relationship between polishing repairability and film adhesion after baking. The following results were obtained through this study.

- (1) Even with 80°C baking-type clearcoats, it has been confirmed that E' in the baking process approaches a coefficient of multiple correlation of 0.999 with respect to the 1st-order reaction rate equation, and curing behavior can be traced.
- (2) To satisfy polishing repairability, E' in the final stage of baking should be increased.
- (3) To satisfy film adhesion, the time until E' rises should be delayed and the transition amount of the curing agent to the basecoat should be increased.

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Editorial Afterword

As part of my job, I often have occasion to look over collections of technical papers sent to us from other companies. These come in a range of forms, from presentations in which the sense of quality commences with the cover design, to those with a more “hand-made” feel, offering short papers covering a range of interesting areas, and I look forward to every issue. With these collections in my hands, I can see the efforts of every member of the editorial teams, marshaling the efforts of a disparate group of authors, bringing projects to completion.

These days, we often hear the phrase “open innovation.” This concept, propounded by Professor Henry Chesbrough, is an approach to generating innovation (groundbreaking business models, research outcomes, product development, service development, structural reorganization, social innovation, etc.) involving the collaboration of companies with outside entities, including other companies, universities, local administrations, and research organizations, to organically bring together the technologies, ideas, services, data, and knowledge encompassed by other industries and other fields, in initiatives such as joint research projects, all working towards the creation of new value. As you will already have realized, the publication of technical papers incorporates many of the elements of open innovation. Today, the tendency is towards the reduction of development periods; there are also restrictions on the amount of resources able to be invested, and it can be challenging to receive acceptance for the publication of papers that are not directly related to these types of practical outcomes. At such a time, my impulse is to attempt to enhance the environment surrounding the writing of technical papers, even if only slightly, by appealing to their publication as an aspect of open innovation.

Hisato Tomonaga

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