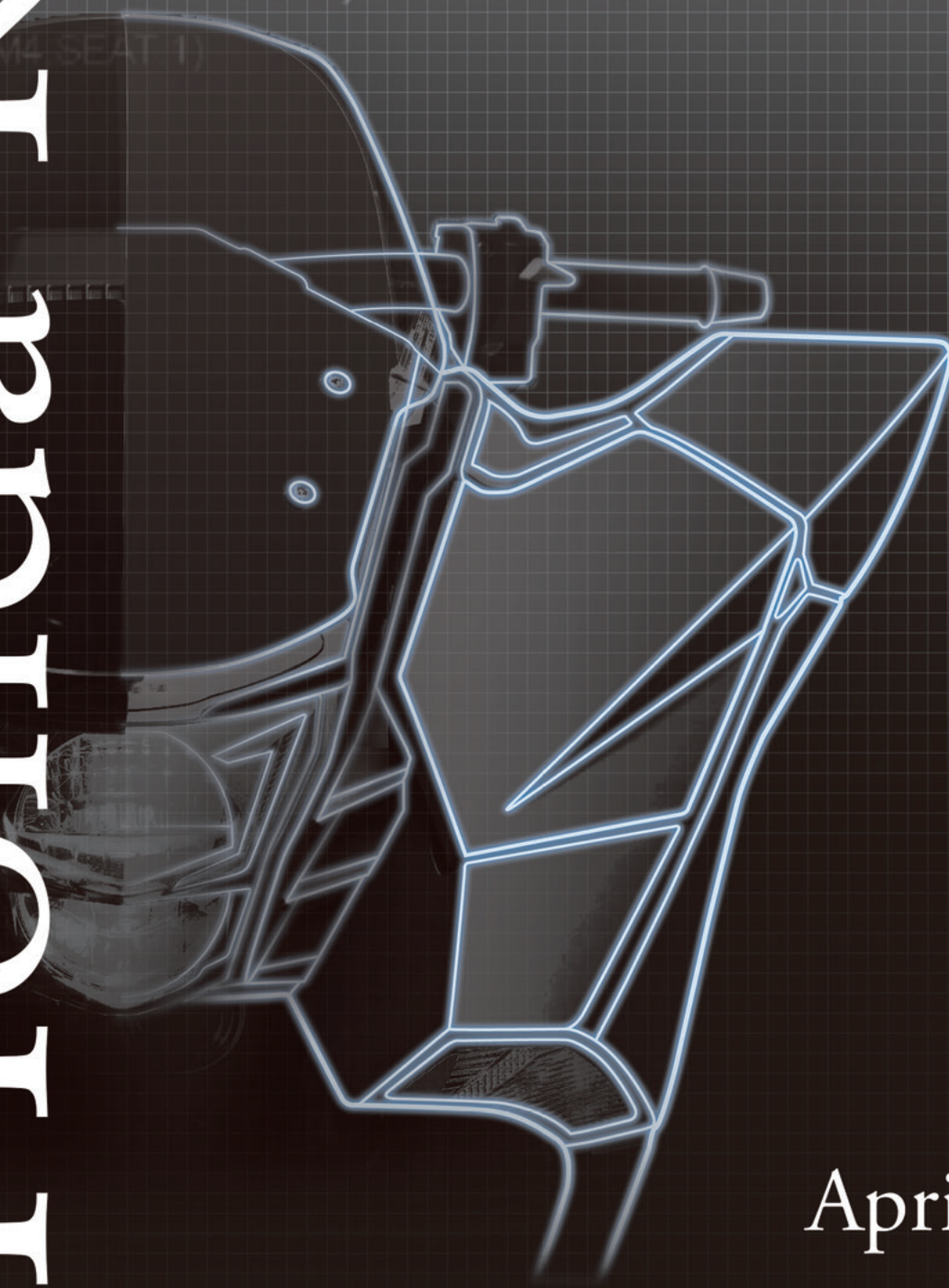
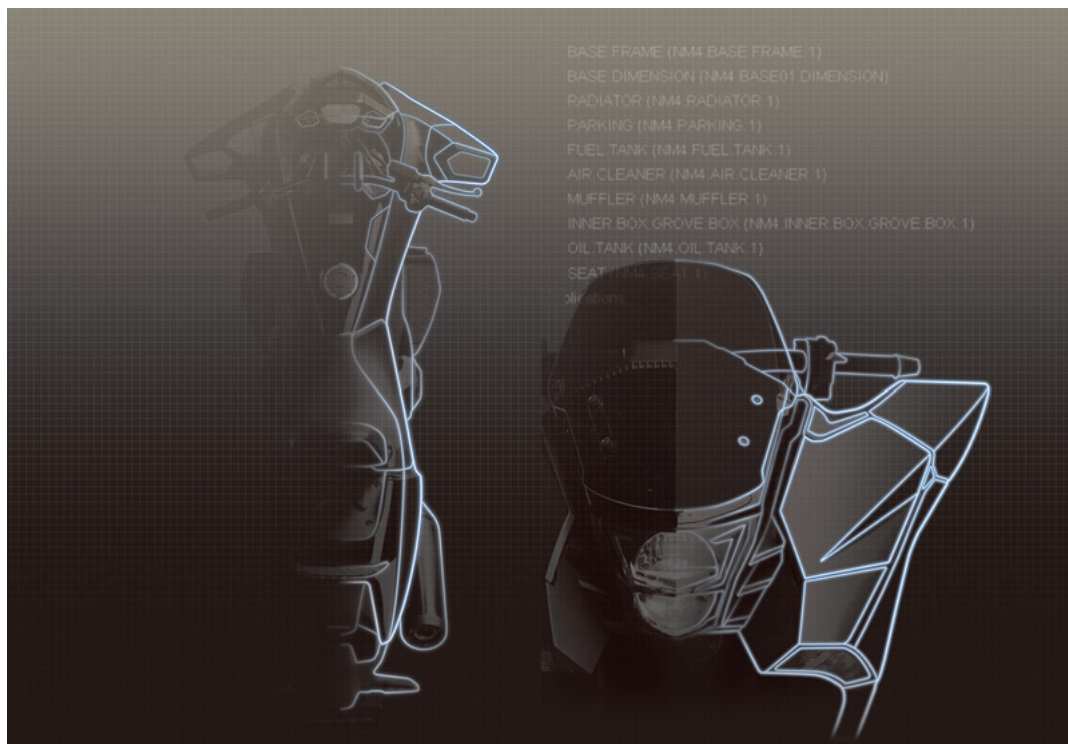


Honda R&D

Technical Review



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Comment on the Cover

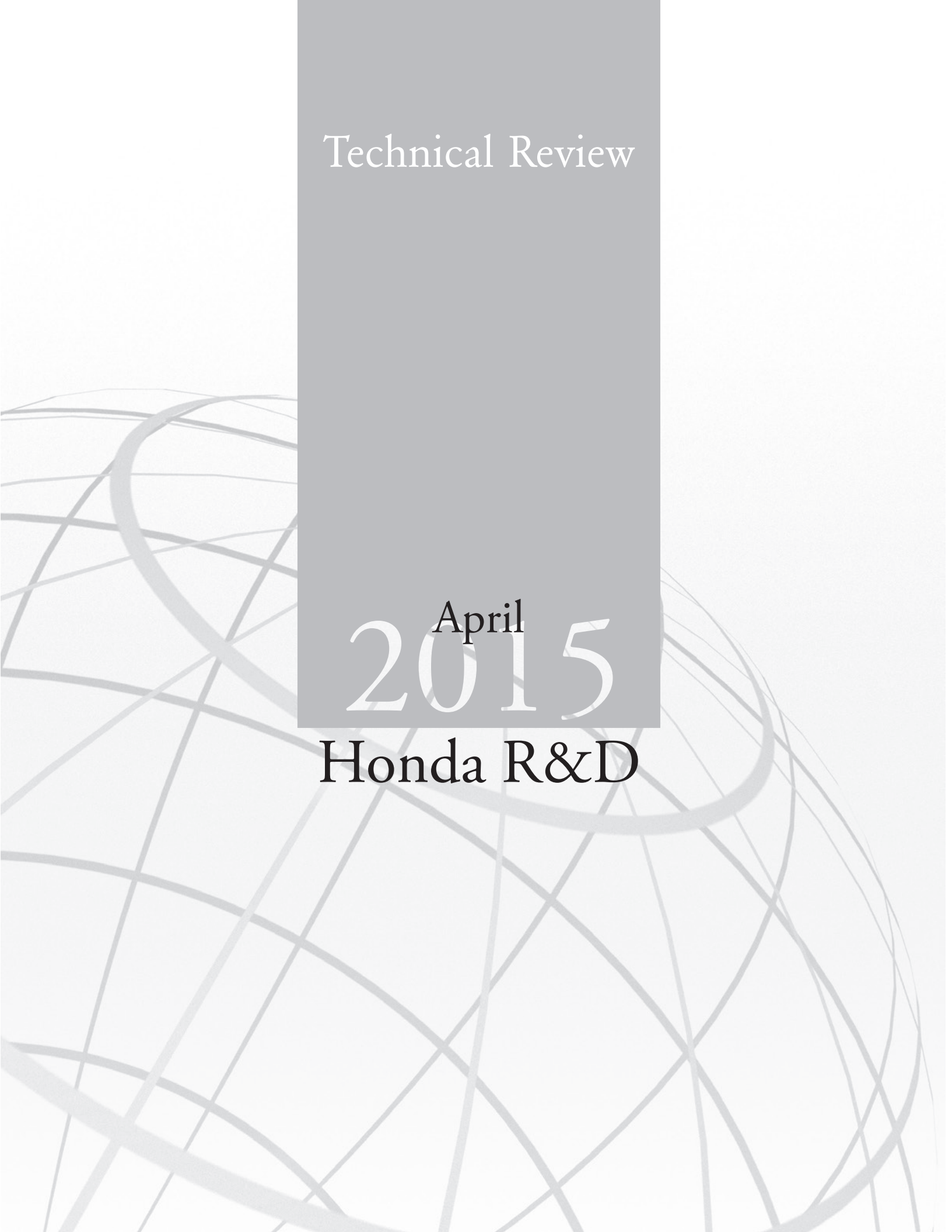
Honda continues to undertake challenging developments, seeking to offer its customers products of ever-greater quality. In designing the cover of this issue, we first wanted readers to feel the aspirations of our developers. Using a product discussed in the issue as a motif, we sought a mode of expression that would enable readers to really imagine the process of development.



Motorcycle R&D Center
Shota NAKAHIRA



Motorcycle R&D Center
Ryo ITO

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.

Technical Review

April
2015

Honda R&D

CONTENTS

Introduction of new technologies

Concept and Styling Design of the NM4	Taro NISHIMOTO	1
Defining the Identities of Motorcycle Model Lineages by Converging, Inheriting and Enhancing the Vehicle Frontal Styling	Yoshitaka SUZUKI•Masahiro MIKI	8
Styling Design of New Crossover VEZEL	Hiroyuki YAMAMOTO	13
Development of Inverter Generator Equipped with Fuel Injection Engine	Shigeru SAITO•Taiyo ONODERA Takashi HASHIZUME•Takeshi FUKAWA	24
Development of High-Efficiency Water Pump Using CFD Simulation	Naohiro AKIYAMA•Takahide KONCHI	30
Development of UNI-CUB	Wataru YADA•Yoshiki TATSUTOMI•Makoto HASEGAWA	37
Vibration Reduction of Two Motors of Rear Wheel Drive for SPORT HYBRID SH-AWD	Manabu YAZAKI•Tadanobu AOKI	45
Extension of Drive Recorder Function of In-vehicle ECU and Record Information Collection Technique	Hirofumi OHBUCHI	55
Development of Headlight System with Cost Advantageous Design Using Light Emitting Diodes	Yosuke TSUCHIYA•Teppei MATSUZAKI Tetsuo TAKESHIGE•Tsuyoshi OGUCHI	62
Development of ACG Using Regulator Rectifier with Phase Control	Yutaka SONODA•Kazuhiko ONO Miku OTSUJI•Katsuhiko OUCHI	71
Actual Proof Experiment of Electric Wheelchair “Monpal” for Enhancing Elderly QOL	Tadahiro YAGUCHI•Yoshinori MASUBUCHI•Makoto YAMAMURA Go NAKAMOTO•Hidetoshi KAWASHIMA	77

Technical papers

Research of the Technology for Reducing the Load of Yarding	Yoshinari TAKEMURA•Hiroto YAMAOKA Ukyo MATSUSHITA•Tomohiro KAWAKAMI	85
Particles Wear-Out Behavior of Reciprocating Engine Crankshaft During the Initial Running-in Operation	Kenji MATSUMOTO	96
Synthesis of Facet-controlled PtNi Nanoparticles and Evaluation of Performance in PEM Fuel Cell	Ryogo SAKAMOTO	103
In-plane Visualization of Oxygen Partial Pressure Distribution on Cathode Side during Fuel Cell Operation	Shohei TOYOTA•Chikara IWASAWA	111
Prediction Method for Vibration Transmission of Hydraulic Engine Mount	Masahiro FUKAZAWA•Tsuyoshi MURAO•Shingo UNIGAME	119
A Fundamental Study of Tool Embodiment for Human Dynamic Analysis Relating to Handling and Stability of Driving	Koji TANIDA	126

Concept and Styling Design of the NM4

Taro NISHIMOTO*

ABSTRACT

One of the issues in motorcycle business is that young people's interest in motorcycles is declining year by year. Accordingly, there has been a need to consider a new model targeting such young generations. To respond this need, Honda has started to create a motorcycle design category that has exceptional features and does not belong to any of the conventional motorcycle categories to explore new motorcycle market. The basic features of the design structure was decided as "Low & Long," and the descriptions of "Massive front styling" and "Cockpit position" were coined as two keywords. Actual methods to materialize these design concepts in a real motorcycle were investigated by having serious involvement in structural design work as well to take practical vehicle requirements into account.

Following this process, the model of the NM4 was brought into mass-production and it was confirmed, through the numbers appeared in the responses on Twitter, that our objective to get a wider recognition among customers not currently using motorcycles was achieved.

1. Introduction

Looking back the historical background, the market of large motorcycles in developed countries expanded since 1990's. Due to the Bankruptcy of Lehman Brothers in 2008, the market in those countries started to decline and that brought about a fierce competition among automotive brands within a limited pie of the market with a size of less than a million units (Fig. 1).

In such markets, users are increasingly concerned with the individual life style with a focus on the personality rather than absolute performances of a vehicle. Consequently it led to a diversity of requirements for large motorcycles. In the meantime, young people's interest in the motorcycle decreased. As a result, the average age of

riders increased year by year. Accordingly, the market situation got increasingly difficult, in which the number of potential users who kept their interest and, eventually, enjoy large motorcycles inevitably decreased to a large degree.

Hence, the development of the NM4 was initiated to investigate a new model targeting young generation that has little interest in motorcycles.

2. Development Concept

As the model was developed for getting a new cluster of customers, it was understood important to be recognized by the people who have no interest in motorcycles. In our process of creating styling designs, a priority was set to make the vehicle immediately recognized at the first look of people who have only a slight interest in motorcycles, rather than getting consent from existing motorcycle users. It was also regarded as important to present a concept of the exterior design that was exceptional and not categorized in any existing motorcycles. In addition, it was defined as an indispensable requirement to make the best use of the unique technologies of Honda. As another important requirement, lowering the height of a hurdle for an inexperienced customer who was potentially becoming a motorcycle rider was also defined.

In the pursuit of lowering the hurdle for beginners, not only an easy riding for inexperienced customers but also a creation of a different value, which conventional

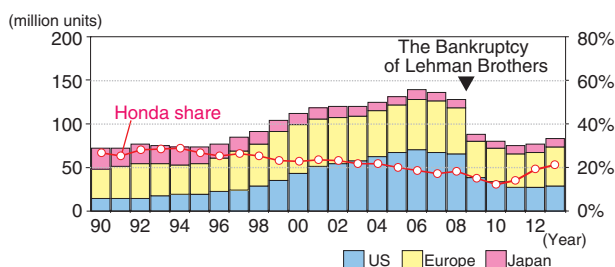


Fig. 1 Sales of large motorcycles in Japan, Europe and US (not including ATVs and off-road motorcycles) (from Honda in-house survey)

* THINK Lab., Honda R&D

motorcycles did not have, were envisaged. For achieving those objectives, the development was given a less priority in absolute performances, such as speed or power, as well as not seeking a high riding technique to a rider.

The basic idea was to increase motorcycle fans in the future by having more avenues to enter the world of motorcycles that was created through expressions of a new conceptual view and through the lowered hurdle for beginners to access.

3. Styling

3.1. Defining Basic Features of Structure

As a first step, a thorough consideration was conducted to find what kinds of transportations or vehicles were giving an impression of attractiveness to ordinary people and our directions of the structural design was defined.

Examples were collected from transportations and vehicles widely recognized, from the past to the present, by people in 20s or 30s. They were not limited to existing transportations but included the ones that appeared in the movies or animated cartoons. Moreover, our collection was expanded to include apparel and other products that are attractive enough in recent years. Through the results, it was found that futuristic styling, low and long form, fat tires and low height seating were universally recognized as attracting features. Consequently, these factors were defined as important points to vigorously design the basic proportion (Fig. 2).

In the styling design of the outer surfaces, implementation of synthetically characterized neat form was selected. Accordingly, the expressions of the outer forms that appear in the shapes of smartphones or electric appliances with the latest designs were implemented instead of using forms with expressions conventionally applied to motorcycle designs such as “vigorousness” or “speediness.”

The engine equipped with Dual Clutch Transmission (DCT) was decided to adopt, in terms of application of a unique technology of Honda, contributing to lower the hurdle to beginners as well. It was aimed to realize an easy riding, simple operations and the feeling inherently characterized by a motorcycle. Basic components exhibiting key features of a motorcycle, such as a bar type handle, a muffler of cylindrical shape and other parts around the

wheels and the braking system, were made visible. Through those implementations, the impression as a motorcycle was made emphatically noticeable and a room for customizing for personalization was maintained. The space allocation of utility compartments was also examined considering conveniences in practical use. The possible need for having even more utility spaces was investigated as well.

3.2. Styling Directions and Design Elements

As mentioned above, the styling design of the NM4 was aimed at the creation of a fundamental concept view that was exceptional and was not categorized in any motorcycle.

Among various options of our design directions to take, the design that gives us a futuristic atmosphere was set as our design orientation while considering attractive features to the younger generations who had been brought up surrounded by digital culture of movies, animations and games as their familiarized items.

3.2.1. Massive front styling

This styling keyword involves in overall silhouette of the vehicle. The structures composed of boldly shaped surfaces and the front fairing extruded to lateral directions, together with rearview mirrors built in it, were installed in the front area. These design components enhanced the massive appearance in the vehicle front area. On the contrary, rear area was streamlined into a low and small form. With those compositions, representations of boldness and dignity were achieved to create a unique silhouette.

The rear cowl design with descending line to the rear is contributing to make the vehicle design represent the complete antipode against conventional designs with the rear cowl with ascending line that frequently appears in sporty models in which the absolute performances are of great importance. That descending design is also for a representation of the concept that has a different sense of value from that of sporty models.

3.2.2. Cockpit position

The riding position was designed to realize a relaxed riding for even a rider without enough experiences. For that purpose, the height of the seat was designed low and a backrest to lean against and footrests to stretch out his or her legs on them were equipped. Moreover, the instrument panel, which is usually placed in the position to be looked down, was located in front of the rider. In those designs, it was aimed at to have a rider feel as if he or she were sitting in a cockpit, which was totally different from the feelings of any existing motorcycles. Those measures were designed to create an unexperienced feeling in dynamic tastes of riding as well as providing visual appeals in conjunction with a strongly claimed personality.

The design expressing a new identity was created while it could get a wider acceptance by people to some extent, just like in the cases of consumer products appearing in our daily lives. Therefore, it was designed with expressions

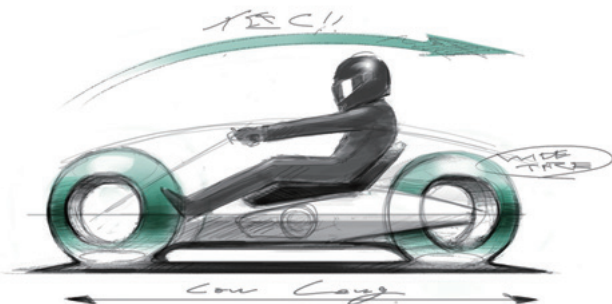


Fig. 2 Conceptual proportions of exterior design

of uniqueness yet without applying excessive complexity by implementing simplified outer surfaces and character-defining lines. That was because it was intended to make it stay showing the realistic functionalities as a vehicle in the real world avoiding it looked like an object in some virtually created world, while reflecting the sense of younger generations.

Keeping these ideas in mind, idea sketches were roughly drawn followed by implementation of them into actual vehicle configurations and equipment. On the other hand, the process of feeding-back the technical ideas and comments to the sketches yielded from engineers was repeatedly conducted to make it a realistic design (Fig. 3, Fig. 4).

3.3. Issues in Realization of Styling and Solutions

Issues of creating a styling with a new identity, while realizing a lower hurdle for beginners, are described below with the solutions.

3.3.1. Creating Low & Long form satisfying caster angle requirements

For creating Low & Long form, it is desirable to locate the front tire as forward as possible to constitute a stylish and bold proportion of the vehicle. For such front



Fig. 3 Design sketch of side view



Fig. 4 Design sketch of front view

tire arrangement, it was necessary to increase the caster angle extensively. With a large caster angle, the natural maneuverability is generally hard to be obtained. It was one of the inevitable requirements for the NM4 to have a natural maneuverability because the vehicle is targeting beginners in riding motorcycles. The issue to be tackled was to create a well-balanced design of Low & Long form while maintaining a natural maneuverability.

To solve this issue, the positions of the front tire and the head pipe were determined to have a minimum allowed caster angle within the range that does not affect the balance of the design. Finally, the issue was settled by setting the optimized trail distance yielded through a fork angle of 37 degrees, composed of a leaned caster angle of 33 degrees and a slant angle 4 degrees. In addition, the front fairing was designed to cover up the front fork. This visually enhanced the merged appearance of the front tire and the body, and the silhouette of lower and longer posture was expressed.

3.3.2. Realization of low seat height

Regarding the seat height, it was aimed to make rider's feet touch the ground with ease without sacrificing the unique proportion. Accordingly, it was set at 650 mm. This height is the lowest among the large motorcycles of Honda. However, how it could be materialized in the actual body parts arrangement became an issue.

Firstly, through reviewing the conventional installation positions, the electrical components, which are installed collectively under the seat in many cases, were moved to other locations as far as possible. In addition, the frame pipes under the seat were laid out at lower positions with a smaller distance between them. To examine whether or not the seat height, which was set ultimately the lowest position, didn't affect the natural riding posture, a simplified mock-up model was prepared (Fig. 5). Based on this examination, slight adjustments were made to the shapes of the seat and the fuel tank. Through the above mentioned trials and changes, the target seat height was successfully established maintaining a sufficient seat cushion thickness to grantee a comfortable riding.



Fig. 5 Simplified mock-up model

3.3.3. Clearance between rear cowl and rear tire

Another issue to be tackled was the clearance between the rear tire and the rear cowl that was positioned at the lowest possible height. The lowest height and the small-sized design of the rear cowl was an inevitable requirement to realize the Low & Long proportion and Massive front styling at the same time. However, the issue was that using a fat rear tire with a sufficient suspension stroke naturally requires a large clearance around the tire. The low and compact rear cowl confronts to that requirement.

The balance between the design and the functionality was pursued through elaborations of repetitive sketches and arrangements. Pro-Link suspension, the damper system of Honda Multi-Action System (H.M.A.S) and swing arm made through fine die-casting of hollow aluminum structure, which offers light weight and high degree of freedom in its design, were incorporated into the rear suspension system. By implementing those measures, a compact rear cowl design was established to enhance the impression of fatness of the rear tire while maintaining a comfortable riding and a good driving stability with a minimum required suspension stroke.

3.3.4. Allocation of utility space

A sufficient space for the utility compartment was inevitably required when the conveniences of a variety of users were considered. Utilizing the space made available by Massive front styling, the utility compartments were arranged in the front fairing. Thus, an additional convenience was offered together with a new perception of the bold front design and improved protection from the wind.

3.3.5. Layout of built-in mirrors

The built-in mirrors play an important role as one of the crucial factors that highlight the new styling. In the meantime, the locations of the mirrors that provide an adequate viewing capability were hard to be determined only by considering through sketches or views on a computer screen.

Through the repeated trials on a computer simulation, the mirror positions were roughly arranged. Following that, the validation of visibility was conducted using the simplified mock up model in the final step and the optimized arrangement was fixed. This mirror arrangement also contributed the enhanced comfort of a rider because this arrangement was determined considering a wind protection to the hands grabbing the handlebar as well (Fig. 5).

4. Prototype Model

Based on the styling sketches refined through the process aforementioned, a prototype model, which was compatible to an actual driving, was made. Regarding utility space, an additional version of the vehicle model

that has extra utility compartments on the sides of the rear cowl was also lined up. The rear utility compartments were designed intentionally as undetectable type parts to keep the consolidated body form although detachable ones are commonly used. This utility space configuration made this model differentiated enough compared to the standard version. Figure 6 shows the final prototype model.

It was also verified through the test riding of the prototype model whether our objectives, i.e. an easy maneuverability and a new ride feeling, were created beyond the new appearances. It was confirmed through the test riding that a natural and unexperienced riding taste further than our expectations was created by the combination of the Cockpit position of leaning against the backrest and the engine equipped with DCT. Moreover, lateral inline arrangement of the built-in mirrors and the instrument panel in front of the rider creates a visual effect that gives enhanced feeling of leaned vehicle body angle to the rider when running through curves. These impressions proved to us that an unprecedented feeling of riding enjoyment was fully established.



Fig. 6 Prototype model

5. Transition to Production Model Development

Following the evaluations on basic drivability of the prototype model, the development process moved to the next step of the actual production model development. The production model development was completed through the process of making some changes on specifications and finalizing the detailed modifications to realize further enhancement of the expression of the unprecedented unique feature of the product while achieving easy access and riding of the vehicle (Fig. 7).

The features added in the revised specification are described below.

5.1. Gauge with Switching Colors

An ambient air temperature gauge, a fuel gauge and a clock were also installed on the instrument panel. In

addition to regularly equipped functions, the side gauges present an illumination effect on their perimeters by changing the brightness like heartbeats. It is not merely a visually designed effect but a demonstration that makes the user feel more engaged to the motorcycle.

A gauge unit with automated color change function was adopted that shows the driving modes of DCT by changing the colors of the background lighting and the perimeter illuminations (Fig. 8). The colors of the background



Fig. 7 Mass production model of the NM4-01



Fig. 8 Instrument panel

lighting and the perimeter illuminations can also be set to fixed colors chosen from 25 color options to fit the user's preference (Fig. 9).

5.2. Erectable Pillion with Adjustments

The pillion was designed to be erected to become a backrest and was structured to have an adjustment mechanism for shifting in longitudinally four steps and in three angular steps. That made the best fitting riding positions available for a variety of users to provide them with an enhanced comfort of riding (Fig. 10).

5.3. Model Name Indication with Debossed Shaping

A simplified expression was applied by employing a

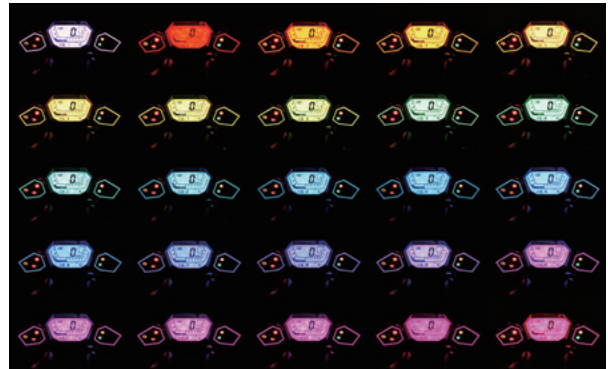


Fig. 9 25 meter color variations



Fig. 10 Upright positionable pillion (4 angular positions including 3 upright positions with longitudinal adjuster)

debossed shaping for the model name indication to associate it with a flavor of recent sophisticated products of smart phones or electric appliances (Fig. 11).

5.4. Utility Compartments

Utility compartments were provided in the right and left sides of the front fairing. In the left side container, a securing lock and an outlet of 12 volts electric power were additionally installed to enhance its utility (Fig. 12).

Furthermore, another vehicle version, which was provided with additional utility spaces in the sides of the rear cowl, was also lined up. Those utility containers were intentionally designed as undetachable parts, while they are usually detachable, to fully maintain the consistency with the mono-solidity design. By doing so, the design of this version was made express a totally different identity from the original version (Fig. 13).



Fig. 11 Embossed emblem of the model name



Fig. 12 Front utility space (Left side) (Shown in the photograph is the model for Japanese market)



Fig. 13 The NM4-02

6. Responses after Product Release

The NM4 was released at The 8th Osaka Motor Show in 2014. The survey result (in-company investigation by Honda) showed the number of responding tweets on Twitter reached 1858 and the accumulated number within 10 days on and after the release date rose to 4061 tweets. It can be evaluated that it attracted a lot of interest even though no previous information had been provided in advance (Fig. 14). Among the generations of responders, the degree of interest was high in the late 20s for males and the late 30s for female (Fig. 15).

Moreover, it was noticed that a considerable number of re-tweets were from the people outside of the motorcycle businesses or from discrete individuals. This illustrated that the developed model was noticed as a topic among the people who had not involve in the communications on conventional motorcycle relating topics so far.

Regarding exterior design, opinions were distinctively separated into two groups of likes and dislikes. However, the results indicated that not a few people showed their favors on it.

These results could not be directly translated as the positive indicators towards good sales but they proved that the initially aimed objective of broadening recognitions

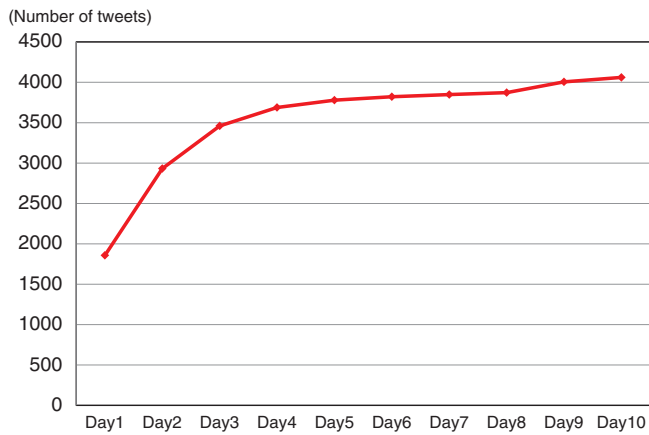


Fig. 14 Cumulative number of tweets after the announcements from public relations (from Honda in-house survey)

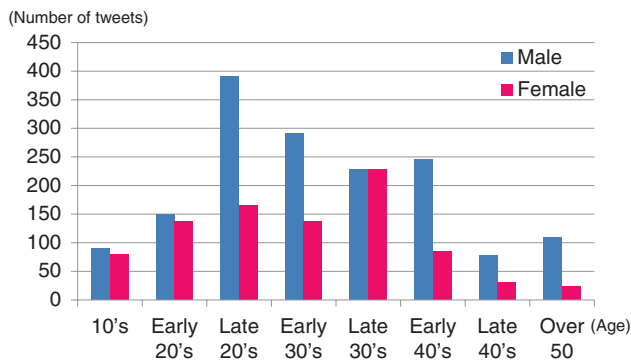


Fig. 15 Tweets number of in another age/gender (from Honda in-house survey)

among the people who did not use to be the users was successfully achieved.

7. Conclusion

The NM4 created a styling design, which could be recognized even at the first look, and a fundamental concept view, which was exceptional and did not categorized in any conventional motorcycles, by applying the factors of futuristic styling, Low & Long form, fat tires and low height seating, together with lowered hurdle for beginners' use. The expression of a novelty was successfully realized by applying Massive front styling that offers a unique silhouette and Cockpit position that offers new experiences of dynamic riding as well as its visual appearance.

We hope the development of the NM4 is contributing to make the first step towards the ultimate goal of exploring new customers in the market.

■ Author ■



Taro NISHIMOTO

Defining the Identities of Motorcycle Model Lineages by Converging, Inheriting and Enhancing the Vehicle Frontal Styling

Yoshitaka SUZUKI* Masahiro MIKI*

ABSTRACT

In the development of motorcycles, Honda has been implementing the latest technologies. At the same time, the exterior designs have been kept evolving constantly to create new values. Meanwhile, to respond to the changing demands from the markets, a different vehicle front-design was sometimes adopted even though it was not fitting to the symbolic representation inherited through the specific model for generations. Such designing practices eventually diluted the succeeded identity resulting in failing to live up to customer expectations. To solve this, the issue of design identity was repeatedly discussed. The discussion was concluded that it is important to define a key feature of a vehicle front design that symbolizes a series of models having the same product name. Moreover, that design definition should be inherited while incorporating advanced technologies in time. To realize that, we delineated the direction by three key words: “convergence, inheritance and enhancement” as the guidelines for the design of a vehicle front. These guidelines were practically implemented and contributed to establishing a valuable principle of exterior design for our motorcycles.

1. Introduction

Since the establishment of our company, Honda has been producing products that satisfy various needs in different regions around the world by applying the latest and/or unique technologies and offering those products to the customers. That has been the same for our motorcycle developments as well. The latest technologies in the era have been applied at each model change and the designs have been relentlessly enhanced to a large extent to create a new value. Through those efforts, the heritage of motorcycles that have the same succeeded name, like the CB or the VFR, has been established. In those circumstances, to express an explicit feature owned by each shared name vehicle series, we have been trying to create the vehicle front design through which we can establish a consensus with our customers in its design identity being quoted like as saying “This is exactly the design of the VFR’s face!” In the meantime, with the worldwide expansion of motorcycle business, the number of models, for which an identical vehicle is marketed for both users in developed countries and in developing countries, has been increasing. However, what they expect of the exterior design differs depending on the market-specific preference even when an identical vehicle is marketed. To respond to a

different demand from a particular market, in some models, a design presenting a different design character was applied from the original one, which is succeeded through the history of that vehicle series with the same name. However, due to the application of such a different design, the signature identity succeeded through the generations of the vehicle series was diluted and didn’t fit to the customer expectation in some market regions. To solve this issue, firstly, the history and the current status of the designs of the CB, the VFR and other models were investigated and design factors to be succeeded through generations to represent the vehicle identities were discussed over and over. As a result, it was concluded that vehicle front design should be defined as a clearly distinguishing feature for a specific vehicle series that shares a common vehicle name, and the design features should be made converged into a single design norm to be succeeded from generation to generation while applying the latest advanced technologies to keep enhancing it. By setting three keywords of “Convergence, Inheritance and Enhancement” as the design guideline to determine the vehicle front design, it was considered that a vehicle front design that meets the customers’ expectation can be offered for a long time. The details of the guideline and its application example will be described below.

* Motorcycle R&D Center

2. Drawing Up Guidelines

Sometimes, a vehicle front design, which gave an impression different from the one that had been succeeded for a long time with that particular vehicle name, was applied. In that case, that design negatively affected the inherited vehicle identity and diluted its unique impression. Based on the results of investigation on the history of our vehicle exterior designs and the status quo, three key words of “convergence, inheritance and enhancement” were defined as the guidelines to solve the issue mentioned above. The principles behind each key word will be described in the following.

2.1. Convergence

Based on the knowledge yielded from the results of customer surveys (carried out by Honda), it was one of the known facts that the customers attach great importance to the vehicle front design when they are buying a motorcycle. As reported by Maruyama et al. in their paper⁽¹⁾, it is a proven fact that humans have an extremely high cognitive sensitivity to a figurative pattern that evokes an animal’s face. Accordingly, if a group of motorcycles are applied with the vehicle front designs that are sharing the same fundamental design framework, on which the design is converging, it is possible to make the customers believe that this particular group of motorcycles has a specific commonality in their temperament and features. Based on this understanding, for each of the motorcycle series sharing the same model name, a fundamental design framework was defined, as shown in Fig. 1, to establish an expression of the design commonality, on which every exterior design of headlight area was to converge. Each design framework was fabricated of the design elements extracted from the shapes and lines that appear in the recently proposed conceptual models or the models that have already established a high recognition of their identities over a long time. To be

specific, those design frameworks are described as below:

VFR series: The shape of letter X, which was applied based on the design of the conceptual model exhibited in 2008.

GL series: That includes the Goldwing as a flagship. Featuring bird’s wings, lines horizontally expanded were applied recollecting a large scale of the continent with majesty.

CB series: The traditional shape was employed emphasizing its unchallenged heritage.

CBR series: The shape of tightened narrow eyes was used to create an impression of keenly swift movements.

The basic principle of applying the common design framework was determined only for presenting the root design scheme for each design idea to converge towards that direction. It was not meant to be any restriction that would diminish the designers’ freedom of creativity.

2.2. Inheritance

It was decided to make each fundamental design framework to be succeeded from generation to generation to establish a firm unchanging impression unique to the vehicle series name. It is just like it is for a brand image to a brand name.

It was understood that the front design of each vehicle series had been recognized as a shared identity between customers and Honda, and it had become an established symbol through succession of the design for generations. To confirm this understanding of us, interviews were arranged to the exterior designers who involved in the development of the former models. In the interviews, the comments witnessed to our understanding saying “We were largely conscious of the established impressions and fundamental design scheme that the previous model was offering and reflected them to the vehicle front design of the developing model.” This was one of the proofs that Honda had been trying to create vehicle faces so that they represented their

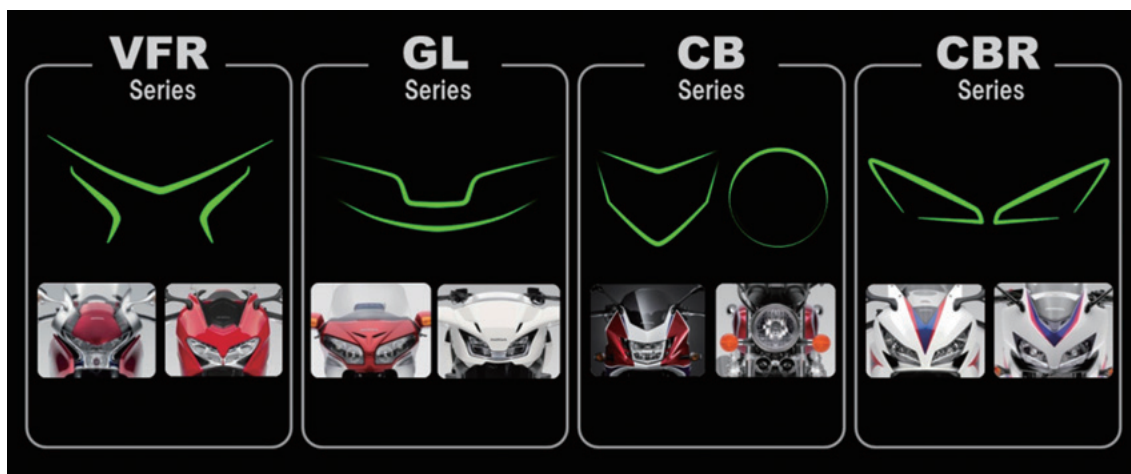


Fig. 1 Styling design motifs

own characteristics defined by the individual vehicle names. This was especially true for the designing of the CB, the VFR and other models that had long histories with their own vehicle names. Moreover, those were designed with an intention to succeed to their heritages. As a good example of succeeding product identities, there is the measure that European premium automobile manufacturers are doing to maintain their brand images. It is commonly understood that those manufactures are pretty successful in keeping their established brand images. One of the points to be noticed in their products is that they do not largely change the identities expressed by the designs of vehicle front area, including headlights, for quite a long time. This fact implies that those car companies fully understand what they should do to the customers in matured societies. Furthermore, the customers also sympathize with that principle. Honda has been responding the customers' demand, which changes to the transitions of their preferences, by markedly changing the product designs. Then, now, the efforts to respond the demand from customers in matured societies are requested to us more strongly than ever before. Accordingly, it has become more important to succeed the vehicle front designs of the motorcycle series that have long established histories.

2.3. Enhancement

Succeeding previously presented features of a vehicle front design may eventually leads to make them look old-fashioned. To prevent that, it is required to keep expressing fresh flavor of the designs as well, while letting them feel a sense of conversion on the succeeded design framework commonly shared through the vehicle series. To make it possible, it is highly important to incorporate the latest technologies to enhance design features. The example of the technologies are provided below.

Regarding the lighting devices for vehicles, new devices have been continually developed in the history. Accordingly, various lighting devices have been utilized to enhance the feature of vehicle front design. Among those devices, light emitting diodes (LEDs) have begun to be used recently as one of the latest technologies applicable to vehicle lighting components. LEDs are small-sized, of low power consumption and long lived. With these advantages, they are substituting for conventional incandescent light source devices. LEDs that have these advantages are also contributing to the enhancement of vehicle designs. In the following, this contribution will be explained describing one of the models released in 2014 as an example.

In the early stage of applications to vehicle lightings, LEDs were used for taillights and/or stoplights. In that stage, LEDs were used as single point light sources and applied mainly in the forms of separately located arrangement or a group of LEDs plurally arranged (Fig. 2). These techniques were good for exhibiting the light sources themselves. By using these techniques, it was aimed to show off the use of new light sources and their advantages mentioned above. After white LEDs became available, they started to be

used as components featuring vehicle front designs. In the CBR600RR of the 2007 year model, front position lights with LEDs were equipped. This was the first case in the models from Japanese brands. The application of LEDs made it possible for designers to create a compact styling (Fig. 3). In the CBR1000RR of the 2008 year model, LEDs were applied to front position lights and that realized the compact size of the lights. That compact size enabled them to be installed in the right and left mirror housings. Thus, the position lights were arranged at the locations away from the positions of headlights and it contributed to present a unique design together with enhanced conspicuity from surrounding vehicles. In those application examples, LEDs were adopted mainly for functional enhancement (Fig. 4).

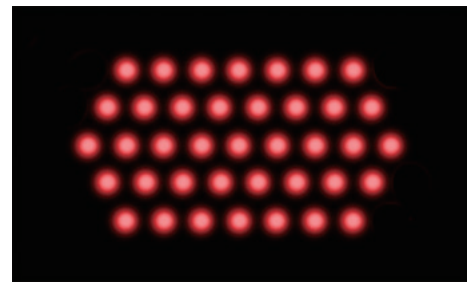


Fig. 2 Dotted arrange of LEDs in tail light



Fig. 3 Front position light (at center) in the CBR600RR, 2007 year model



Fig. 4 Front position lights (at rear view mirror) in the CBR1000RR, 2008 year model

In the next phase of LED applications, by applying advanced optical path analysis technologies, the forms of LED light sources evolved from positional light sources to light sources in various shapes, such as a line-shaped light source formed by a light guide or a surface emitting light source (Fig. 5). On the other hand, the power of white LEDs was more enhanced and become compatible with other light sources used for a headlight making a freedom enlarged significantly for vehicle front designs. By these technological advancements in LEDs, a transition was made possible, from the conventional design expressions just based on the application of predetermined parts shapes, to a new expression using flexibly designable shapes of light sources. Those evolutions in technologies provided us wide options for the methods in expressing a vehicle identity through a vehicle front design. Furthermore, this offered a large propulsion power to step forward our efforts to the implementations of the three key words, “convergence, inheritance and enhancement” (Fig. 6).

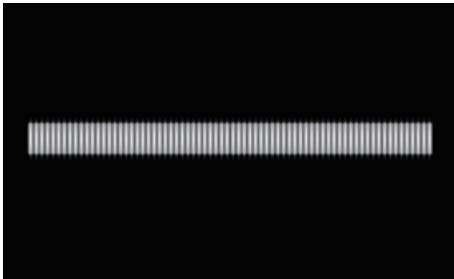


Fig. 5 Light guiding panel



Fig. 6 Application of light guiding panel in the PCX, 2014 year model

3. Example of Application of Guidelines: VFR Series (VFR1200F, VFR800F)

The VFR series is one of the important vehicle series in Honda motorcycle products. The first model of VFR series, the VFR750F, was released in 1986. Since then, the

VFR series have been receiving a long lasting preference from the customers. All of the vehicles in the VFR series have been applying V4 engines. VFR series is only the motorcycles selecting this engine configuration among all the motorcycles in sports-tourer category. The vehicle concept of the VFR series has been aiming at combining the unique vehicle packaging of hardware pursuing both high performances and high functionalities and the sophisticated styling for matured adults. Honda has kept materializing this concept by applying the latest advanced technologies⁽²⁾. The concept model of next generation VFR was exhibited at Esposizione Internazionale Ciclo Motociclo e Accessori (EICMA) in Milan, Italy in 2008 (Fig. 7). One of the design features of this concept model was the vehicle front design characterized by X-shaped framework of design. The production model of the VFR1200F, released in 2010, was designed to create the same impression as the one in the concept model (Fig. 8). However, in that model, an incandescent light bulb was still applied to the headlight and X-shaped framework was created by combining the outer shape of light lens and the shape of surrounding ducts. As mentioned before, X-shaped design was originally created in the concept model in 2008 and applied to the VFR1200F in 2010. Thereafter, the essence



Fig. 7 Concept sketch of the VFR, 2008



Fig. 8 X image representation in the VFR1200F, 2010 year model

of this X-shaped design was extracted as the fundamental framework for the VFR series and defined as X-shaped scheme.

To the VFR800F released in 2014, X-shaped design, which was created based on the fundamental framework for the VFR series, was succeedingly applied (Fig. 9). In this way, the creation of converging design to the unified framework of the VFR series was successfully achieved. The succession of inherited unique identity of the VFR series was carried out by adopting the design elements appeared in vehicle front designs of former vehicles in the VFR series. Moreover, “enhancement” by technologies was represented by applying LED headlights. The expression of the identity for the VFR series was made possible by applying an enhancement method to X-shaped form by using a pair of line-shaped illumination parts with LED light sources. Line shaped light guides were installed in the headlight unit and the shapes of illumination of these light guides were arranged to provide X-shaped scheme (Fig. 10). Consequently, the shape created by these illuminations played a significant role to show that the vehicle was given the same unique identity of the vehicle series.



Fig. 9 Image representation using LED light guiding panel in the VFR800F, 2014 year model



Fig. 10 Applied light guiding panel (shown in green color)

4. Conclusions

To enhance the establishment of the unique identity inherited by each vehicle series, the guidelines for creating vehicle front design were defined as follows:

- (1) Convergence: A fundamental design framework for each vehicle series was defined. A guideline was set the vehicle front designs of all the vehicles, which belong to the same established vehicle series, should be designed to be converged on that unique design framework.
- (2) Inheritance: A guideline was set that the defined fundamental design framework should be succeeded from generation to generation for the vehicle series sharing the same vehicle name
- (3) Enhancement: A guideline was set that the latest technologies should be continuously implemented to the design measures to avoid the succeeded design features become out-of-fashion.

The VFR800F, in which the vehicle front was designed complying with these guidelines, was put into actual markets in 2014.

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Styling Design of New Crossover VEZEL

Hiroyuki YAMAMOTO*

ABSTRACT

The 2014 model VEZEL is a new product, similar to a compact SUV but combining the personal feel of a coupe and the utility of a minivan. The keywords during the development of the VEZEL were “specialty car”, not just a small SUV, because the developers wanted to create a sensual car. The grand concept, therefore, was “Sensual, Crossover.” The concept of the package design was “Smart Cross PKG.” This was embodied by combining the attractive points of SUVs, coupes, and minivans. The concepts of the exterior design and interior design were “Dynamic Cross Solid” and “Expansible Cockpit” respectively. The exterior dynamically combines strength and sultriness, while the high-class interior brings out both spaciousness and a personal feel. Moreover, using the concept of “coordination” for the color material, the designers put together an internal and external design such that each variation was like a new work. By combining utility and “sensuality”, the VEZEL development team did more than just appeal to consumers by being better than competing products in fragmentary ways, such as performance or equipment. Rather, they brought out a product with multifaceted value that consumers would choose based on sensitivity.

1. Introduction

The CR-V, announced in 1995, was a light cross-country vehicle based on a passenger car which was quite unusual for the time. By now it has grown into a global brand with more than 500,000 units sold annually in 160 countries. As such, the CR-V is recognized as the standard of SUVs. As the downsizing trend spread around the world, Honda began developing a new SUV. But rather than simply develop a small CR-V, the development team wanted to create an attractive “real-car” product that would redefine the world concept of the compact standard.

“Specialty car” are the key words that express the “real-car” quality that the development team was thinking of. The PRELUDE (Fig. 1) and ACCORD INSPIRE (Fig. 2) were once very popular cars with beautiful styling and high-quality interiors that gave the driver the leading role. These models offered an attractiveness that clearly differed from the mainstream family sedans of the time. More than just tools for getting around, they supported drivers as a partner, helping them enjoy lives with greater quality and prosperity.

As the times changed, however, the values that consumers sought in their automobiles became more diverse and grew to include spaciousness and ease of use. Products such as these one-time specialty cars no longer resonated with many customers. Honda therefore decided it was necessary to develop products that would combine



Fig. 1 PRELUDE



Fig. 2 ACCORD INSPIRE

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utility (made possible by Honda's unique technologies) with attractiveness that appeals directly to the customer's sensitivity. "Sensual, Crossover" (Fig. 3) is the grand concept that the development team established in its pursuit of a specialty car for a new age, targeting urban dwellers around the world. The standard during development was not just utility, but whether this vehicle was attractive to the customer.



Fig. 3 Grand concept

2. Package Design

2.1. Concept

"Smart Cross PKG" (Fig. 4) was the concept that the development team used in order to combine coupe value and minivan value, built upon a base of SUV values such as a sense of confidence and safety, status, and ease of use. Moreover, the technique for realizing the core SUV values of reliability and sense of confidence was to emphasize three elements (large-diameter tires, a high eye point, and high road clearance) while pursuing a framework as a "sensual" car.

2.2. An SUV-Like View

The SUV value that the development team particularly focused on was the eye point (Fig. 5). The higher the eye point, the more drivers can feel they are looking down on the road and traffic; but if it is too high, the end result gets away from the specialty car image that the team was aiming for. The team therefore verified the eye-point height that would allow an SUV-like view and sense of confidence while keeping the overall height down.

The team compared many vehicles to confirm at what eye-point height drivers would be able to feel a clear difference from ordinary sedans or hatchbacks. As a result, they decided that an eye point 100 mm higher than an ordinary sedan or hatchback was necessary for drivers to recognize a vehicle as an SUV (Fig. 6). Additionally, the

more upright the passenger sits, the stronger the image of a commercial vehicle, but the more reclined the passenger position, the greater the nonvisible length of road in the front. By designing a passenger position close to that of a sedan, the developers were able to provide a suitable personal feel as well as the sense of a good view.

2.3. Coupe Value and Minivan Value

In order to achieve coupe value, the development team created a sporty cockpit space for the driver. They started with the assumption that the vehicle would use a high-deck console, and then they secured the maximum dimensions

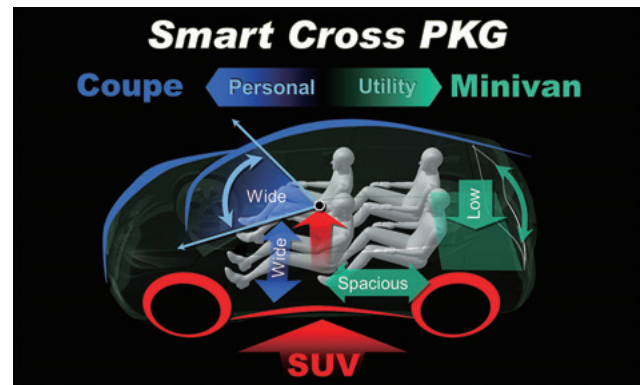


Fig. 4 Package concept

Optimal visibility for driving and ease of entry and exit

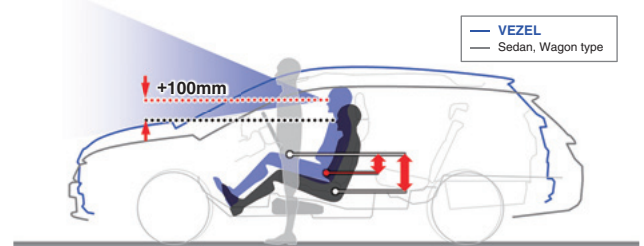


Fig. 5 Eye point of SUV

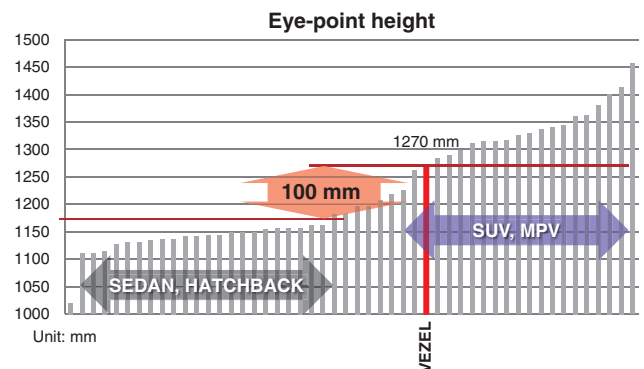


Fig. 6 Eye-point height of SUV and sedan

laterally to give front passengers a personal feel and ample space. They were also adamant about providing a wide front view so that the driver could feel as one with the car and drive safely and enjoyably. To do that, they located the base of the front pillar as far back as possible and made the pillar section narrow (Fig. 7), which enabled them to achieve the targeted front view.

The development team achieved each of two minivan values: spaciousness in the rear seat and an easy-to-use luggage compartment. To do so, the backseat provides 990 mm of legroom which is enough space for adults to cross their legs. They also optimized seat-face length and seat-back angle by using high-end sedans as reference. The focus here was not just spaciousness, but also a sense of relaxation.

The luggage compartment makes it easy to load and unload large objects, since the opening is low and the width of the opening is about the same as the STEP WGN (Fig. 8). Additionally, the low-floor center-tank layout means that the luggage compartment is high enough so that, with the backseat folded down, a mountain bike with its front wheel removed can be loaded into the compartment standing up.

A-pillar section

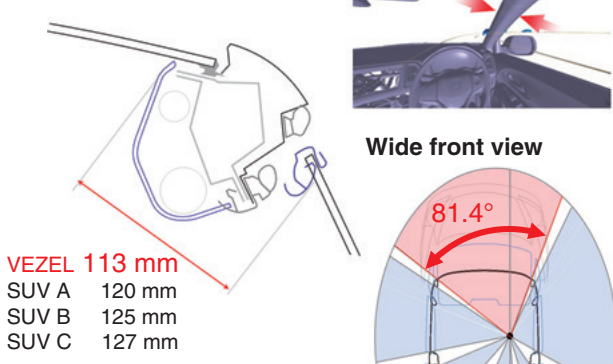


Fig. 7 A-pillar section and wide front view

Usability equivalent to one-class higher SUV

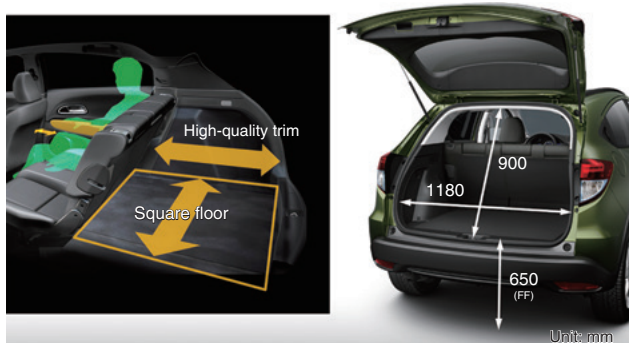


Fig. 8 Rear space

3. Exterior Design

3.1. Concept

“Dynamic Cross Solid” was established as the concept by the development team to help them dynamically combine the strength expected of an SUV with the “sensuality” of a coupe (Fig. 9).

To impart an urban SUV look for a new age, the development team started with the assumption that it would have fewer rugged (uneven surface) elements that invoke the conventional SUV image. Then, a strong front was designed by pulling the front pillar towards the rear and giving the nose a greater sense of volume than in an ordinary sedan. Also, to give straight expression to the real-car attractiveness, the bumper area was modeled to emphasize a sense that the four tires are firmly planted on the ground (Fig. 10).



Fig. 9 Exterior design concept



Fig. 10 Final exterior rendering

Next, the development team endeavored to provide a character line with a long stroke to give a coupe-like feel (Fig. 11). A long character line boldly cruising down the road on a compact body creates a more beautiful impression. The stretching sultriness moreover gives the vehicle a greater presence than one would expect in this body size. In particular, the character line, which starts from the C-pillar, straddles the shoulder, and thrusts all the way to a point in front of the front wheel arch, was carefully analyzed and treated as the point where the design “sensuality” and strength cross over. Additionally, the rear door handle is integrated into the rear tip of the side window (part of the C-pillar) to give the VEZEL the personal look of a two-door car (Fig. 12).

3.2. Aerocabin Offering Great View, Comfort, and Ease of Entry and Exit

SUVs typically encounter more air resistance than sedans because of their greater height. The development team’s target was to build a new-generation SUV with fuel economy similar to that of a sedan. However, a shape that is ideal in terms of fluid mechanics does not necessarily match up with attractive styling. Furthermore, balancing package performance (view and comfort) with fuel economy is also an important element of product development.



Fig. 11 Character line

Honda’s clay modelers worked to provide a cabin shape close to the fluid dynamics ideal after first satisfying the need for coupe-like styling, view, comfort, and ease of entry and exit. To do this they performed repeated wind tunnel simulation and modeling (Fig. 13). They also consulted not only with exterior designers but also package designers and interior designers to come up with the most complete product possible.

The basis of the cabin modeling was a shape that starts from the strongly curved front window and narrows towards the rear. From the rear seat to the luggage compartment the VEZEL provides rear seat comfort and a good rear view of minivans. Meanwhile, the side window graphics converge sharply at the rear to give a compact, personal impression from the outside.

The pursuit of aerodynamic performance, including below-floor rectification (Fig. 14), resulted in achieving the team’s aerodynamic targets. The VEZEL’s $CD \times A$ (air resistance $\times$ frontal projected area) is in the sedan category.

3.3. Front Face and Lighting Design

The front face expresses a sense of unity between the headlights and grille which conforms to the new Honda face



Fig. 13 Exterior clay model

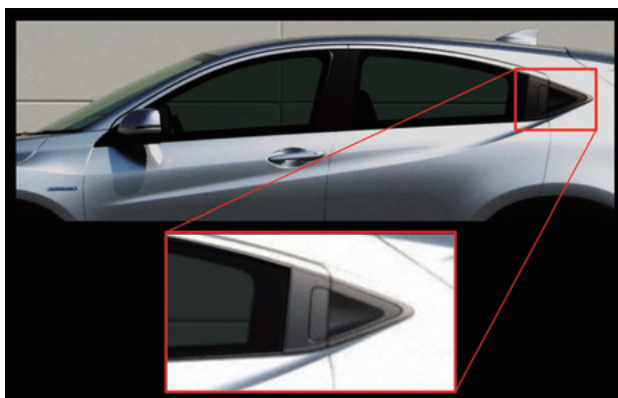


Fig. 12 Rear door handle

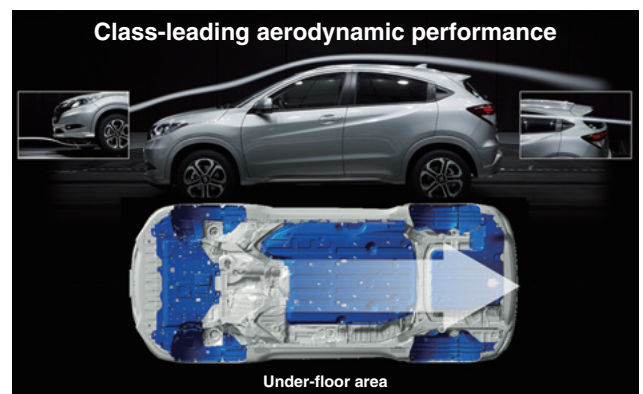


Fig. 14 Aerodynamics

idea called “SOLID WING FACE” (Fig. 15).

The grille of hybrid vehicles uses a new technique that applies a plating-like coating from the back of smoke acrylic resin. Additionally, the development team fastidiously used simple, clean modeling to create an image of pure metal to express SUV-like strength in a high-quality manner. The idea behind the gasoline version similarly used a dark metallic coating on a specially designed grille to evoke strength. Together with the chrome-plated molding this evokes a high-quality look.

The headlight (Fig. 16) evokes sensual strength by bringing out a metallic shine against the overall dark tone of the front. The hybrid version uses a projector-type lamp with two LED lights on each side. The development team strove to make the small, square, luminous body of the LEDs appear to be floating in a deep, dark space. The gasoline version has a black-toned multi-reflector-type headlight, giving the two versions a common identity.

The rear combination lamp (Fig. 16) uses an LED guiding stripe for the hybrid version and direct-type LED lighting for the gasoline version to help ensure that the lights are highly visible and advanced looking.

3.4. Design That Sparkles around the World

The exterior design had to have a tough look. It had



Fig. 15 Front face design

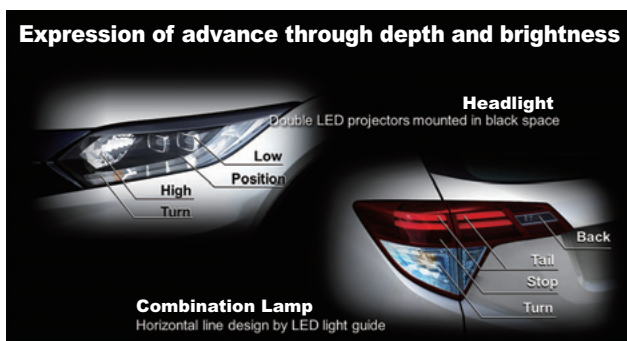


Fig. 16 Lighting design

to look as if it were on a German autobahn, for example, grabbing the road and not budging even if a larger car got close to it.

Japanese cars sometimes appear delicate in other countries. This is because environmental factors in these places, such as the breadth of the roads, the size of surrounding cars, and the quality of light, differ from those in Japan. The development team set about to give the VEZEL strong styling that is competitive enough for world markets (Figs. 17 and 18). Thus, the team parked larger, higher-priced vehicles next to their VEZEL model and proceeded to develop the product to have enough presence and quality to stand up to those competitors. In addition, to finish their strong “sensual” design that could shine no matter where in the world it cruises, the members visited many of the regions where the VEZEL was intended to sell and researched the environments in which it would actually be used. They also advanced the design process by reflecting the necessary elements into the model each time they were discovered.



Fig. 17 Strongly styled front



Fig. 18 Strongly styled rear

4. Interior Design

4.1. Concept

The concept established in the quest to develop a next-generation specialty car was “Expansible Cockpit” (Fig. 19). That expression brings together “expanse”,

referring to a spacious area, with “cockpit”, which evokes an image of a tight, sporty space. The aim of development was to combine these two contradictory values under the keyword “sensual” (Fig. 20).

Once the sense of confidence and ease of use expected from an SUV were achieved, the design task that arose from this concept was how to combine these with the “sensuality” of a coupe. The development team felt that the techniques for expressing all of these characteristics would not lead to high quality if the high-end feel and advanced characteristics of the VEZEL were only on the surface. The team explored a new styling approach based on the essence of the car’s value rather than play the eccentric artist. They additionally worked on the expression of the interior framework and texture so that customers who really knew cars would connect with the VEZEL.

4.2. Initiatives on Interior Framework

4.2.1. Instrument panel

One of the tasks performed in the initial stage of development is molding the instrument panel framework. Up to now, the trend has been to create a refreshing space by making the instrument panel look thin and light. However, customers demand a sense of confidence from SUVs, and giving them a sense of insecurity, such that they feel exposed, is not an acceptable trade-off for a

refreshing feel. The development team judged that it was appropriate to model the instrument panel about 70 mm thicker than in a same-class compact car that they had developed (Fig. 21). This was deemed to be the section necessary to give customers a sense that they are well protected even if cruising at top speed on, for example, a German autobahn. Generally speaking, a thick section gives passengers a strong sense of being pressed in. Therefore, the development team reduced elements like the character line as far as possible to provide a simple surface structure and reduce visual noise. The result is a refreshing feel that the interior is continuous with the outside world. They were also fastidious about the horizontal base tone to help ensure that passengers would be aware of the expansive, rich space. Thus the team minimized vertical elements, for example by getting rid of the center cluster panel (an element that partitions the space vertically) and giving the air conditioner outlet a long horizontal shape (Fig. 22). Due to such steps, the instrument panel appears wider than it actually is.

The result of emphasizing a simple, horizontal look is that the upper surface of the instrument panel, having very little character line, does not reflect very much in the front glass thus giving the driver a good view.

4.2.2. High-deck console

In the interior, the high-deck console is symbolic of the



Fig. 19 Interior design concept

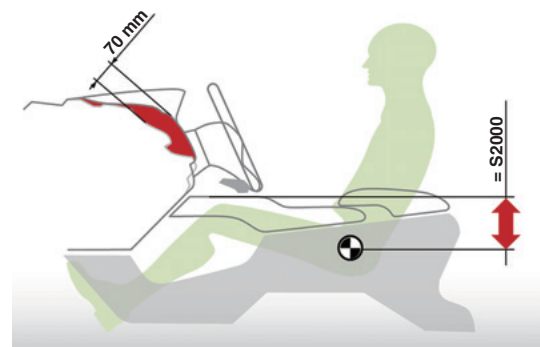


Fig. 21 Sectional view of instrument panel



Fig. 20 Instrument panel



Fig. 22 Passenger-side air outlet

character of the VEZEL (Fig. 23). As early as the initial stage of development, people within Honda had different opinions about using a high-deck console which divides the interior space. The development team, however, felt they could provide the high quality of a coupe that they were aiming for by providing personal areas for both the driver and front-seat passenger, and therefore worked to embody this.

The height of the console was set to be the same as that of the S2000, a sports car representative of Honda passenger standards terms (Fig. 21). This height evokes a sense of separation such as one might have in a business-class seat. The layout also provides the greatest possible couple distance for the body framework in order to give the driver and front passenger a comfortable sense of distance (Fig. 24).

Among European makes, even some compact cars in recent years have begun to use a soft pad on the top of the instrument panel, and this has gradually become an established signal to those with higher-end preferences.

From the customer's point of view, however, the development team felt it was more desirable to have a soft pad on the high-deck console, which is closer to the customer. Some argued that this was excessive, since no other model in this class had used a soft pad on the console. However, the team proceeded on the assumption that it would not use a soft pad on the top of the instrument panel as it had planned. As a result, the console, a large part of which consists of soft padding, created a value and characteristic that the VEZEL could easily convey to the



Fig. 23 High-deck console



Fig. 24 Wide couple distance

customer and further accentuate the personal feel that the team was aiming for.

Personal space was not the only value offered by the high-deck console. This layout also made it possible to use by-wire technology for the parking brake and made the cup holder easier to use. The unique and beautifully curved console design opened up utility space below the shift lever thus helping to achieve new and smart ease of use that had never existed before (Fig. 25).

4.2.3. A quality feel born of inevitability

The instrument panel built for a sense of confidence and the high-deck console designed for a personal feel thus completed the interior framework for embodying the “Expansible Cockpit” concept.

The simple, functional expression that was created by these initiatives and arose from inevitability combines high utility with beauty. This idea was set as the direction for the high quality that the development team was aiming for in the VEZEL interior and also led to the new idea of texture expression described below.

Simply expressing its functionality straightforwardly makes the interior design beautiful and enhances its value. Being too forward with styling and unnatural exaggeration of function is not the equivalent of high quality and can even diminish the value of the product. Although both interior and exterior design are forms of industrial design, interior design is somewhat different from exterior design, which has sculpture-like, pure art elements.

4.3. Initiatives for Expressing New Texture

4.3.1. From gorgeous to sensual

The keyword of texture expression in the VEZEL was “beguiling,” which relates to the grand concept. Wood and metal materials are frequently substituted with plastic. In recent years, coating and film materials have begun to offer higher quality at lower cost, so even some compact cars are decorated to be as gorgeous as high-end cars. Given the world view expected of the VEZEL, however, the development team wanted it to be “sensual” rather

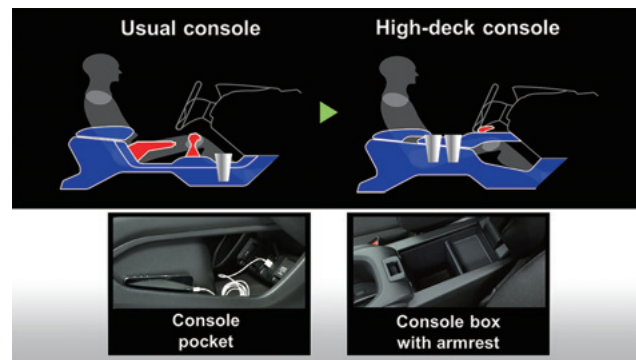


Fig. 25 Console utility

than gorgeous, so it was necessary to explore different techniques of texture expression than had been used before.

Since the model was meant to offer a high degree of utility, it inevitably assumes simple shapes; bringing out high degrees of beauty and quality as was the focus of the initiative to create a new framework as previously described. Thus, the development team believed it should be possible to bring out a “beguiling” expression by pursuing the inevitable in material expression as well. Therefore, they started with the assumption that they would not simulate wood and metal. Instead of decorating with the kinds of texture that have been used up to now, they moved to a new way of thinking: texture expressed by shape.

4.3.2. Three rules of texture expression

Advances in resin molding technology have made it possible to create products in all types of shapes. It is possible to make character lines that resemble leather while looking sharp enough to cut skin, or to create materials that look like metal but have the soft expression of organic matter at the same time. However, not every shape that can be formed necessarily looks like high quality. The development team felt that three inevitabilities (rules) were necessary to embody high-quality “sensuality”. These three rules help reduce inconsistencies and flaws that cause “noise” in the interior space. The team believed that these would certainly be conveyed to the customer as a sense of invisible quality.

The first rule was inevitability in respect to function. One has to select materials that reflect the functionality that the part is intended to have. One has to choose accurately based on whether that part will be viewed, touched, or operated during driving.

The team felt that this should be considered at the sketch stage (Fig. 26). For example, materials that drivers and passengers touch might be smooth and soft; those that are farther away might be dry and non-glossy; information displays and parts that are operated might be hard to the touch and designed to feel very precise. Therefore the team

set many material samples next to their sketch work and correlated functions to the tactile impression each material actually gave. Along with this they created a simple and dynamic expression with as few lines as possible.

The second rule was inevitability in respect to materials. This rule means that expression should follow the material that one expects to use. For example, if starting with the assumption that a leather expression is appropriate, one should follow the characteristics of leather even if the part is made of molded plastic. The team felt that this should be considered at the clay model stage (Fig. 27). In this case, most of the design consisted of large surfaces. Thus the clay modelers had to use a new modeling technique for those parts where a character line could not fool the eye. So in order to fashion high-quality surfaces that are simple but not dreary, the modelers started by understanding the characteristics of the material, determined how they could be expressed in delicate and dynamic ways, and reproduced these in the clay model. Additionally, for those parts where molding was to be used to create a sewn look, they analyzed and quantified the subtle tension in leather that has been stitched through with thread and reflected this in the clay model.

The third rule was inevitability in respect to manufacture. A product’s styling motif has to be consistent with the way it is manufactured. As manufacturing conditions may cause the motif to be disrupted, developers have to evolve a motif that is in keeping with how the product is manufactured. This is the attitude that designers take to their work. It reflects their ability to be flexible according to changes in conditions that happen during the development process. In the process of working with the design department, the development team encountered a number of unexpected situations. However, they had decided that instead of sticking stubbornly to the form they had previously chosen, they would take these unexpected situations as good opportunities for further creation. Each time conditions changed because of unexpected situations, the development team evolved their design by discussing and understanding the validity of these changes and turning them into new ideas (Fig. 28).



Fig. 26 Concept sketch



Fig. 27 Interior clay model



Fig. 28 Final interior rendering

Through this thorough pursuit of inevitability, from large surfaces to small details and even the very attitude of the design initiatives, the team developed an expression that exudes “sensuality” instead of depending on decoration.

In this manner, by developing a new interior framework and new texture expression, the team completed an interior that is personal, usable, simple, and “sensual.”

5. Color and Material

5.1. Concept

“COORDINATION” was chosen as the concept to express the idea of combining body and interior colors in the same way that people do with their fashion (Fig. 29). Instead of developing the body and interior colors separately, the development team expressed their world view that the interior and exterior of the car should be an integrated unit. In this manner they completed the “sensual” expression.

The body color expresses the toughness of an SUV and the bewitching look of a coupe while conscientiously appealing to the sultriness of an adult. The interior color expresses a high-quality, vivid space that is exhilarating to customers riding inside. Additionally, the body and interior colors were designed around three keywords – Mode, Cool,



Fig. 29 Color concept

and Elegance – and were completed to reflect each of those world views (Fig. 30).

The Mode color scheme, targeted at independent adult females, suggests a sparkling black world that is both alluring and strong. The bewitching purplish gray body and the contrast of textures combine with the glamorous black interior.

The Cool color scheme is targeted at people who are expressive and sensitive to sports and fashion. It evokes an active and classy feel. This scheme combines a magical blue body color with a glamorous black interior.

Finally, the Elegance color scheme offers a playful spirit in the midst of a calm setting for adults with a sultry side. The green body color is refreshing but deep. It combines with an orange-brown that imparts an active image.

5.2. Body Color

Three new body colors – a gun metal, a blue, and a green – express the toughness of an SUV and the bewitching look of a coupe. Each effectively changes expression according to the angle, taking full advantage of variations in the dynamic surfaces of the exterior styling.

Ruse Black gets its name from a black flower (the word “ruse” refers to playing tricks). The bewitching look of purple on deep gun metal was intended to look mysteriously

attractive as it reflects the nighttime cityscape.

Morpho Blue gets its name from the beautiful morpho butterfly characterized by its metallic brilliance. Its range of variation, from blue to purple, gives the VEZEL an attractive expression that is deep and multi-faceted.

Misty Green is not the lush green of early summer, but rather the calm reddish-green of late autumn. The addition of gold accents creates a refreshing mellow image.

5.3. Interior Color

The aim of the interior color was to make the simple interior styling, with its emphasis on functionality and texture, more conspicuous. Thus the development team narrowed down the decorative expression to plating and piano black, creating a vivid sense of tension in a space regulated by its underlying tone. The seat cover contains a pattern created by weaving and knitting techniques and takes advantage of the characteristics of the material to create a look of depth.

Passion Black completes a new black interior characterized by youthfulness and enthusiasm. It was intended to be a black that is actively chosen, not a black that one chooses because it is “safe”. The emphasis here was the contrast in glossiness created by the material. The upper surface of the instrument panel has large grains that form a

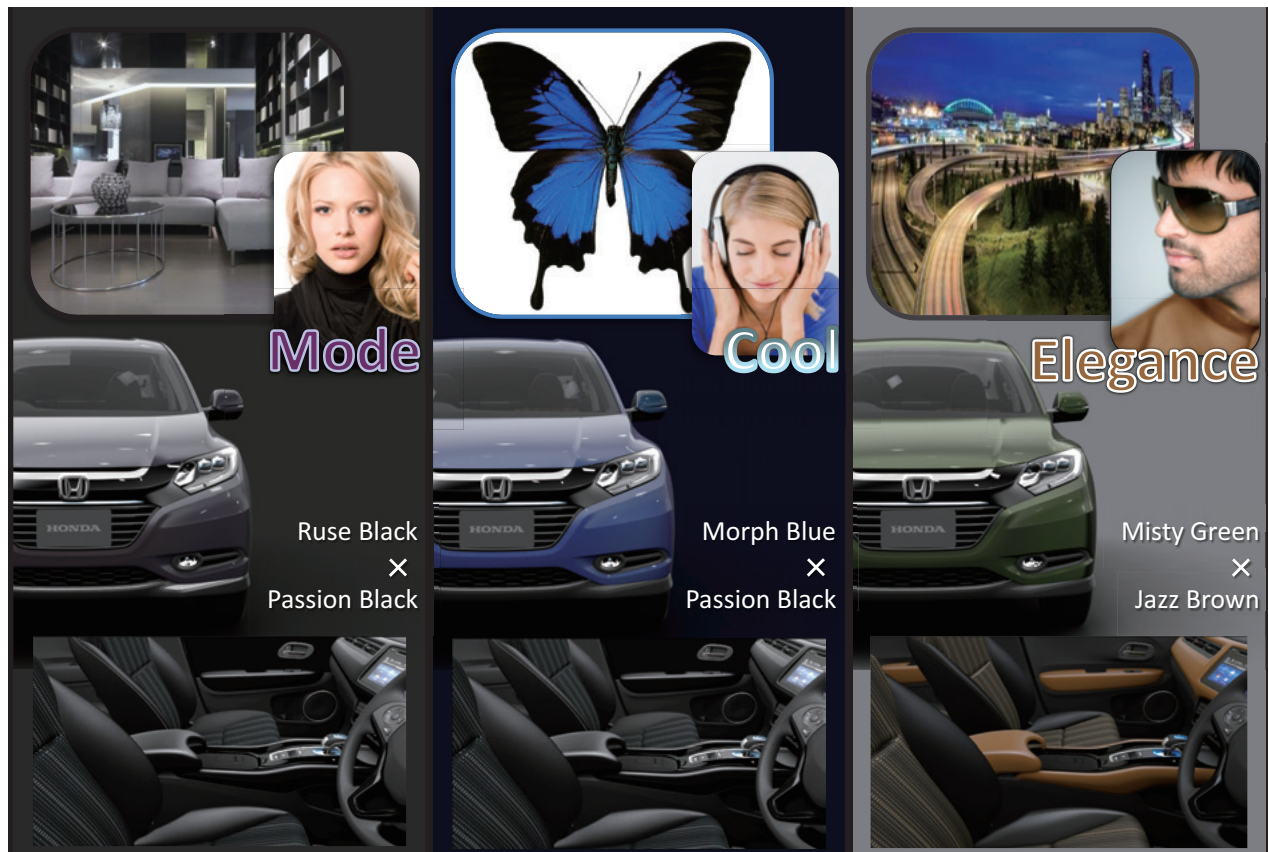


Fig. 30 Three types of coordination

pattern with low reflectivity emphasizing functionality. The middle pad is soft with a small-grained, smooth leather-like material. Typically, leather materials have a texture that restrains glossiness as far as possible, but the middle pad of the VEZEL is engineered to be highly glossy. Its expression is quite different from that of the top surface of the instrument panel. The contrast among the three levels of glossiness – the dry top of the instrument panel, the smooth middle pad, and the piano black panel that sparkles as if wet – produces a glamorous black world.

In contrast to the conventional image of calm brown interiors, Jazz Brown completes a new brown interior that expresses the playful spirit of active adults. The seat covers have a main material of calm dark brown with glossy gold stripes running throughout. This coordinates the seats with the Misty Green Pearl. In addition, the instrument panel middle pad, the center console, and the armrests use a jaunty orange-brown to create an energetic brown world.

5.4. The Chemistry of Combination

Green body colors are not supposed to sell well in the Japanese market, so the development team anticipated that it would not be easy to convince everyone concerned that it would be a good idea to develop Misty Green. In addition, many customers who consider a brown interior like Jazz Brown when they are thinking about their purchase ultimately choose a safe black interior, so these have also not increased sales.

The aim in this color development process was to achieve both toughness and elegance. The team therefore came up with a challenging proposal: combine Misty Green and Jazz Brown, neither of which would supposedly sell. The result of this experiment was a synergy such that each color brought out the attractiveness of the other. Ultimately, this proposal raised some high expectations such that it would be treated as an appeal color when sales started. In fact, whereas the sales plan anticipated a certain percentage of customers favoring the Misty Green body and Jazz Brown interior, the actual percentage who did so exceeded the plan numbers several times over. This is currently driving the strong sales of the VEZEL. This shows how important it will be to use coordination to propose world views during color development in future. Additionally, the ability to offer customers a wide range of choices can help them realize things they never noticed before, and allow Honda to bring more color into their lives.

6. Conclusion

In recent years, one does not hear people use expressions like “That is so much like Honda”. The development of the VEZEL was a way for team members to ask themselves what it means to be Honda-like. It is not enough for a car to be convenient and comfortable. To be Honda-like is to make people feel positive when they get in. To be Honda-like is also to bring new feelings into the lives of those

passengers. The desire to build such a dream car was shared by the members of the development team as they created the VEZEL.

The package combining the personal feel of a coupe with the utility of a minivan; the exterior design that is both brawny and sultry; the interior design with both spaciousness and a personal feel; the color design evoking intelligence amidst strength: all of these were achieved by a team truly committed to the customer as it pursued its common theme of “sensuality.” The VEZEL development team imagines a customer seeing this vehicle for the first time and knowing instinctively, “This is what I want”. Or riding in it for the first time and knowing for sure. And living with the VEZEL day after day and becoming convinced beyond all doubt: “This is so much like Honda”. Nothing would make the development team happier.

Honda is known for delighting customers by building things that never existed before. However, because of their experience and habits, developers tend to work in ways that avoid failure, unconsciously putting up barriers that make them unable to take on new challenges. And in many cases the things that never existed before are on the other side of that barrier. There is only one source of the strength to get over that barrier: the firm conviction that “this is exactly the right value to offer customers”. Honda’s true identity does not reside in ideas or new technology: it is the courage of each developer to confront that barrier when necessary.

■ Author ■



Hiroyuki YAMAMOTO

Development of Inverter Generator Equipped with Fuel Injection Engine

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ABSTRACT

The EU6500is generator, which has an established reputation for realizing the world's top level of compactness and quietness in the 5.5 kVA class, has been employed as the base model in the development of the EU7000is, further increasing the value of the unit as a home back-up generator.

The use of a fuel-injection system able to optimally control engine air-fuel ratio irrespective of external factors has increased fuel efficiency by 22% against the existing model.

The integration of the injector and the throttle body has made it possible to employ the developed generator fuel-injection system while maintaining compactness, and the mounting of the atmospheric pressure and intake air temperature sensors on the circuit board of the generator control unit and the removal or simplification of various other sensors have helped to enable the use of the fuel-injection system with minimal cost increase.

The use of the fuel-injection system has enabled continuous operation of the unit for up to 12 hours without refueling. Modification of the power supply circuit and reduction of the minimum operating voltage of the generator control unit allow starting of the unit using a battery-less recoil starter. The realization of increased inverter efficiency and the optimization of ignition timing have increased maximum output from 6,500 VA to 7,000 VA. This has made it possible to respond to the motor load represented by air conditioners and other pieces of equipment that draw large amounts of power at startup, expanding the range of applications of the unit as a generator.

1. Introduction

The price of gasoline is increasing worldwide simultaneously with the number of planned power outages as a result of power shortages in developing countries and increased outages due to hurricanes and other natural disasters. This situation is producing demand for greater fuel efficiency and extended continuous operation in portable generators.

In addition to its fuel efficiency, Honda's current EU6500is portable generator has been well received due to its compact body, quietness, and reliable generating performance, is employed in a wide variety of applications and relied on as a power source for film shoots and for construction work using precision equipment in addition to functioning as a backup power source during outages⁽¹⁾.

However, taking into consideration responses to the environmental issues that are currently increasing in severity around the world, there are limits to the ability to balance fuel efficiency and emissions reductions using

a carburetor system, which is affected by external factors such as temperature and altitude (air pressure).

In response to this situation, for its latest generator model change Honda developed its first fuel-injection (FI) system for a generator, seeking to realize an enhanced balance between high fuel efficiency and reduced emissions.

In contrast to carburetor systems, FI systems necessitate the use of fuel pumps and a large number of sensors, thereby increasing cost. In addition, considering the use of the generator during a power outage caused by a natural disaster, it is necessary to be able to start these devices when the battery is exhausted. It was also necessary to consider the infiltration of dust into the fuel tank and long-term storability, given the characteristic use modes of generators.

This paper introduces the EU7000is, Honda's new model generator fitted with the unique FI system described above.

* Power Products R&D Center

2. Development Goals

The goal was the development of a generator that maintained the world's top level of compactness and quietness for a 5.5 kVA-class unit while realizing enhanced value as a backup power source (extended continuous operation, long-term storability). Figure 1 shows an external view of the EU7000is, and Table 1 shows a comparison of the specifications of the developed and existing models.

According to market surveys, the power generation demanded during an outage is between 2,000 and 3,000 VA (corresponding to 50% of the unit's rated load) in the case of a normal U.S. household. If 12 hours of continuous operation were possible at this load, the unit could be continuously operated throughout the night until morning without refueling, giving it considerable appeal as a home back-up generator.

Realizing this goal would require increasing the volume of the fuel tank as much as possible while maintaining the compactness of the existing model, as well as increasing fuel efficiency by 20%.

The following development goals were set:

1. Goals for generator FI system
 - (1) 20% increase in fuel efficiency
 - (2) Reduction in number of sensors and optimization of devices
 - (3) Start-up using battery-less recoil starter
 - (4) Protection of exhaust gas catalyst when unit stops due to low gasoline levels
2. Targets as backup generator
 - (1) 12-hour continuous operation without refueling
 - (2) Increased maximum AC output
 - (3) Long-term storability and increased maintainability
 - (4) Greater ease of start-up



Fig. 1 Appearance of EU7000is

Table 1 Comparison of specifications

	EU7000is (New model)	EU6500is (Current model)
Engine displacement (cm ³)	389	389
Fuel system	Fuel Injection	Carburetor
Max. AC output (VA)	7000	6500
Rated AC output (VA)	5500	5500
Fuel tank capacity (L)	19.2	16.0
Rated operating noise level (L _{WA} : dB)	91	91
Dimensions (L × W × H: mm)	848 × 700 × 721	850 × 666 × 699
Dry mass (kg)	118.6	118.2

3. Methods of Realization of Targets and Achieved Values

3.1. Generator FI System

3.1.1. 20% increase in fuel efficiency

While realizing a lean air-fuel ratio (A/F) by reducing the ratio of fuel increases an engine's fuel efficiency, if the ratio of fuel is reduced when a carburetor system is used, the fuel ratio is further reduced at low temperatures, when the density of the intake air is high, and combustion becomes unstable.

An FI system able to optimally control A/F irrespective of external conditions such as temperature and altitude (air pressure) through the use of a variety of sensors was therefore employed in the new model generator. In combination with the use of an exhaust gas catalyst, this has realized a good balance between increased fuel efficiency and reduced exhaust emissions.

Figure 2 shows a comparison of fuel consumption between the developed and the current models. Fuel efficiency is 22% higher in the developed model (at 50% of rated load).

3.1.2. Reduction in number of sensors and optimization of devices

The number of sensors employed in the FI system was reduced and sensors were simplified in order to maintain the compactness of the existing model while minimizing

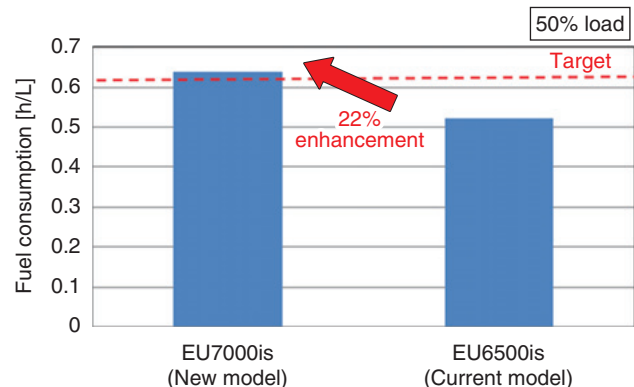


Fig. 2 Fuel consumption

cost increases. Figures 3 and 4⁽²⁾ show diagrams of the configuration of the FI system.

(1) Injector and throttle body

The integration of the injector and the throttle motor with the throttle body enabled fitting of an injector and throttle motor without changing the compact layout of the existing model (Fig. 5).

(2) Generator Control Unit (GCU)

FI control functions were added to the existing GCU employed to control the generator, enabling FI control without the addition of a new FI control unit.

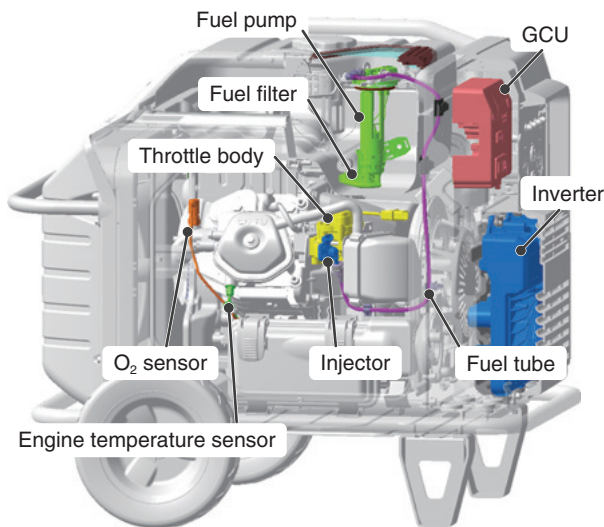


Fig. 3 Fuel injection system

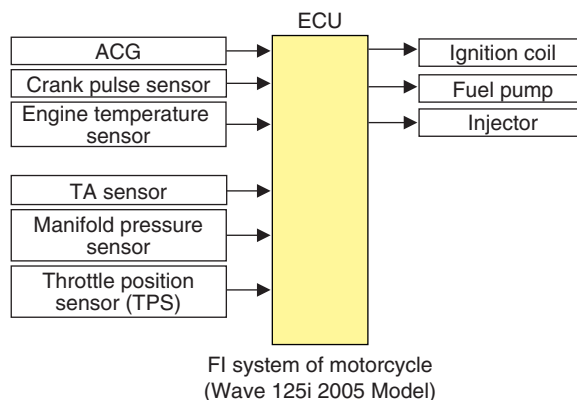
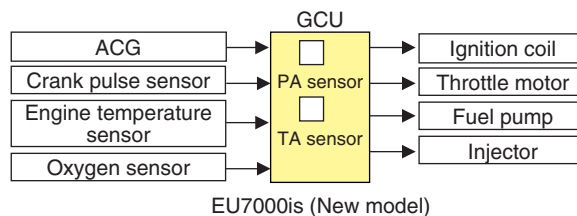


Fig. 4 Schematic diagram of fuel injection system

In response to the increases in power consumption and number of parts from the use of an FI system, a two-level circuit board was employed in the unit, enabling fitting of the FI system with no increase in size compared to the existing model.

(3) Atmospheric pressure sensor and intake air temperature sensor

Direct mounting of the atmospheric pressure sensor (PA sensor) and intake air temperature sensor (TA sensor) on the circuit board of the GCU lowered the cost of the sensors and reduced the need for harnesses (Fig. 6).

The readings of the TA sensor can deviate from the actual engine intake air temperature due to factors such as the heat produced by other components. To avoid the sensor being affected by heat, the layout divided the circuit components into high-temperature and low-temperature sections, and the sensors were positioned in the low-temperature section (Fig. 7).

An air vent was also positioned in the upper section of the control panel, helping to ensure a correlation with the actual intake air temperature through the introduction of external air to the area around the sensors.

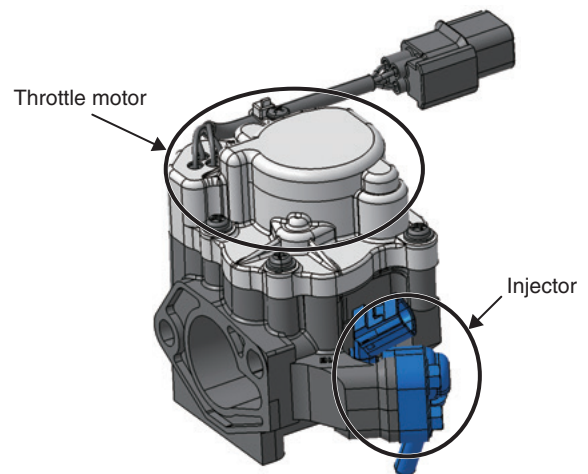


Fig. 5 Throttle body

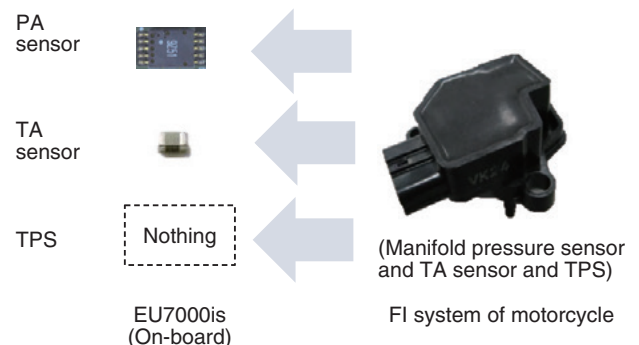


Fig. 6 PA sensor and TA sensor and throttle position sensor

(4) Throttle opening sensor

Because the GCU controls the degree of throttle opening using a stepping motor, in the developed system the output pulse to the motor is counted, helping to ensure the GCU is constantly aware of throttle opening. Recognition of the degree of throttle opening by the GCU has eliminated the need for a throttle-opening sensor while applying throttle-speed control.

(5) Reluctor for detection of engine speed

Control of conventional FI systems is realized by mounting a reluctor able to detect a number of reference positions (e.g. 13 pulses) for each single rotation on the flywheel (F/W) or another part in order to detect engine speed and crank angle.

In the developed generator, the engine speed and crank angle are detected by combining the reference signal for ignition (one pulse per one rotation) as used in the existing model and the alternator output signal (10 pulses per one rotation).

As a result, it is possible to detect the engine speed and crank angle using the F/W of the existing model without the addition of a new reluctor. Figure 8 shows a comparison of the reluctors employed in the developed model and in a conventional FI system.

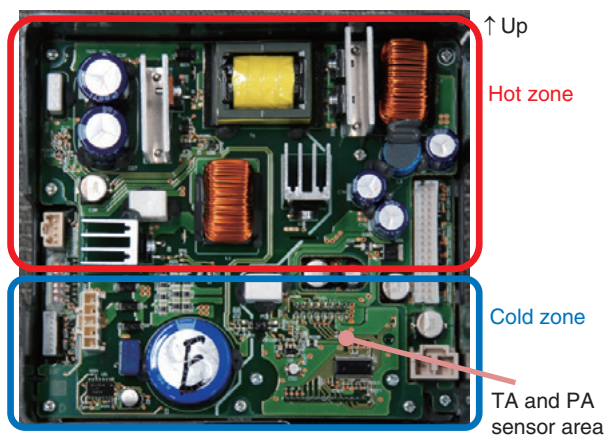


Fig. 7 GCU circuit board

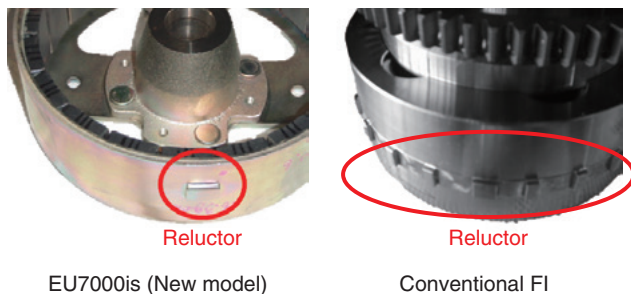


Fig. 8 Reluctor

3.1.3. Start-up using battery-less recoil starter

While the developed generator is normally started using a starter motor, it was also necessary for it to be started when the battery was exhausted. The system configuration enables manual starting using a recoil starter even if the battery is removed.

An FI system uses more power than a carburetor system due to the necessity of driving the fuel pump and injector at start-up. Employing the existing power supply system would result in a shortage of power when the unit was started using a battery-less recoil starter. The power supply circuit was therefore modified to realize the same level of startability using a recoil starter as in the existing model.

The rotational speed for ignition start in the developed model is 200 rpm. Since at lesser speeds it is necessary to start the system up, the minimum operating voltage for the GCU was reduced. Figure 9 shows the power increase characteristic of the unit when started using the battery-less recoil starter. Using power from the alternator coils (ACG), sufficient power can be supplied from 100 rpm.

3.1.4. Protection of exhaust gas catalyst when unit stops due to low gasoline levels

There are occasions on which a generator will be used until the gasoline in the fuel tank runs out. When the gasoline runs low, fuel is intermittently supplied to the injector and a governor automatically controls the throttle to maintain constant speed. This results in significant fluctuations in A/F and engine speed. When this happens, uncombusted gas flows to the exhaust gas catalyst, resulting in unusually high temperatures, as well as in possible declines in catalyst performance.

A method of detecting that the system is running low on gasoline was therefore developed using the existing engine speed control function, enabling response without the addition of a fuel level sensor or other components. This control judges that gasoline is running out when engine speed remains at the minimum level without rising despite the throttle being close to wide open, and rapidly stops the

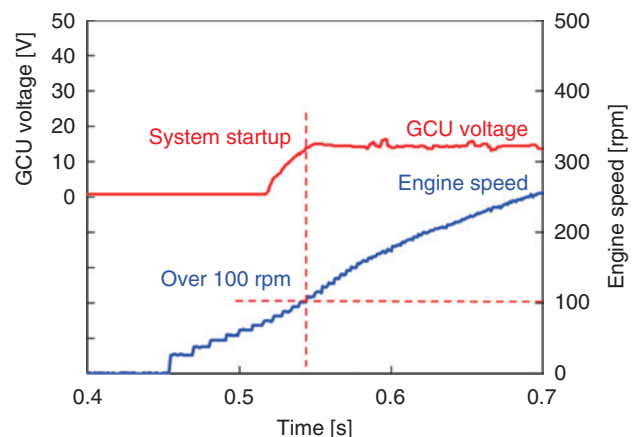


Fig. 9 Power supply at startup

engine, helping to protect the exhaust gas catalyst without increasing cost.

3.2. Backup Generator

3.2.1. Continuous 12-hour operation without refueling

Increasing the volume of the fuel tank by 20% and employing the FI system technology discussed above has increased the period for continuous operation from full tank to low gasoline levels at 50% of rated load by 1.5 times against the existing model, enabling 12 hours of continuous operation without refueling. Figure 10 compares the existing and developed models.

3.2.2. Increased maximum output

The use of the generator FI system in the developed unit eliminated the venturi, an important element in a carburetor system, increasing the engine's maximum output by 3% against the existing model. In addition, the realization of increased inverter efficiency and the optimization of ignition timing increased maximum output from 6,500 VA in the existing model to 7,000 VA in the developed unit. Figure 11 shows the power characteristics of both models at startup.

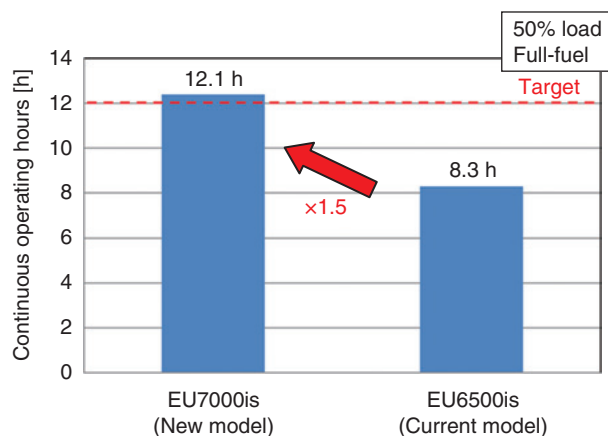


Fig. 10 Continuous operating hours

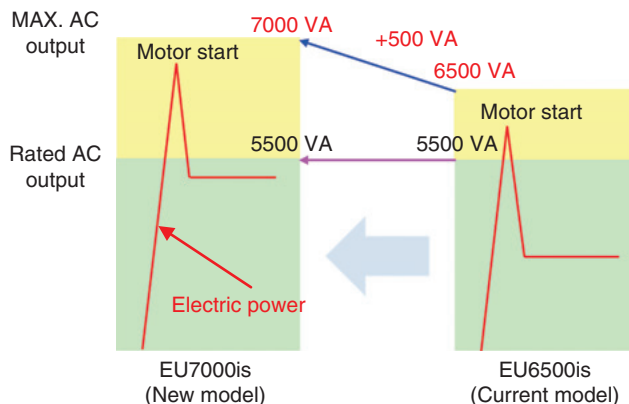


Fig. 11 Maximum power

These enhancements compensate for the motor load represented by air conditioners and other equipment that require large amounts of power at startup, expanding the range of applications of the unit as a generator.

In order to increase power, the magnetic force of the magnets in the alternator coils was increased by modifying the material, and the efficiency of the inverter was increased by redesigning the power module.

Because increased maximum power also increased the maximum amount of heat produced by the inverter, simulations were employed to optimize the shape of the cooling fins and enhance cooling performance.

Figure 12 shows the temperature distribution indicated by the inverter heat simulations. The use of a radiating fin shape disperses the flow of wind, enhancing cooling performance.

3.2.3. Long-term storability and increased maintainability

Backup generators are often stored for extended periods. Due to the configuration of the system, when the generator uses a carburetor system, gasoline comes into contact with the external air, necessitating removal of the fuel from the carburetor float chamber when storing the unit over a long period. With an FI system, however, gasoline makes little contact with the external air and thus tends not to become degraded, eliminating the need to remove the fuel from the FI system (the injector, fuel hose, and other parts) and easing maintenance prior to storage.

In addition, because generators cannot be directly supplied with fuel from a gasoline pump, they are often refueled using stored gasoline from portable gas cans, with a significant amount of dust entering the fuel tank. In response, the fuel pump in the developed unit is positioned at the top of the fuel tank (Fig. 3), and can be removed and reattached, increasing the ease of fuel filter maintenance.

3.2.4. Easier start-up

The use of an FI system eliminated the need for a fuel cock and choke, as used in carburetor systems, simplifying startup.

A push-start system has been employed to further emphasize this benefit. While the existing model is cranked by turning an ignition key, startup has been completely

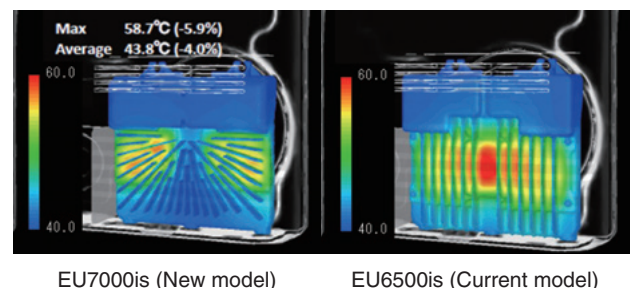
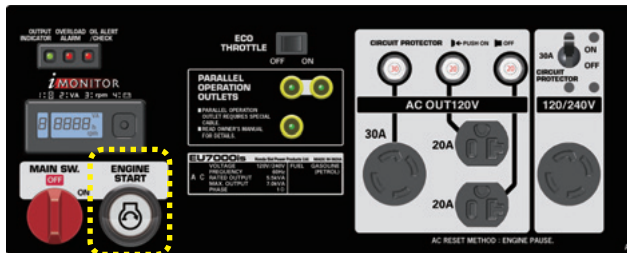


Fig. 12 Simulation result

refurbished in the developed model by the use of push-button cranking (Fig. 13).

Briefly pressing the push-start button automatically operates the starter motor for a maximum of five seconds, with the starter motor ceasing operation when the engine starts. This startup method increases convenience for users in comparison to the existing model, and offers more advanced operability.



Push start button

Fig. 13 Control panel

4. Conclusion

A generator employing an FI system has been developed that realizes increased appeal as a home back-up generator while maintaining the compactness of the previous model.

(1) Development of generator FI system

- The development of a generator FI system increased fuel efficiency by 22%.
- The integration of the injector and the throttle body allowed incorporation of an FI system while maintaining the compactness of the existing model. In addition, the mounting of the PA and TA sensors on the circuit board of the GCU and the removal of the throttle-opening sensor realized the system with minimal cost increase.
- The optimization of the power supply circuit and the reduction of the minimum operating voltage of the GCU allow the unit to be started using a battery-less recoil starter.
- The application of control when the unit is running out of gasoline helps to protect the exhaust gas catalyst.

(2) Development of backup generator functions

- The application of the generator FI system has realized continuous operation for 12 hours without refueling.
- The realization of increased inverter efficiency and the optimization of engine specifications have increased maximum output from 6,500 VA to 7,000 VA.
- The use of an FI system has increased long-term storability, and the ability to remove and reattach the fuel pump from the top of the fuel tank has increased the ease of fuel filter maintenance.
- The use of a push-start method has increased the ease of start-up.

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Development of High-Efficiency Water Pump Using CFD Simulation

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ABSTRACT

Water pumps are often used for many continuous hours, and as a result, they account for a large part of the CO₂ emissions of general-purpose products. Therefore, it is desirable that the fuel consumption of such pumps be improved.

In order to make such an improvement, computational fluid dynamics was used to develop water pump specifications that would adjust the working performance and enhance the efficiency of such pumps.

The water pump developed herein was targeted at users of three-inch pumps doing irrigation work with low head (lifting height) in Southeast Asia. The researchers forecast that the new pump could improve fuel consumption by more than 20% compared to a current model within the operating range of the market, thanks to adjustment of the pump performance in line with the needs of the target market, enhancement of pump efficiency, use of a low-displacement engine, and adjustment of air-fuel ratio. The effect was then confirmed by testing.

1. Introduction

1.1. Issues Concerning Water Pumps

Ensuring adequate water resources on the global scale has become a major issue in light of population growth and global warming in recent years. Projections indicate that food production will continue to increase in the future (Fig. 1)⁽¹⁾, a trend which is likely to increase water demand. Water pumps are used around the world as machines for helping irrigators use water resources, and as food production and water demand rise, the demand for water pumps is expected to increase as well.

These pumps perform a number of jobs, including irrigation of paddies and dry farm fields, draining and adjusting the water levels of ponds and pools, and filling water tanks.

Pumps are often used for four to eight hours continuously, so they tend to have higher CO₂ emissions than other equipment. Based on an analysis of the various general-purpose products sold by Honda, it is forecast that water pumps will account for 85% of the CO₂ emissions of this product category (Fig. 2).

Thus, as demand for water pumps rises in the future, CO₂ emissions are expected to increase all the more. As a manufacturer of water pumps, Honda therefore wishes to improve water pump fuel consumption and lower the CO₂ emissions of these products.

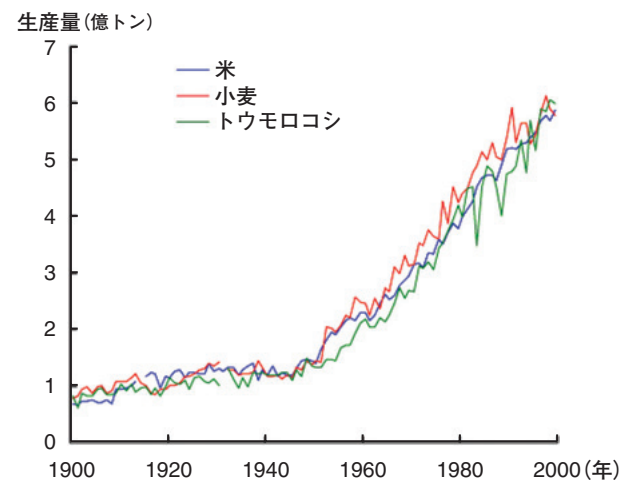


Fig. 1 Quantity of crops production

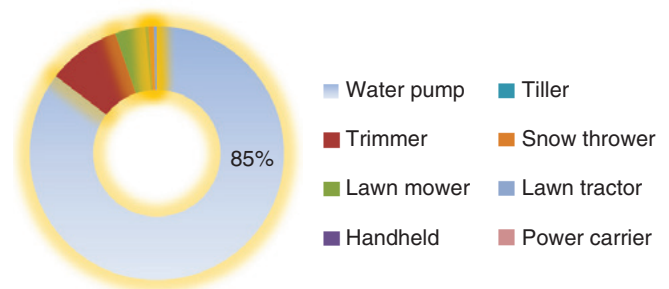


Fig. 2 CO₂ emission ratio of Honda power products

* Power Products R&D Center

1.2. Analysis of Honda Water Pump Sales Patterns

This section discusses sales patterns for water pumps at Honda. Honda began selling water pumps in 1967. Its product lineup is categorized in inches according to the diameter of the pump's inlet and outlet. Sales results from FY2011 indicate that the three-inch class had the most sales, accounting for 52% of all pumps sold (Fig. 3).

By region, the results indicate that about 44% of Honda pumps were sold in China, Southeast Asia, or Oceania (Fig. 4).

1.3. Market Characteristics

Figure 5 shows a work point map for water pumps in various regional markets as indicators of discharge capacity and head. The operating range of water pumps in each region is determined by such factors as application, installation environment, and awareness of oil fuel. Southeast Asia clearly differs from other parts of the world,

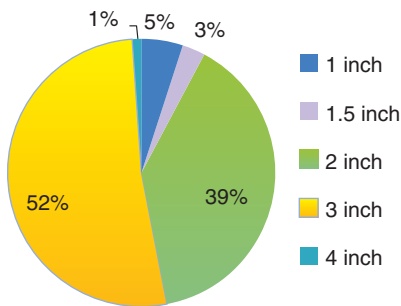


Fig. 3 Inch categorized sales result of Honda pumps

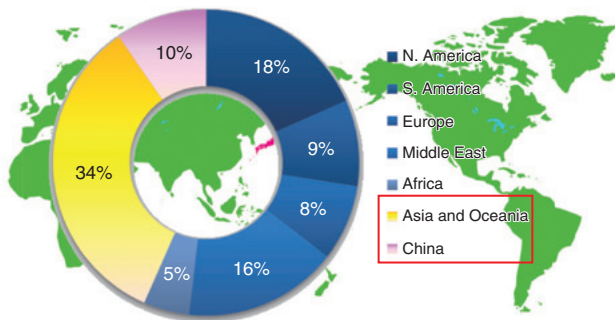


Fig. 4 Area categorized sales result of Honda pumps

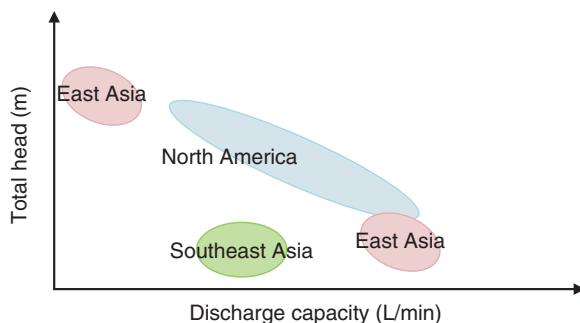


Fig. 5 Work point map of water pump

where water pumps are frequently used to irrigate paddy fields. The work point here is characterized by low rotation, meaning limited discharge capacity, and low head.

2. Characteristics and Performance Targets for the Newly Developed Pump

2.1. Characteristics of the Newly Developed Pump

Water pumps sold by Honda are mostly self-priming. Pumps need to have appropriate pump performance (the transport performance of water) as well as be self-priming, meaning that upon starting up, the pump can lift water from the source all the way up to the pump itself. Self-priming is the process in which a pump expels inlet-side air once only the inside of the pump is filled with water (Fig. 6). During self-priming, air and water mix inside the pump, after which only the air that is close to the outlet becomes separated and expelled (Fig. 7).

There are several ways to get good self-priming performance, such as increasing the turbulence at the air-water interface to encourage mixing, and encouraging separation by drawing the mixed fluid with a centrifugal flow. However, during ordinary work after self-priming has already occurred, the structure of a pump that enhances these self-priming properties tends to lower pump efficiency. Thus pump performance and self-priming performance often conflict with each other.

2.2. Component Configuration

As Fig. 8 shows, the major components of a water pump are the impeller, volute, casing, inlet, and outlet.

While the form of each component has to be decided based on a balance of pump performance and self-priming performance, the newly developed pump favors pump performance.

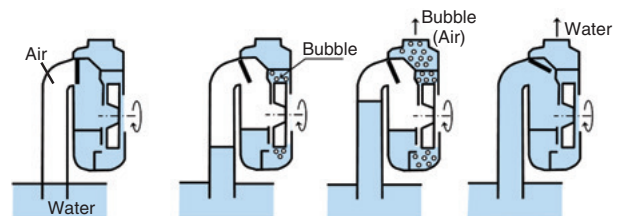


Fig. 6 Self-priming image

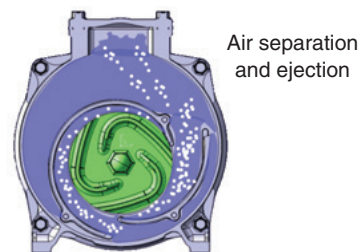


Fig. 7 Water circulation image of self-priming process

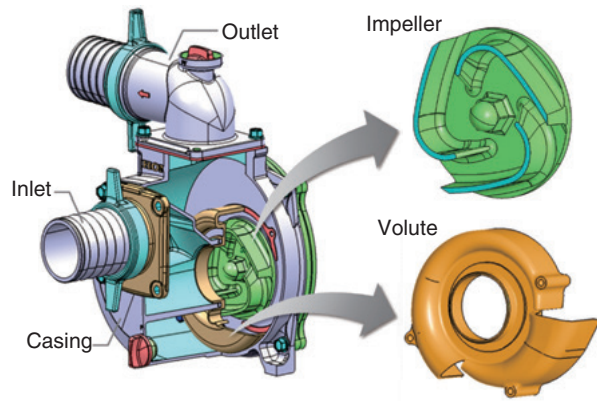


Fig. 8 Main parts of water pump

2.3. Development Target Market and Performance Targets

The newly developed water pump was targeted at users of three-inch pumps doing low-head irrigation in Southeast Asia. It was intended to improve fuel consumption in actual use.

The performance target was to improve fuel consumption in actual use by at least 20%, in part by optimizing impeller form to enhance pumping efficiency and by making adjustments like switching engines.

3. Examination of Specs

3.1. Pump Performance Adjustment Concept

The researchers examined pump performance suitable for low-head, low-rotation operation. As an example, two pumps (A and B) with the same maximum discharge capacity and efficiency were compared. B has a lower maximum head than A. Figure 9 illustrates operation of the two pumps at a low-head, low-rotation work point. The figure shows how the efficiency of pumps A and B differs at the work point under these conditions. B can operate at higher efficiency.

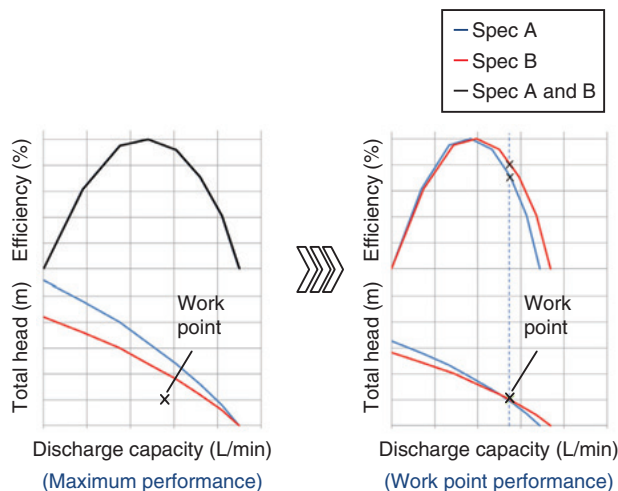


Fig. 9 Concept image of pump performance tuning

Table 1 CFD setting

Solver	Pressure-based
Viscous model	k- ω Standard
Motion	Mesh motion
Scheme	SIMPLE
Fluid materials	Water

Therefore, the pump performance was adjusted in the newly developed pump to prioritize efficiency at the work point and lower the maximum head.

3.2. Specs Examination Technique

To develop the new pump, the researchers used computational fluid dynamics (CFD) software to forecast pump performance and consider pump form. Table 1 lists the CFD settings, while Fig. 10 gives a CFD image and Fig. 11 shows results of confirming the forecasting precision on

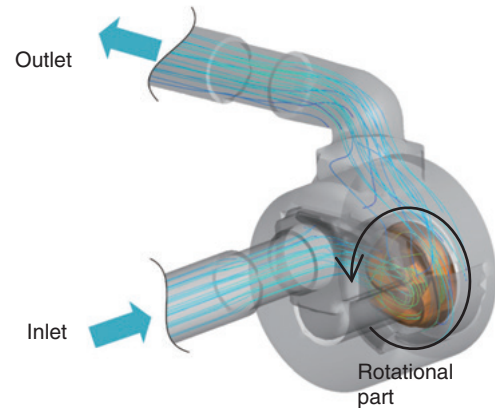


Fig. 10 CFD image

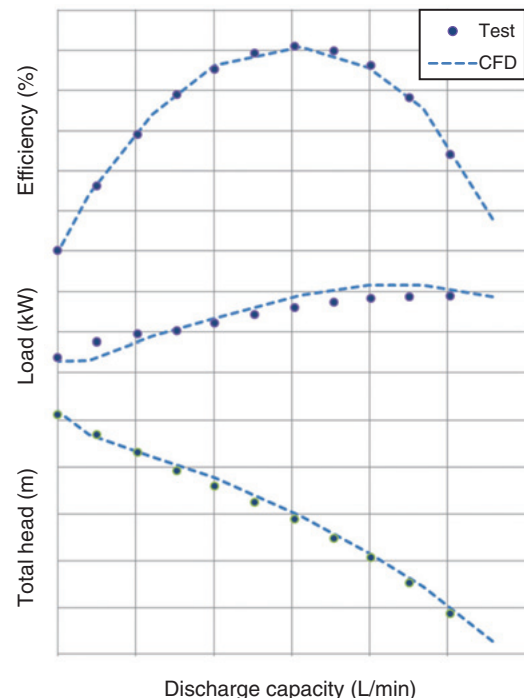


Fig. 11 Correlation result compared with test and CFD

a current model. Pump performance forecasting precision was within 5%, required load properties forecasting precision within 7%, and water pump efficiency forecasting precision within 3%. Cavitation is prone to occur close to the shutoff head, and enhancing precision in this range is an issue for the future, but the technique is sufficiently practical for a basic examination of pump performance. Analysis of self-priming performance involves the two phases of water and air, and it was determined that forecasting precision is insufficient as the technique currently stands, so testing was done to confirm trends in self-priming performance in respect to form.

3.3. Examination of Impeller Form

The researchers examined the form of the impeller for the newly developed pump by adjusting the various parameters shown in Fig. 12. Figure 13 gives a correlation

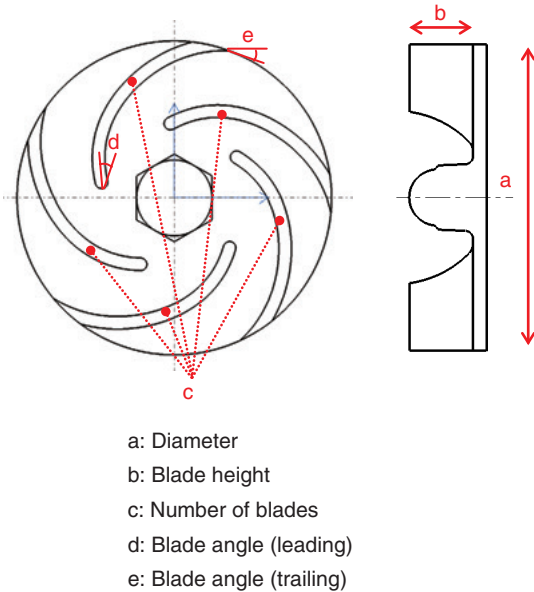


Fig. 12 Impeller parameters

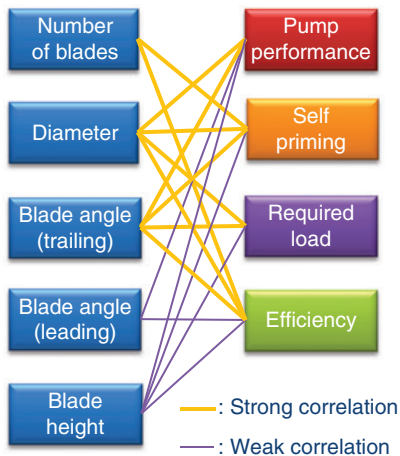


Fig. 13 Correlation map of parameter and pump performance

map between the parameters adjusted during this development and pump performance.

The first parameter selected for the development was the number of blades. A check of the correlation between number of blades and pump efficiency as based on the impeller from the current model resulted in the trend shown in Fig. 14. In general, a large number of blades tends to inhibit mixing of water and air in the impeller perimeter and lower self-priming performance, but for this development, the number of blades was chosen by prioritizing efficiency.

Next, the researchers examined diameter, which has a great impact on required load and head. Achieving the pump performance adjustment concept requires lowering the maximum head, but when the diameter was made smaller on the current model, pump efficiency tended to decrease, so for the new development, the same diameter was chosen as in the current model.

Finally, adjustments were made to the other impeller parameters. Larger blade angles on the outflow side tend to increase self-priming performance, but for this development, a smaller angle than the one used in the current model was chosen, since pump efficiency was the priority. Moreover, depending on the nature of the user's water source, foreign matter such as pebbles and plants could get sucked into the water pump. To help prevent such matter from getting stuck in the impeller, there has to be at least a certain blade height and a certain distance between blades.

3.4. Pump Performance Forecast

The impeller form, which the study results show has a major effect on pump performance, is shown in Fig. 15.

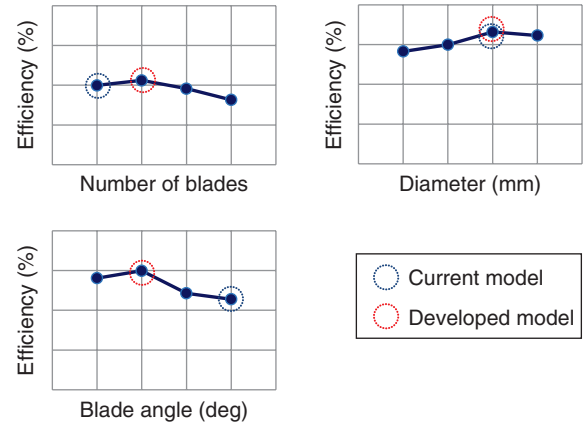


Fig. 14 Correlation of impeller parameters and efficiency

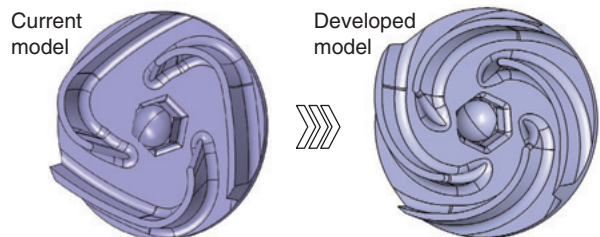


Fig. 15 Comparison of impeller

According to CFD, the current model exhibited areas on the backs of the blades where total pressure dropped (areas inside the red dashed lines in Fig. 16). However, the blade form of the newly developed irrigation model was designed to increase efficiency by eliminating these drops in total pressure, as shown in Fig. 17.

The researchers checked the head balance by considering the percentage of total head, as well as head loss in each part of the channel inside the pump, to theoretical head⁽²⁾ (Fig. 18). While the head loss in the

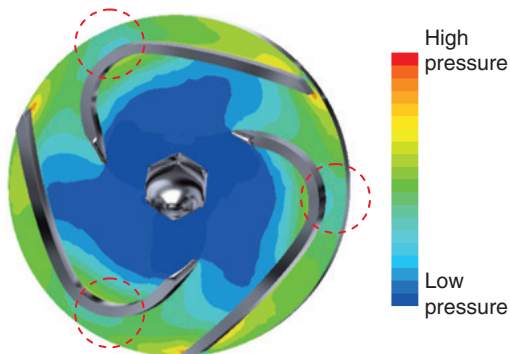


Fig. 16 CFD analysis result (Current model)

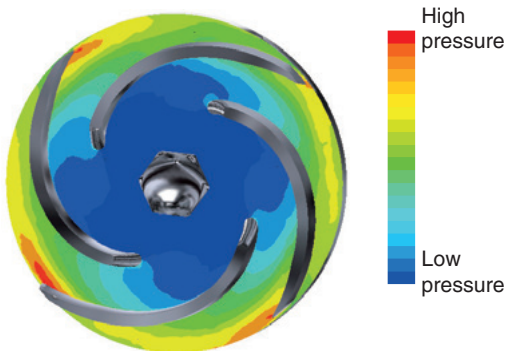


Fig. 17 CFD analysis result (Developed model)

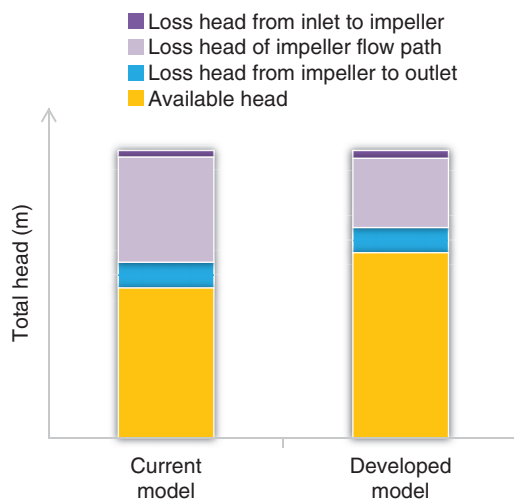


Fig. 18 Head balance

flow before and after the impeller was largely the same in the current model and irrigation model, the head loss in the impeller itself was smaller in the irrigation model. This was the result of enhancing the impeller form. As a result, the irrigation model, which has less head loss in total, has a higher percentage of head that is available as pump output.

Results of analysis of different aspects of pump performance are shown in Fig. 19. The forecast indicates that adjusting impeller form will yield pump performance as envisioned in the concept. It also indicates that the maximum required load declined, yielding an increase of about eight points in pump efficiency.

3.5. Fuel Consumption Forecast

Following is the forecast of fuel consumption improvement. (1) Fuel consumption was improved by about 7% as a result of enhanced pump efficiency and a lower required load. (2) In addition, if the GX160 engine is replaced with the GX120, fuel consumption is improved by about 8% as a result of differences in the fuel consumption properties of the two engines. (3) Furthermore, at the matching point with the pump, if the air-fuel ratio of the GX120 is optimized, fuel consumption is improved by about 7%.

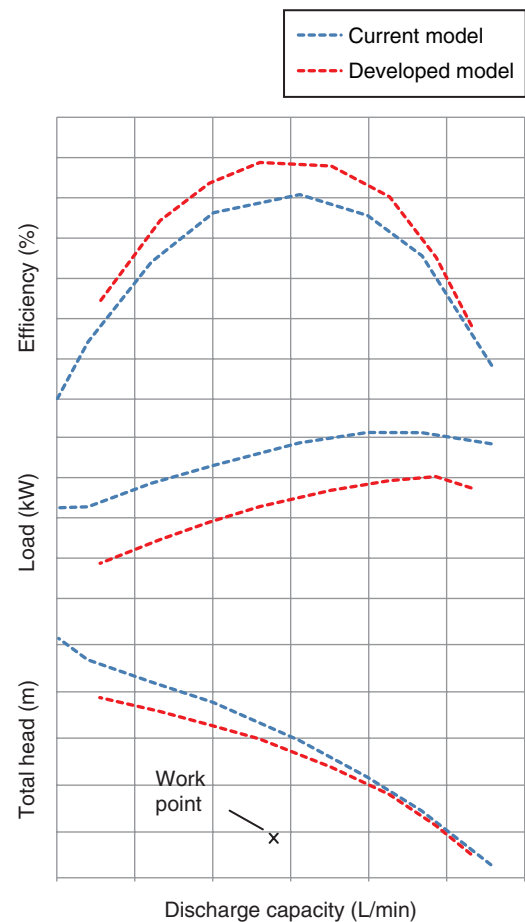


Fig. 19 CFD analysis result of pump performance

The forecast indicates that (1) - (3) above could lead to fuel consumption improvement of about 22% in total (Fig. 20).

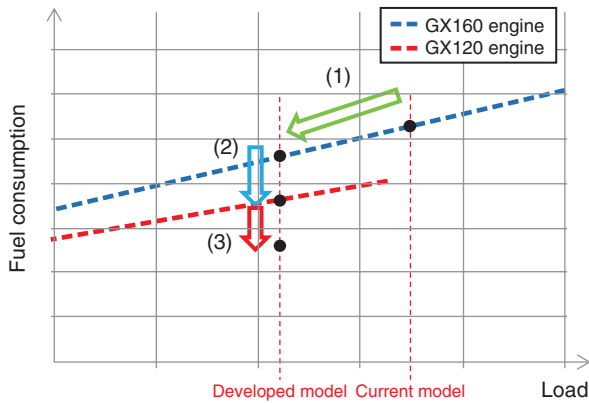


Fig. 20 Calculation of fuel consumption enhancement

4. Test Results

4.1. Results of Performance Testing

Measurements of the performance of the newly developed irrigation pump are shown in Fig. 21. The results indicate that the maximum efficiency rose by about eight points, just as forecast by CFD. Additionally, efficiency at a

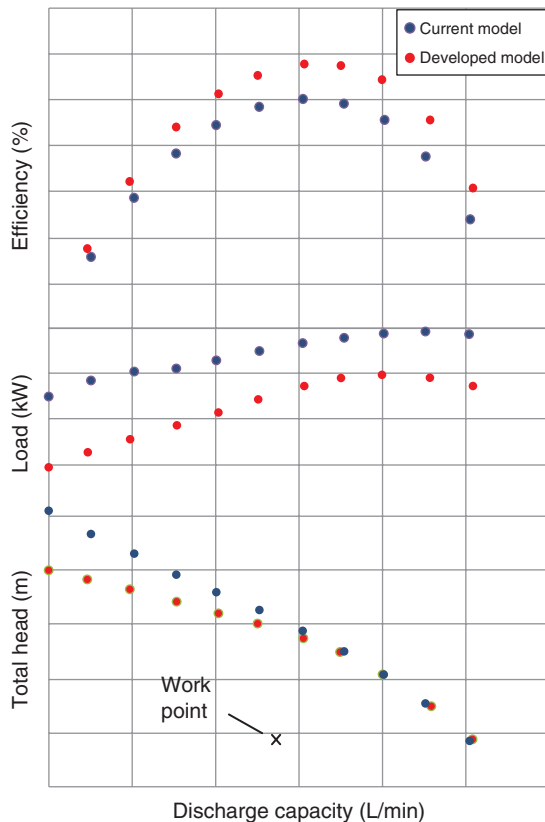


Fig. 21 Test result of pump performance

low-head, low-rotation work point rose by about 10 points, confirming the effectiveness of adjusting pump performance (Fig. 22).

The researchers also checked fuel consumption when the GX120 engine was used and the air-fuel ratio adjusted (Fig. 23). The results confirm that fuel consumption at the work point in Southeast Asia was improved by about 24% as compared to the current model, so that the newly developed model exhibited the fuel consumption effect that was forecast.

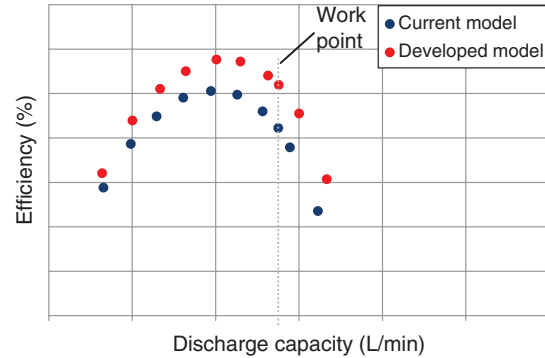


Fig. 22 Test result of pump efficiency at work point

	Engine	Work point CO (%)
Current model	GX160	4.7
Developed model	GX120	5.5

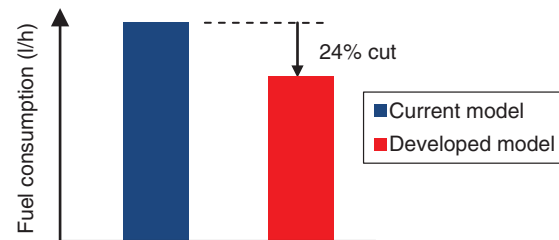


Fig. 23 Test result of fuel consumption at work point

5. Conclusion

The researchers attempted to use forecasting technology with CFD analysis to adjust various water pump performance requirements in line with low-head irrigation and thereby develop a pump with improved fuel consumption. They were able to increase pumping efficiency by eight points, which, when combined with the use of a low-displacement engine and adjustment of the air-fuel ratio, led to the development of a water pump with an improvement of greater than 20% in fuel consumption in actual irrigation use in Southeast Asia.

The issue of forecasting self-priming performance and cavitation will have to be addressed in the future. The researchers hope that developing these technologies will lead to CFD development of greater precision.

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- (2) Turbomachinery Society of Japan: Turbomachinery -introduction-, JAPAN INDUSTRIAL PUBLISHING CO., LTD., 234p. (2013) (in Japanese)

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Development of UNI-CUB

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ABSTRACT

Honda has been engaging in development efforts aimed at new personal mobility that allows people to move in harmony with others in indoor spaces, facilities, and other such places where there are people coming and going.

In 2009, Honda announced the U3-X, in 2012 the UNI-CUB, and then in 2013 the UNI-CUB β .

All these are personal mobility devices capable of movement in all directions, which are also sit-on style, inverted pendulum-type, compact devices that fit between the rider's legs.

This paper describes the technological evolution of the UNI-CUB, which uses the Honda Omni Traction Drive System adopted since the U3-X that enables movement in all directions. This paper will also introduce the implementation in society of this new form of mobility known as the UNI-CUB. The demonstration tests carried out with the National Museum of Emerging Science and Innovation starting in June 2012.

1. Introduction

Research on the inverted pendulum control model was already being conducted in the 1970s in the field of human body engineering called biomechanics. Together with theoretical analysis of a uniaxial inverted pendulum, work at the demonstration level was carried out using models⁽¹⁾⁻⁽³⁾.

A quarter of a century ago in 1989, in advance of the rest of the world, two inverted pendulum-type vehicles (uniaxial type driven by two parallel wheels, biaxial type driven by a single sphere) were exhibited at the Idea Contest, an in-house event at Honda R&D Co., Ltd. This attracted attention in Japan from many people in different areas of endeavor⁽⁴⁾⁻⁽⁶⁾ (Fig. 1). The uniaxial vehicle was subsequently commercialized by Segway Inc. in December 2001, and it has come to be recognized as a new form of mobility^{(7), (8)}.

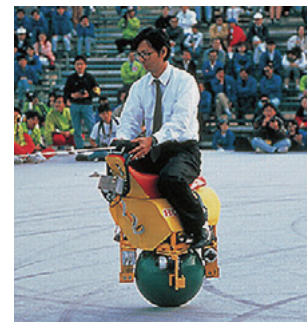
Meanwhile, the biaxial type driven by a single sphere has continued to undergo research and development for practical application in recent years⁽⁹⁾⁻⁽¹¹⁾. Having devised a proprietary drive wheel that applied an omnidirectional wheel for the drive mechanism, Honda began developing mobility that strongly appealed to people.

Aiming for a personal mobility device that provides for movement in harmony with other people in indoor spaces, facilities, and other such places where there are people coming and going, Honda announced the U3-X in 2009. In

order to make the vehicle rideable by a wider range of age groups, both men and women, and in more locations, further technical development was carried out. While the U3-X is characterized by Honda Omni Traction Drive System (HOT drive) and balance control technology, the UNI-CUB also has another wheel added in the rear to allow easier turning. The resulting more evolved vehicle was named the UNI-CUB⁽¹²⁾. The following will introduce the technological evolution of the UNI-CUB in 2012 and UNI-CUB β in 2013 and the aspects of demonstration tests using the UNI-CUB β .



(a) Single-axis type



(b) Dual-axis type

Fig. 1 Original mobility devices with inverse pendulum

* Smart Mobility Development Division

2. Research and Development Leading to the UNI-CUB β

The balance control technology cultivated through the ASIMO bipedal walking robot research and the HOT drive, which allows all direction movement, were combined in research and development of a new personal mobility device that enables riders to alter their speed and movement in any direction at will by inclining their body to shift their weight. The U3-X (Fig. 2, Table 1) was announced in 2009 as a show model that would verify the value of this approach.

During development of the U3-X, the aim was to come up with a personal mobility device that could harmonize with the rider as well as with the surrounding people and satisfy the following product requirements:

- (1) Easy hands-free operation and movement
- (2) Easy foot-to-ground contact for rider's sense of security against over-turning
- (3) Compact size to fit within width of a person's body
- (4) Same eye level as surrounding pedestrians

The next model of UNI-CUB was developed for the purpose of use in demonstration tests started in 2012. The aim was to realize operation so intuitive for the rider that it would enable freedom of movement similar to that of a person walking. The personal mobility was successfully developed that enables rotating motion as well as movement forward, backward and side to side with a size compact enough to fit between a person's legs (Fig. 3, Table 2).

In order to further enhance the practical usability of the UNI-CUB β , the results of the UNI-CUB demonstration tests were provided as feedback, and development addressed the following issues accordingly:

- (1) Compact, lighter in weight
- (2) Design to further enhance the sense of unity of the user and the device
- (3) Exterior design that is soft to the touch in order to make the seat more comfortable and have an affinity to surrounding people.

The result was announced in 2013 as a business demonstration model (Fig. 4, Table 3).

Table 1 Specifications of U3-X

Size (L × W × H) (mm)	315 × 160 × 650
Seat height (mm)	650
Battery type	Lithium-Ion Battery
Maximum speed (km/h)	6
Duration time (hour)	1

Table 2 Specifications of UNI-CUB

Size (L × W × H) (mm)	520 × 345 × 745
Seat height adjustment range (mm)	745 - 825
Battery type	Lithium-Ion Battery
Maximum speed (km/h)	6
Range (km)	6
Application environment	Barrier-free indoor environments

Table 3 Specifications of UNI-CUB β

Size (L × W × H) (mm)	510 × 315 × 620
Seat height (mm)	620
Battery type	Lithium-Ion Battery
Weight (kg)	25
Maximum speed (km/h)	6
Range (km)	6 (approximately 1.5 hours at speed of 4 km/h)
Application environment	Barrier-free indoor environments



Fig. 3 UNI-CUB



Fig. 2 U3-X



Fig. 4 UNI-CUB β

3. Proprietary UNI-CUB Technology

Figure 5 shows an external view of the UNI-CUB.

The device body is structured with the HOT drive that serves as the front wheel supported by an axle on the lower part of the seat frame on the UNI-CUB body. A swing-arm extending to the rear from the axle is interposed between that wheel and the rear wheel, which serves as the turning wheel for the omnidirectional wheel (Fig. 6). The front wheel produces driving power that can move it forward and backward and side to side, and functions to move and balance the device body. The rear wheel functions solely to turn the device body.

3.1. The HOT Drive Principle

The principle of HOT drive movement is characterized by the exterior appearance, shown in Fig. 7, of a large-diameter wheel with multiple small-diameter free rollers positioned around its periphery. Internally, it has a drive disc positioned on either side, and around their periphery are free rollers (hereafter, drive rollers) positioned at angles one to the other. The structure of the drive is such that these drive rollers press against the free rollers on the large-diameter wheel, causing both the large wheel and the free rollers to rotate.

Driving the left and right drive discs at the same angular velocity (in the same direction of rotation) stops the axial

rotation of the small-diameter free rollers, leaving only the axial rotation of the large-diameter wheel in operation. This causes the device body to move longitudinally. Conversely, driving the left and right drive discs at opposite angular velocities (in the opposite direction of rotation) stops the axial rotation of the large-diameter wheel, leaving only the axial rotation of the small-diameter free rollers in operation. This causes the device body to move laterally. When the left and right drive discs are run at different angular velocities (magnitude and direction), a compound axial rotation of the large-diameter wheel and small-diameter free rollers is generated, enabling movement in a diagonal direction.

This principle was applied in the HOT drive, which was adopted for use in the UNI-CUB.

3.2. Balance Control Technology

An advanced control system was constructed that responds to the behavior of the center of gravity of the device body and the rider seen as a single body. That center of gravity is changed by the rider's shifting center of gravity. The left and right drive discs take that change as a command value relating to the rider's movement intentions and operate accordingly while simultaneously stabilizing the rider's position. The speed and direction of movement, longitudinal or lateral, constitute command values that are read from the amount of relative displacement of the rider's center of gravity from that of the device. Balance control to stabilize the rider's position takes signals from the device body acceleration sensor and angular velocity sensor as input. The control drives the HOT drive wheel forward and backward and from side to side and functions to generate an appropriate restoring force against tilting (Fig. 8).



Fig. 5 External view of UNI-CUB

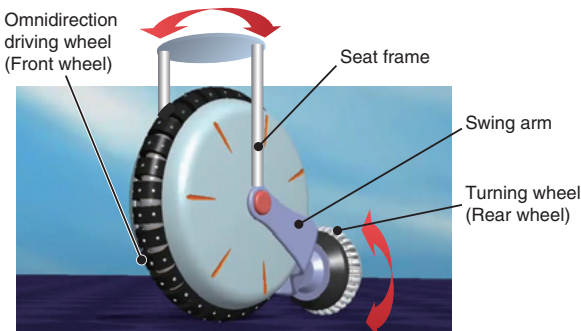


Fig. 6 Drive train with omnidirectional wheels

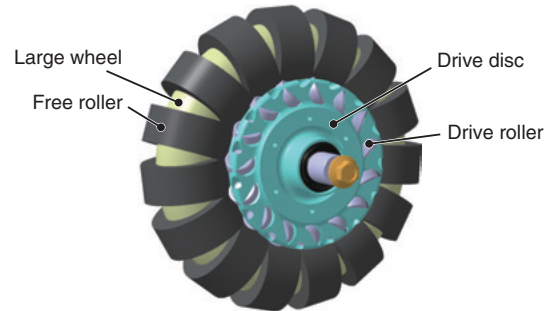


Fig. 7 Principle of HOT drive system

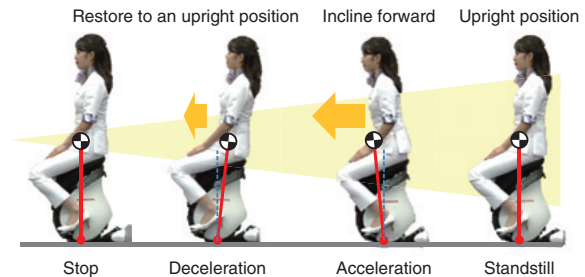


Fig. 8 Balance control

4. Evolution of the UNI-CUB

4.1. Necessity of a Turning Function

The U3-X had only the HOT drive as a drive source and had a single point of contact with the ground. Given its construction, it is not capable of generating yaw moment (moment around the axis perpendicular to its contact point with the ground), and so it is unable to turn on its own. In order to cause it to turn, therefore, the rider would touch a toe lightly to the ground, as shown in Fig. 9. The U3-X could then use that contact point with the ground as a pivot for turning. The need for this operating technique meant that ordinary people could not readily operate the U3-X.

These issues were addressed by adding a turning wheel to the UNI-CUB to give it a turning function. The turning wheel is a drive wheel with a structure like that of the HOT drive large-diameter wheel, with multiple free rollers placed around its periphery. The wheel and rollers are controlled by detecting the difference in the lateral speed of movement between the front and rear wheels and generating a turning angular velocity, as shown in Fig. 10.

With movement control implemented by the addition of



Fig. 9 U3-X turning procedure using toe

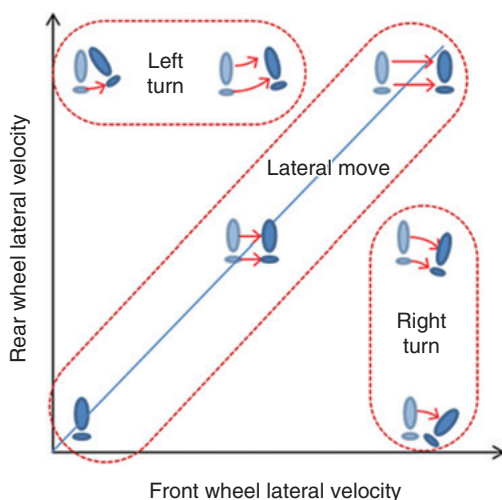


Fig. 10 Schematic diagram of lateral movement and turning

a turning wheel, smooth transitions from forward movement to turning and from sideways movement to turning were achieved by the rider leaning the upper body to shift the body weight while the device is moving. This enables turns.

4.2. Relationship between Forward Movement and Turns

In order to achieve a smooth transition from forward movement to a turn, the rider leans the upper body to the side while the device is moving forward. The shift in body weight not only causes the device to turn, but also starts a sideways movement. Under the initial control configuration, however, the orientation of the device body during a turn was toward the outside of a line tangent to the turn circle, and this caused some discomfort because the direction of the turn was not readily visible. Repeated organoleptic evaluations were therefore conducted of the device body's response characteristics with regard to shifts in the rider's body weight. This led to adoption of characteristics such that when the forward speed is greater, the ratio of the angular velocity of the turn to the sideways shift in body weight becomes higher. Figure 11 is a schematic diagram showing the relationship between forward speed, the sideways shift in body weight, and the angular velocity of the turn.

This realizes operability matched to the rider's intentions across the entire speed range, from low to high.

4.3. Relationship between Sideways Movement and Turns

In places such as art museums, there is a need to be able to move sideways at a slow pace when viewing paintings that are lined up on the walls. When moving to another exhibition area, there is also a need for riders to be able to change the direction of movement and the orientation of the device body toward the direction of movement by inclining their body weight farther to the side while in motion. Realizing actions like these required control that balanced the sideways movement gain and turning gain.

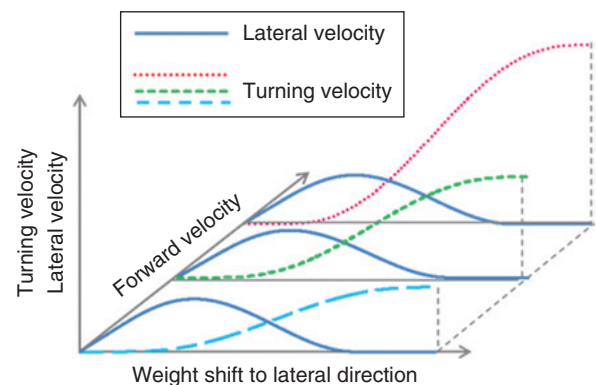


Fig. 11 Schematic diagram of turning motion generation (Velocity-dependent)

Figure 12 shows a schematic diagram of the relationship between turning angular velocity and lateral velocity with respect to the rider's lateral weight shift. This is movement realized by the control implemented in this device.

When the lateral weight shift is smaller, the device simply moves sideways without turning. The control is configured so that when the lateral weight shift is greater, the device moves in a combination of sideways movement and turning. The device body response characteristics were configured so that when the lateral weight shift grows still larger, the device only turns. This realized the kind of movement desired in art museums and other such locations, and conveyed the desired impression with that movement.

4.4. Addressing Barrier-Free Requirements

The environment of use envisioned for the U3-X (Fig. 2) was interior space with flat floors. Indoor barrier-free spaces with tactile paving blocks or other such uneven surfaces designed to provide guidance were not envisioned. When demonstration tests were conducted, it was found that the device performance had to allow traversal of 5-mm differences in level. The dimensions of the large-diameter wheel, the small-diameter wheel, and the gear making up the HOT drive (Fig. 7) were modified to enhance the ability of the device to traverse differences in level.

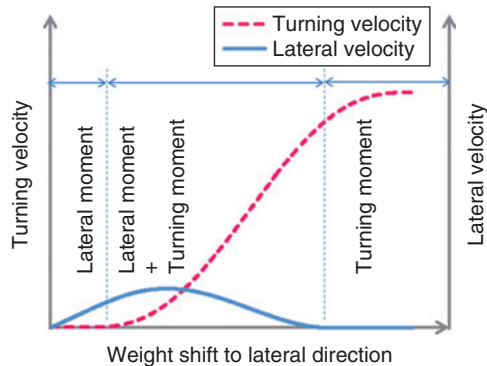


Fig. 12 Schematic diagram of turning motion generation

5. Joint Demonstration Tests with the National Museum of Emerging Science and Innovation

Following the announcement of the UNI-CUB, joint demonstration tests with the National Museum of Emerging Science and Innovation (Miraikan) were begun in June 2012⁽¹³⁾.

Honda's objective was to verify the concept of personal mobility that harmonizes with people. The mission of the National Museum of Emerging Science and Innovation,

on the other hand, was to provide for new knowledge to be shared between society and researchers. These joint demonstration tests were therefore agreed to by the two parties as having substance that was to the benefit of each. For example, it was demonstrated that people who were unable to complete a long guided tour on foot because they grew too tired became able to complete the tour using the UNI-CUB.

The tests were designed and carried out to enable verification of harmony with people in graded stages, as described below.

5.1. UNI-CUB Use in Stage Demonstration

First, Science Communicators (SC) at Miraikan conducted 15-minute demonstrations to communicate the characteristics of the UNI-CUB to visitors (Fig. 13).

The stage was laid out so that visitors could watch at close quarters. The SC riding the UNI-CUB would move close to the viewers to ask them their impressions and so on, with actions that allowed confirmation of a sense of friendliness on both sides.

5.2. UNI-CUB Use in Making Rounds of the Museum and for Guide Operations

SCs used the UNI-CUB to make rounds of the museum interior as well as in guide operations with visitors. These were the first times for the UNI-CUB to move in among the visitors, and confirmed that people sensed a quality of affinity with the device, such that approximately one-half of those who crossed paths with the UNI-CUB did not immediately notice it.

This approach to use of the device allowed acceptance by the people around it without any sense of discomfort, confirming its quality of affinity. It was also observed that a natural dialogue came into being with visitors to the museum.

5.3. Five-Minute Trial-Ride Sessions

Short trial-ride sessions were held for visitors. There



Fig. 13 Scene of UNI-CUB demonstration at an exhibition

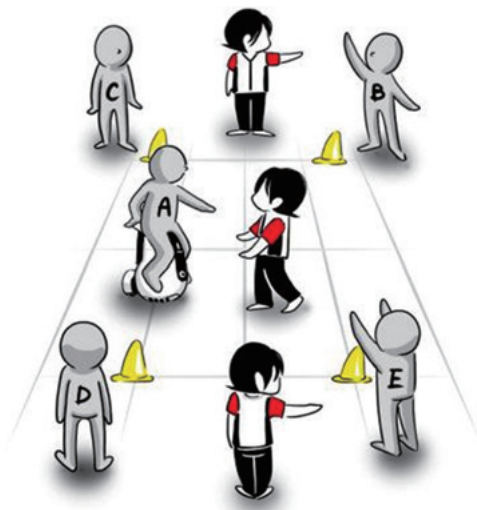
were 89 participants in all spanning the wide range of ages from 11 to 81. The trial-ride sessions were held in groups of five participants, with each group assigned one UNI-CUB. The trial-ride time allotted each person was five minutes. Care was taken to allow participants to feel how the UNI-CUB moves in response to the direction a rider looks, the action of pointing, and other such natural weight-shifting actions. With this approach, almost every participant learned how to operate the device within the given time. The four participants other than the rider were asked to stand at a reasonable distance around the rider to acquire a natural feeling for how the device and people harmonize with one another [Fig. 14(a), (b)].

Figure 15 shows the results of a questionnaire given to trial-ride participants. The content covered three items of affinity with surroundings, ease of controlling the movement of the mobility device, and sense of security. These were rated by five-level evaluation as excellent, good, fair, poor, and very poor. Even though the trial rides of five minutes were very brief, respondents gave high marks for

sense of affinity with surroundings and ease of controlling the movement of the mobility device, confirming their acceptance of the UNI-CUB concept.

5.4. Museum Tour Experience for Visitors

Tours for visitors were held in which they used the UNI-CUB to see the museum exhibits (Fig. 16). The time taken by the tour, including the questionnaire and related matters, was approximately one hour. The tours were organized in groups consisting of several visitors, each guided by one SC. Comments from visitors who experienced the tour confirmed that use of the UNI-CUB allowed people to concentrate more on the exhibits than if they walked

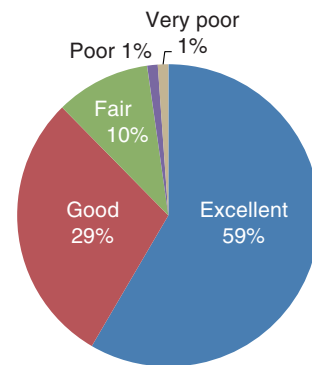


(a) Illustration of training method

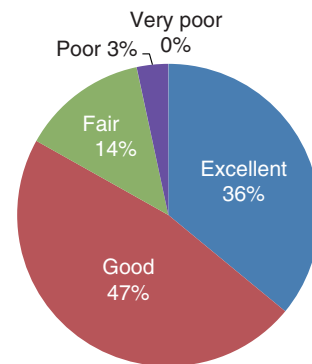


(b) Photo of training scene

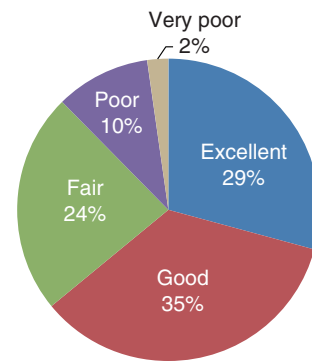
Fig. 14 Test area for 5-min. trial ride experience



(a) Sense of affinity with surrounding people



(b) Ease of controlling mobility device



(c) Secure feeling

Fig. 15 Questionnaire results

through. Some participants also commented that the time they spent seemed to go faster than the time actually taken on the tour.



(a) Scene of riders in motion



(b) Scene of visitors enjoying exhibits

Fig. 16 Guided tour

6. Activities with the UNI-CUB β

Following Honda's announcement of the UNI-CUB β at the 43rd Tokyo Motor Show in November 2013, the device was exhibited at motor shows throughout Japan. Large numbers of visitors had the opportunity to experience the device.

Leasing of UNI-CUB β devices to Miraikan, Honda Cars Osaka, and others for use was begun subsequently as an experiment in for-pay business.

Based on experiences of this kind, UNI-CUB β use has been expanded to guided tours for exhibitions in various parts of Japan. This use is presently underway (Fig. 17).

Miraikan started employing these devices in April 2014, for SCs to use in making rounds. In October, the museum opened a UNI-CUB Station (Fig. 18) and started renting out the devices for trial-ride tours. The tours being provided, on a paid basis, are Miraikan introductory tours providing trial-ride experience of certain zones in Miraikan, and permanent exhibit tours that take participants around

the permanent exhibit floor with explanations by an SC.

A music video made by the popular American rock band "OK Go" in October 2014 featured the UNI-CUB β . The video was viewed worldwide (Fig. 19). Use in this kind of application was beyond expectations.



Fig. 17 Scene of UNI-CUB units on standby at an exhibition



Fig. 18 UNI-CUB station



Fig. 19 Scene from "OK Go" music video

7. Conclusion

Honda has been working for some time to develop mobility devices that harmonize with people. The U3-X in 2009 announced the concept of achieving pedestrian-like movement using Honda's proprietary HOT drive mechanism. The UNI-CUB with further enhanced operability was subsequently used in 2012 to conduct demonstration tests at Miraikan in which the device was implemented in society. In 2013, the UNI-CUB β was announced. This model incorporates the results of demonstration tests in a more compact package that can be used by a wider range of riders. In 2014, Honda successfully started testing UNI-CUB leasing for business.

As the device continues to gain more widespread recognition, its growing dissemination can be anticipated to bring a variety of uses, as seen by its employment in a music video.

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Vibration Reduction of Two Motors of Rear Wheel Drive for SPORT HYBRID SH-AWD

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ABSTRACT

The two motors employed to drive the rear wheels in the SPORT HYBRID SH-AWD system were developed to balance compactness, high power, high torque, and quietness. Stators employing concentrated windings were used to reduce the size of the motors, and development focused on the combination of slot number and pole number, the magnetic circuits, and control methods in an attempt to satisfy one of the development goals, the reduction of torque fluctuation, which is a cause of vibration and cabin noise.

A Gradually Enlarged Air Gap was adopted for the magnetic circuits. The Gradually Enlarged Air Gapshape offsets the centers and modifies the curvature of the rotor and the stator, producing continuous change in the air gaps with the rotation of the rotor. The application of the Gradually Enlarged Air Gap method made it possible to reduce torque fluctuation while also controlling decline in torque. Superposition of higher harmonics was applied as a control method. This control method reduces torque fluctuation by superposing high-frequency components on the motor traction control current in order to cancel the torque waveform peak.

The newly developed motors realize a 50% reduction in cogging torque and torque ripple in comparison to the previous specifications, and motor vibration has been reduced by 10 dB and cabin noise by more than 13 dB.

1. Introduction

Today's increasing demand for environmental performance from automobiles is driving a rapid expansion in the application of several types of hybrid electric vehicle (HEV)⁽¹⁾. While environmental performance has traditionally been the priority in HEV, in the past several years demand has been increasing for the vehicles to offer other forms of added value, including dynamic performance and quietness. With regard to quietness, some HEV systems able to operate on motor drive alone, and which consequently are not affected by engine vibration or noise, have been brought into practical use⁽²⁾⁻⁽⁴⁾. This trend is not limited to HEV; in order to maximize the benefit of quietness, developments are being conducted that focus on vehicle sensitivity and vibration transfer paths in electric vehicles (EV) and other automobiles employing electric drive⁽⁵⁾⁻⁽⁸⁾.

Generally, traction motors utilize distributed windings in a stator, and reduce vibration and noise by reducing torque fluctuation⁽⁹⁾. However, this necessitates a considerable amount of space for vehicle fitting, because the coil ends of the distributed windings are large. A configuration that reduces the size of the coil ends by dividing and overlapping the coils has therefore been proposed⁽⁹⁾, but

this configuration necessitates multi-spot welds, making the manufacturing method complex.

The use of concentrated windings is available as a method of reducing size⁽¹⁰⁾. However, concentrated windings present the issue of producing a greater amount of torque fluctuations (cogging torque and torque ripples) during rotation than distributed windings.

The form of deformation of the stator has been focused on in order to develop methods of reducing vibration in motors using concentrated windings, and proposals have included the selection of basic frameworks that control deformation⁽¹¹⁾, the use of configurations in which the teeth of the core or the poles of the magnets are skewed^{(12), (13)}, the engineering of holes in the rotor⁽¹⁴⁾, and the adjustment of magnetic resistance by means of the shape of the stator⁽¹⁵⁾⁻⁽¹⁷⁾. Methods of reducing vibration through the application of control have also been reported^{(18), (19)}.

This paper will discuss the realization of compactness, high power and high torque in an interior permanent magnet synchronous motor (IPM motor) combining an IPM rotor and a stator using concentrated windings, while also reducing motor vibration and cabin noise. The paper will introduce newly developed magnetic circuit design and control technologies.

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2. Overview of System and Motor

2.1. SPORT HYBRID SH-AWD

Honda's SPORT HYBRID Super Handling All-Wheel Drive (SPORT HYBRID SH-AWD) is a high-efficiency hybrid all-wheel drive (AWD) system fitted with three motors^{(20), (21)}. Figure 1 shows the overall system configuration, and Table 1 shows the system specifications. The V6 3.5L direct injection engine and DCT motor that drive the front wheels and the transmission are positioned in the engine room at the front of the vehicle. The rear wheels are driven by two motors (TMU motors) fitted in a Twin Motor Unit (TMU).

2.2. Hybrid System Operation

Figure 2 shows the operation of the system. As an operating mode using motor power only, the system is provided with an EV drive mode offering takeoff and acceleration realized through TMU drive. It also features an engine drive mode, in which the front wheels are driven by the engine, and a hybrid drive mode, in which assist is provided by the TMU. In response to driver demands and road surface conditions, AWD control is applied, and drive is provided by the engine and the TMU.

2.3. Torque Vectoring

Figure 3 shows the operation of torque vectoring using AWD control. In response to the steering wheel angle and

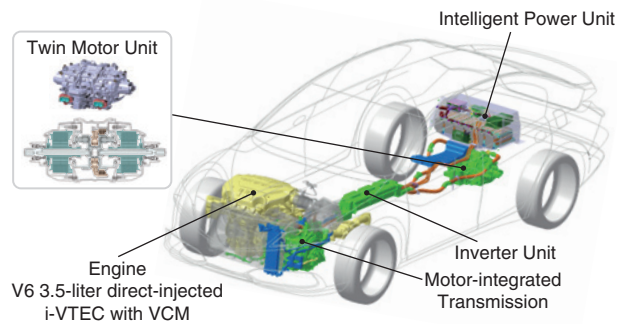


Fig. 1 SPORT HYBRID SH-AWD system

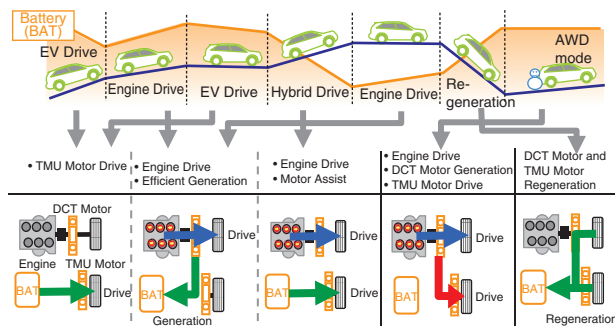


Fig. 2 Operation of SPORT HYBRID SH-AWD hybrid system

Table 1 System specifications

System power [kW]		281
Engine	Type	V6 3.5L, Direct injection, SOHC, VTEC 24-valve
	Power [kW]	231 at 6,500 rpm
	Torque [Nm]	371 at 4,700 rpm
DCT Motor	Type	Interior Permanent Magnet Synchronous Motor
	Power [kW]	35 at 3,000 rpm
	Torque [Nm]	148 at 500 to 2,000 rpm
TMU Motor	Type	Interior Permanent Magnet Synchronous Motor
	Power [kW]	27 at 4,000 rpm (× 2)
	Torque [Nm]	73 at 0 to 2,000 rpm (× 2)
Battery	Type	Li-ion
	Voltage [V]	260

the state of acceleration or deceleration, the system is able to generate a difference between torque in the direction of drive and the direction of braking using the two independent motors for the left and right rear wheels, and allocate torque to the left and right rear wheels. This is a high-efficiency AWD system that is also able to electrically recover the energy produced by the inner wheels when the vehicle is turning and impart it to the outer wheels, thus generating the energy necessary for turning itself.

2.4. TMU and TMU Motor

Figure 4 shows an external view of the TMU. The TMU is made up of left and right motors, a deceleration mechanism, and a disconnect mechanism⁽²²⁾.

Figure 5 shows the TMU motor. The motor is an IPM motor with a stator using concentrated windings, and the combination of slot number and pole number is 8 poles and 12 slots (8p12s). Concentrated windings have been used in the TMU motor in order to reduce size⁽²¹⁾.

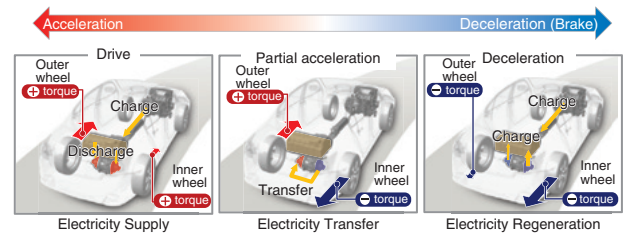


Fig. 3 Concept of torque vectoring

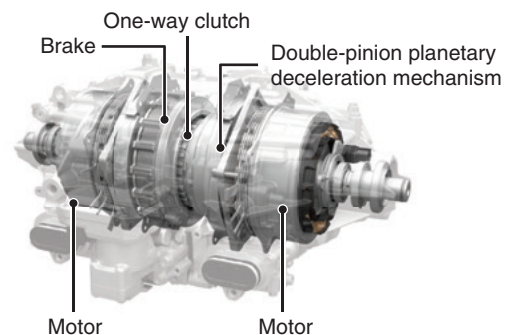


Fig. 4 External view of TMU

2.5. Range of Use of TMU Motor

Figure 6 shows representative operating points for the TMU motor in the hybrid system operation discussed in Sections 2.2 and 2.3. The horizontal axis shows motor speed and the vertical axis shows torque. The range bounded by the solid line in the graph is the motor operating range. Takeoff provided by EV drive mode uses the low-speed high-torque range; the medium-torque range is used in EV drive mode. AWD control uses a range that follows the line of maximum motor power, and the TMU motor can therefore be used irrespective of motor speed and torque.

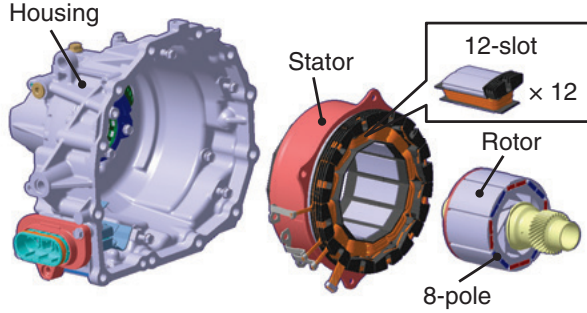


Fig. 5 Configuration of TMU motor

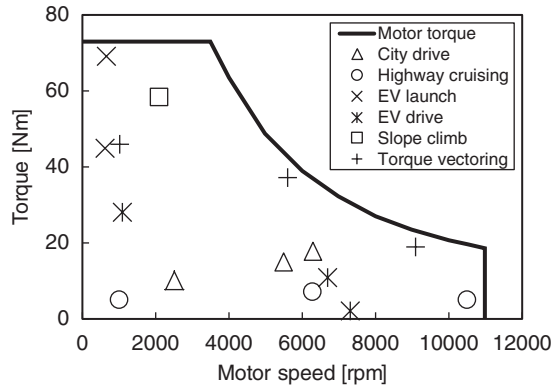


Fig. 6 Operating range of TMU motor

3. Motor Vibration and Cabin Noise

In motors using concentrated windings, annular deformation of the stator produced chiefly by excitation in the radial direction of the electric angle 2nd-order and 6th-order components is generally the factor in vibration and noise^{(11), (18), (19)}. Excitation in the radial direction of the electric angle 2nd-order components results in 4th-order annular deformation of the stator, and excitation in the radial direction of the electric angle 6th-order components results in 0th-order annular deformation of the stator^{(11), (18), (19)}. In addition, torsional vibration of the motor and the unit resulting from torque fluctuation and shaking of the body of the unit also produce vibration and noise. This chapter discusses measurements of cabin noise during vehicle operation following the application of concentrated

windings in the two rear wheel drive motors for the SPORT HYBRID SH-AWD system, making it possible to identify the vibration and noise that represented an issue.

3.1. Motor Vibration and Cabin Noise Due to Electric Angle 6th-Order Components

3.1.1. Order of cabin noise during vehicle operation

Figure 7 shows a representative example of cabin noise for the system when the vehicle is in operation. The horizontal axis shows vehicle speed and the vertical axis shows frequency. These results indicate that for this system, frequency components corresponding to the electric angle 6th order are more remarkable than other components, and represent an issue. Figure 8 shows the cabin noise generated by the electric angle 6th-order components at this time. Cabin noise is 13 dB in excess of the target value.

In order to reduce this type of cabin noise when the motor is in operation, conventionally the relationship between vehicle sensitivity, vibration transfer paths, and gear noise has been focused on and the resonance points of various parts have been set to help ensure that motor vibration does not excite resonance^{(5), (8)}, or a two-fold vibration-damping mount configuration has been adopted in order to extend the vibration-damping characteristic to the high-frequency range⁽⁶⁾. A method of combining the frequency characteristics of each component of the vehicle

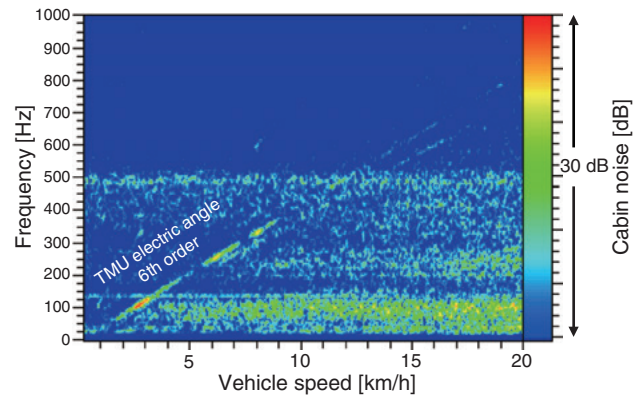


Fig. 7 3D map of TMU motor

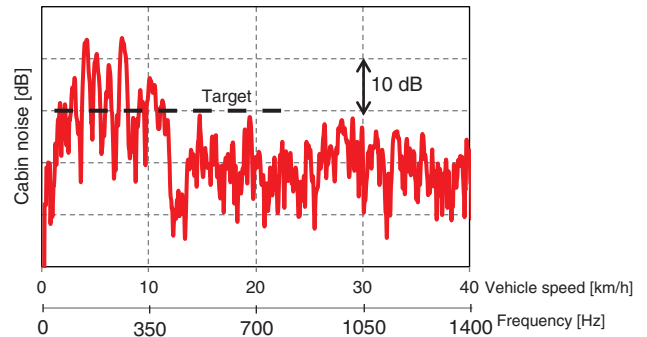


Fig. 8 Cabin noise of TMU motor (Electric angle 6th order)

body in order to develop bodies with low sensitivity to vibration has also been adopted⁽⁷⁾. In the case of the present system, however, vibration was reduced by redesigning the magnetic circuits of the motor and applying control, making it possible to employ SPORT HYBRID SH-AWD.

3.1.2. Factors in occurrence of cabin noise

The electric angle 6th-order components were most prominent in the cabin noise produced by the TMU motors during vehicle operation, as discussed above. This section will discuss the mechanism of production of this noise. Depending on vehicle speed, the frequencies corresponding to these frequency components cover a broader frequency range in a vehicle using a TMU system than in one fitted with a conventional engine. The frequency of the electric angle 6th-order components changes with vehicle speed, and at frequencies that match the natural vibration modes of each part of the vehicle, motor vibration increases⁽²³⁾. This vibration produced by the electric angle 6th-order components and the natural vibration modes of the vehicle body were focused on.

Figure 9 shows subframe and differential mounts with a TMU fitted. Figure 10 shows vibration data during actual vehicle operation at a subframe mounting point (Point B) in relation to the mounting point of a housing (Point A) fitted with the TMU (the vibration source) when the spring rate of the differential mount is changed. These results show that when the spring rate of the differential mount is low, vibration is suppressed across the entire range, but that when the spring rate of the differential mount is high, there is almost no suppression of vibration in the mount below 400 Hz. Balancing the use of a differential mount with a

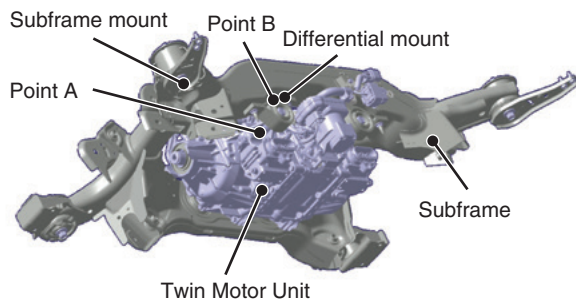


Fig. 9 Bottom view of TMU attached to subframe

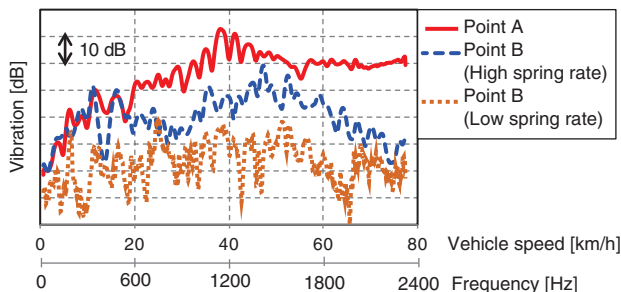


Fig. 10 Vibration of TMU and subframe mounting point

high spring rate in order to boost SPORT HYBRID SH-AWD handling stability with the suppression of vibration therefore represented an issue.

In addition, as Fig. 11 shows, the subframe itself resonates below 400 Hz, and motor vibration increases subframe vibration. For these reasons, motor noise is high in the low vehicle speed range, at takeoff and when the vehicle is about to stop.

As described above, motor vibration excites subframe resonance, producing audible cabin noise. In order to reconcile a high level of dynamic performance with quietness in the SPORT HYBRID SH-AWD system, it was necessary to reduce vibration and noise generated by the electric angle 6th-order components in the TMU motor characteristic.

3.2. Cabin Noise Generated by Torsional Vibration of the TMU

In addition to the vibration and noise generated by the electric angle 6th-order components, as discussed in Section 3.1, a 1.3 kHz noise also occurs. An investigation of the cause of this noise showed that a resonance existed at 1.3 kHz in the vibration mode of the TMU (Fig. 12). In addition, measurement of the deformation mode of the TMU showed that torsional resonance with an eigenvalue existed at 1.3 kHz. It was recognized that this was the noise produced at the vehicle speed corresponding to the resonance peak when the vehicle was operating using the TMU motors.

This cabin noise produced by torsional vibration was

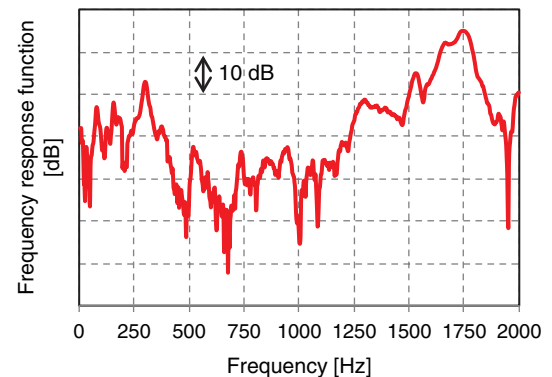


Fig. 11 Vibration of subframe

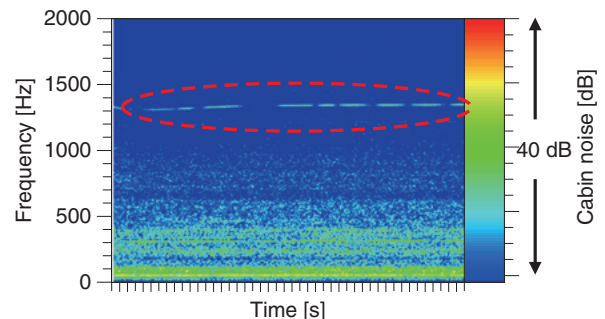


Fig. 12 3D map of TMU torsional vibration

therefore a structural phenomenon characteristic of the left-right two motor configuration.

As indicated in Sections 3.1 and 3.2, it was necessary to reduce vibration and noise across a wide frequency band for both the vehicle and the TMU. Vibration in the motors, the excitation source, was therefore reduced.

4. Reduction of Motor Vibration and Noise via Magnetic Circuits

4.1. Combination of Slot Number and Pole Number

The combination of slot number and pole number for the motor was selected with consideration of attempting to help ensure that the frequencies of the electric angle 2nd-order and 6th-order components, which are determined by the vehicle speed employed and the combination of slot number and pole number, did not correspond to the resonance points of annular deformation of the stator.

Figure 13 shows the results of an analysis of frequency and stator deformation against motor speed for the TMU motors. For a combination of 8p12s, there was no resonance between the electric angle 2nd-order components and 4th-order annular deformation of the stator and the electric angle 6th-order components and 0th-order annular deformation of the stator. Based on these results, 8p12s was selected as the combination of slot number and pole number for the TMU motors.

4.2. Optimization of Stator Shape

4.2.1. Gradually enlarged air gap

In order to reduce the electric angle 6th-order frequency components that were the main causes of cabin noise in the case of the present system, a new magnetic circuit shape was designed as a method of damping the fluctuations in magnetic flux density occurring when switching between U, V, and W phases.

Case 1 in Fig. 14 shows the conventional shape of the magnetic circuits. Partial modification of the shape of the stator or rotor in order to enlarge the air gaps and adjust magnetic resistance is known as a method of reducing motor vibration. Examples include the notched shape shown in Case 2 in Fig. 14⁽¹⁶⁾ and the enlarged air gaps at the tips of the teeth shown as Case 3 in Fig. 14⁽¹⁷⁾. However, while these shapes do reduce the electric angle 6th-order components, higher-order frequency components increase in proportion to the number of partially enlarged air gaps.

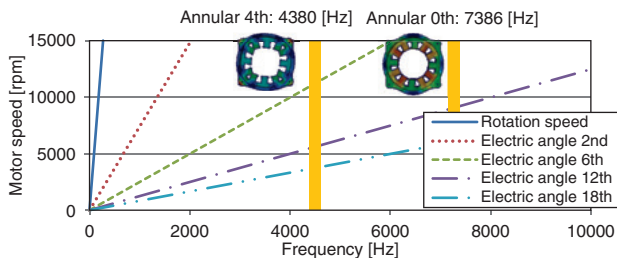


Fig. 13 Natural frequency of 8p12s motor

A method in which holes are introduced in sections of the rotor⁽¹⁴⁾ is also available, but it was decided not to change the shape of the rotor based on considerations of strength.

A method termed Gradually Enlarged Air Gap (GEAG) was therefore adopted for the motors under discussion. This magnetic circuit shape is shown as Case 4 in Fig. 14. The GEAG shape displaces the centers and modifies the curvature of the rotor and the stator.

Figure 15(b) compares the air gaps in relation to the electric angle for the conventional shape (Case 1) and the GEAG shape (Case 4). Case 4 is a shape that generates change in the air gaps along a curved trajectory, with the air gaps at their minimum at electric angles of 0, 120, and 240 deg. Figure 15(a) compares changes in magnetic flux density as determined by a magnetic field analysis for the conventional shape (Case 1) and the GEAG shape (Case 4). The application of the GEAG shape (Case 4) reduces change in magnetic flux density close to electric angles of 72, 192, and 312 deg. Figure 15(c) shows the results of applying FFT to fluctuations in magnetic flux density. High-frequency components (electric angle 2nd-order components and above) have been reduced. These results indicated that it had been possible to reduce the high-frequency components of magnetomotive force, and thus to reduce torque fluctuation and the high-frequency components of the excitation force.

4.2.2. Degree of change in air gaps and reduction of torque fluctuation

Figure 16 shows the reduction in torque fluctuation with the degree of change in the air gaps as a result of the GEAG shape, based on the results of a magnetic field analysis. As Fig. 16(a) shows, torque fluctuation was calculated by varying the degree of change in the air gaps

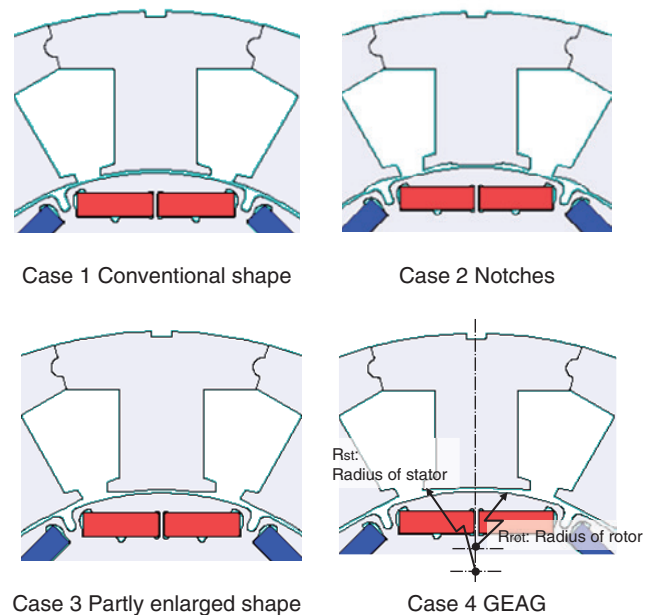


Fig. 14 Difference of magnetic circuits

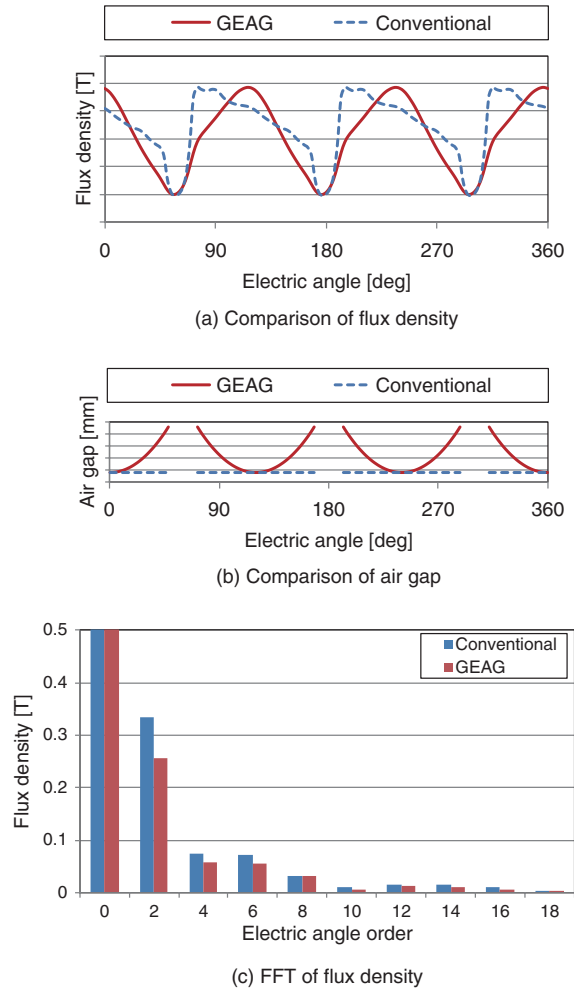


Fig. 15 Reduction of higher harmonic components of flux density fluctuation

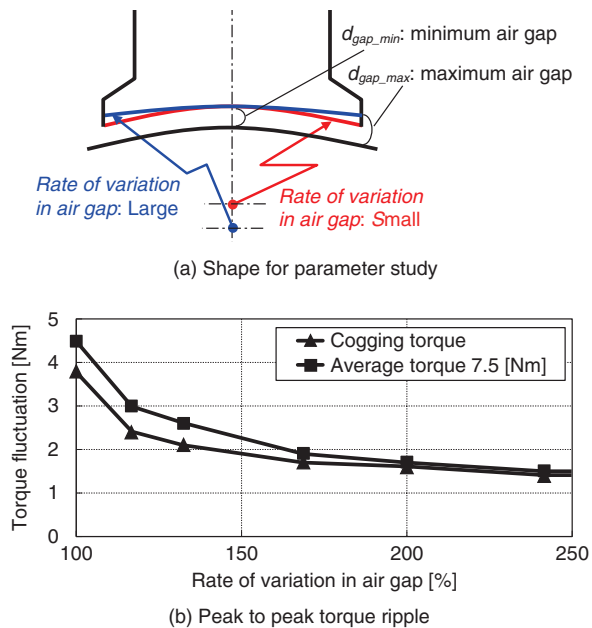


Fig. 16 Results of torque fluctuation parameter study

by changing the inner diameter of the stator. Figure 16(b) shows torque fluctuation against the rate of change in the air gaps between the center and the tips of the stator, as defined by Eq. (1). These results indicated that a degree of change in the air gaps of 200% (twice the air gap at the tips of the stator as at the center) or more would sufficiently reduce vibration, and the GEAG shape was therefore applied in the TMU motors.

$$\text{Rate of variation in air gap} = \frac{d_{\text{gap_max}}}{d_{\text{gap_min}}} \times 100[\%] \quad (1)$$

4.3. Results of Analysis of Torque Fluctuation and Radial Excitation Force

Figure 17(a) shows the results of an analysis of cogging torque for each of the magnetic circuit shapes shown as Cases 1 to 4. Figure 17(b) shows the results of an analysis of the electric angle 6th-order components of torque ripple for torque in Cases 1 to 4. These results indicated that the GEAG shape (Case 4) produced the greatest reduction in both cogging torque and torque ripple.

Figure 17(c) shows the results of an analysis of the electric angle 6th-order components of radial excitation

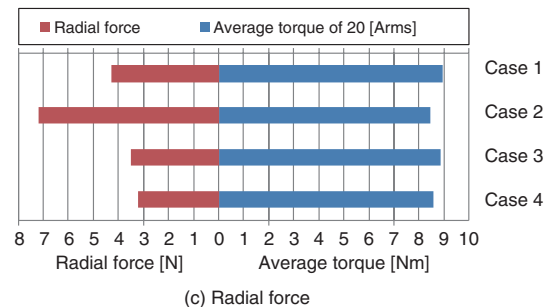
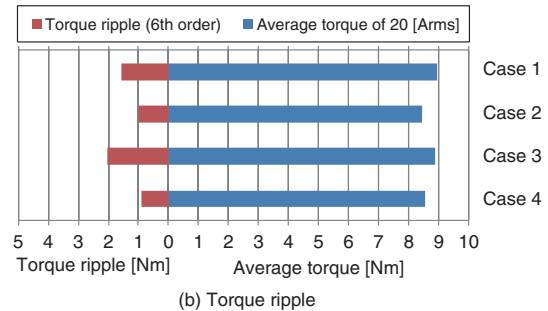
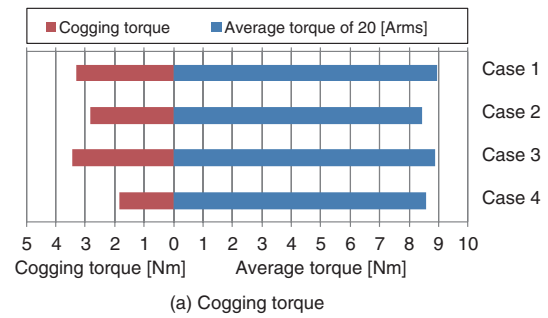


Fig. 17 Results of analysis of different stator shapes

force for torque in Cases 1 to 4. These results indicated that the GEAG shape (Case 4) also reduced radial excitation force. Taken together, the results shown in Figs. 17(a) and (b) show that the GEAG shape achieves reductions in both the circumferential and radial directions.

4.4. Results of Measurement of Torque Fluctuation

Figure 18 shows the reduction in cogging torque and torque ripple in the TMU motors realized through the application of the GEAG shape in the magnetic circuits. The results show a maximum reduction of 50% in overall cogging torque and torque ripple [Fig. 18(a)] and in the electric angle 6th-order components of cogging torque and torque ripple [Fig. 18(b)] in peak-to-peak measurements of torque fluctuation at a motor speed of 5 rpm.

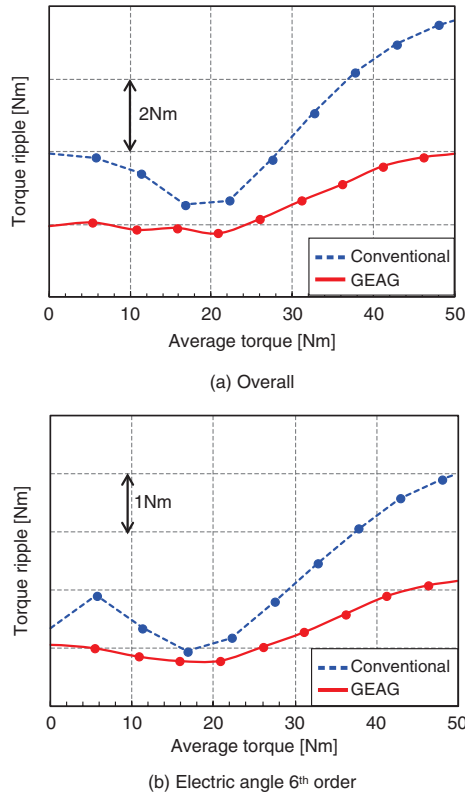


Fig. 18 Results for torque ripple

5. Reduction of Motor Vibration and Noise through Application of Control

5.1. Superposition of Higher Harmonics for Control

Figure 19 illustrates the concept of the Superposition of higher harmonics. With the basic frequency components of 3-phase alternating current as the benchmark, a high-order current of $6n \pm 1^{\text{th}}$ -order is superposed on the 3-phase alternating current. Because the superposed phase is the opposite phase to the target for damping, it cancels the target waveform. The superposed current is set as the minimum value of the torque ripple due to the electric angle 6th-order components, which is the target for damping. This makes it possible to reduce torque ripple resulting from magnetic excitation force (the electric angle 6th-order components). Figure 20 shows an overview of control using Superposition of higher harmonics. The control outputs a final motor torque value by overlaying a map

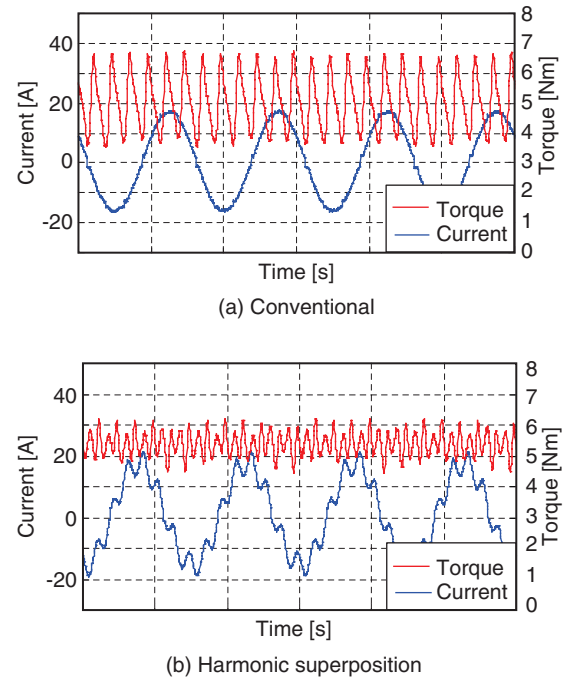


Fig. 19 Concept of superposition of harmonic current

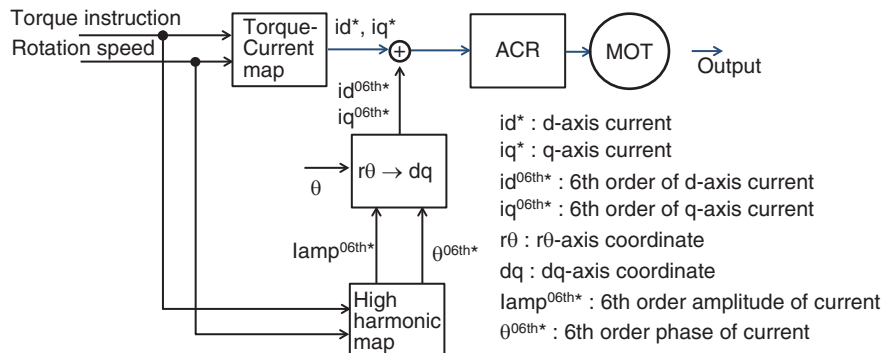


Fig. 20 Control diagram for superposition of harmonic current

of the amplitude and phase of Superposition of higher harmonics organized around the axes of torque instructions and motor speed on a map of torque and current, similarly organized around axes of torque instructions and motor speed. This makes it possible to effectively impress high-order currents up to high motor speeds.

5.2. Results of Torque Fluctuation Measurements

Figure 21 shows the reduction in cogging torque and torque ripple realized through the application of higher harmonics Superposition control to TMU motors using GEAG magnetic circuits. As Fig. 21(a) shows, peak-to-peak measurements of torque fluctuations at a motor speed of 5 rpm show a maximum reduction of 50% in overall cogging torque and torque ripple. Figure 21(b) shows that the torque ripple due to the electric angle 6th-order components, the target of this control, is canceled by the application of the control, as indicated in Section 5.1.

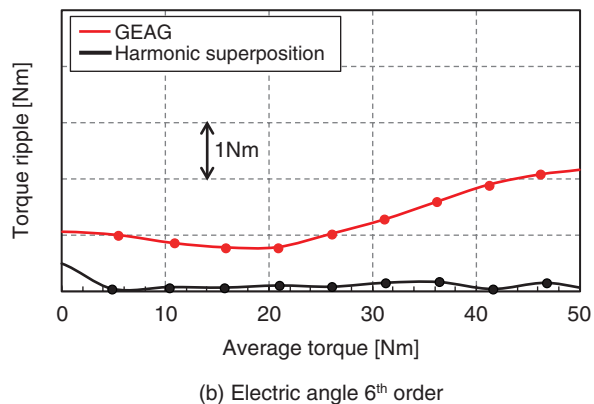
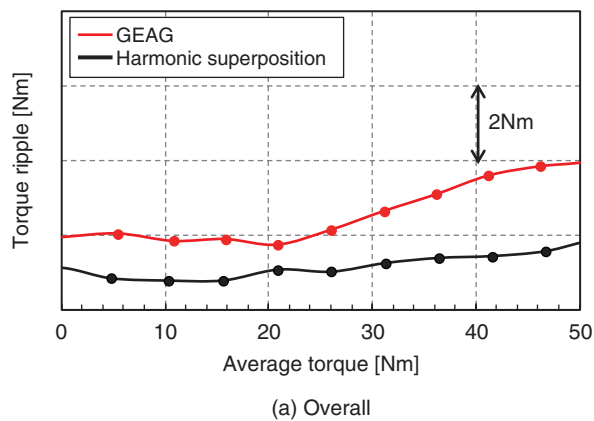


Fig. 21 Results for torque ripple

6. Measurement Results

6.1. Results of Unit Measurements of Motor Vibration

Measurements were conducted using an actual motor in order to verify the effect of the combination of the GEAG

magnetic circuits and the higher harmonics superposition control discussed in Chapters 4 and 5. As Fig. 22 shows, vibration is reduced by 10 dB up to a speed corresponding to 1,000 Hz.

6.2. Results of Measurements of Cabin Noise

Figure 23 shows the results of measurements of cabin noise for TMU motors using the GEAG magnetic circuits and superposition of higher harmonics. The horizontal axis shows vehicle speed and the frequency of the electric angle 6th-order components, and the vertical axis shows cabin noise. The data was measured under relaxed acceleration. The use of the GEAG shape for the magnetic circuits in the TMU motors reduced cabin noise by 5 dB across the entire range against the conventional circuits. In addition, the application of superposition of higher harmonics reduced cabin noise by more than 13 dB. These measurements demonstrated that cabin noise targets had been achieved.

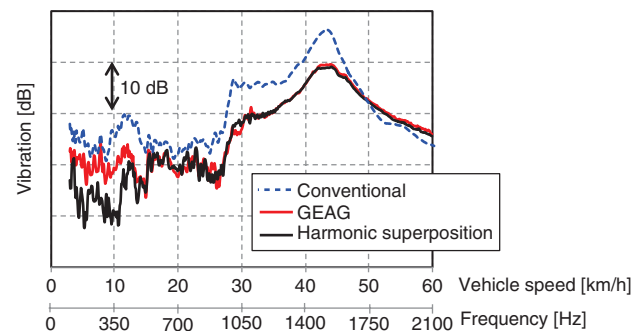


Fig. 22 Results for TMU vibration (Electric angle 6th order)

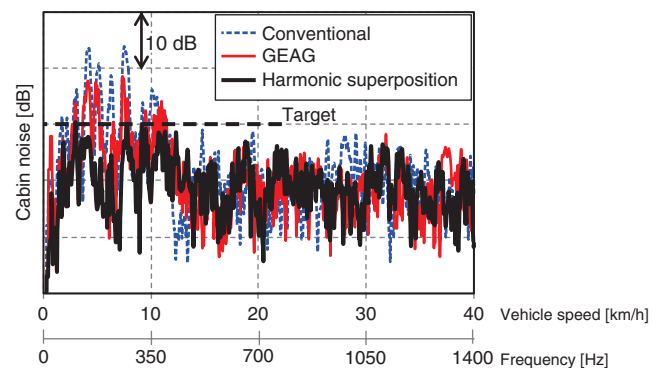


Fig. 23 Results for cabin noise of TMU motor (Electric angle 6th order)

7. Conclusion

The following technologies were developed for application in the two motors of rear wheel drive for SPORT HYBRID SH-AWD

(1) Newly designed GEAG magnetic circuits

Realizes a 50% reduction in peak-to-peak torque

fluctuation at a motor speed of 5 rpm and an average torque of 5 Nm.

(2) High-order current superposition control

In combination with the GEAG magnetic circuits, reduces vibration in a TMU motor by 10 dB.

The application of these technologies has made it possible to employ stators using concentrated windings, balancing a reduction in the size of the motors with reduced vibration and noise. The use of the developed motors in the SPORT HYBRID SH-AWD system has reduced cabin noise by more than 13 dB, making it possible to meet cabin noise reduction targets.

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Extension of Drive Recorder Function of In-vehicle ECU and Record Information Collection Technique

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ABSTRACT

Two of the drive recorder functions of the engine control unit were extended. First, a function was added that can use the vehicle diagnostic tool to freely generate a conditional expression that will record snapshot data as well as to enable modification of the conditional expression. Several patterns of conditional expressions were prepared in advance so that they could be combined to generate the conditional expressions that assure the capability to record the desired phenomena. Next, the system was configured to allow the snapshot data to be transmitted to a server external to the vehicle. The wireless network functionality of the Display Audio unit is used for transmission to the server, and the snapshot data is transmitted from the engine control unit to the Display Audio unit by divided transmission to enable the large volume of data to be handled for transmission between vehicle units, which are intended to handle small volumes of data. This was also done using simplex transmission in order to limit bus load increase on the transmission line. Measures were taken against data loss, as well, by providing for retransmission of the snapshot data even if the transmission is interrupted due to interruption of the power supply or other such reason.

1. Introduction

The electrification of vehicle devices has been progressing and the software used to control those devices has been growing ever more complex. The increased complexity of engine control, in particular, has been conspicuous, and there are various engine behavior phenomena that users may have occasion to consult dealers about. As a result, a growing necessity exists for detailed analysis of engine behavior.

An engine control unit (ECU) is equipped with control software and on-board diagnostics (OBD)⁽¹⁾ functionality for self-diagnosis of malfunctions in sensors and actuators that are used to control the engine. The OBD is able to identify a malfunctioning area by detecting changes in a sensor's output values when there is a malfunction in the area. In addition to identifying malfunctioning areas, it is also important to identify the causes of malfunction. To identify the causes of malfunction, it is necessary to analyze engine behavior up to the point when the malfunction occurs. For this it would be effective to perform analysis using a drive recorder function with the capability for recording engine behavior in time series. Drive recorder functions are generally configured either to mount a dedicated recorder

tool on the vehicle⁽²⁾ or as software mounted internally in the ECU. Configuration with a dedicated recorder enables long-term data recording that is not dependent on the memory capacity of the ECU. However, the number of dedicated recorders is limited, which means that the number of vehicles that can be analyzed will be limited as well. There is also the possibility that mounting a dedicated recorder will have a psychologically oppressive effect on a user. When the functionality is configured in software mounted internally in the ECU, however, a dedicated recorder is not needed, there is no limit to the number of vehicles on which the functionality can be applied, and there will be less of a feeling of psychological oppression for the user. The constraints imposed by ECU memory capacity, however, will not allow lengthy recording. In light of the above, and considering the factors of portability and psychological burden on users, it would be desirable to have the drive recorder function take the latter configuration.

2. Conceptual Approach to Development

At present, the ECU has a drive recorder function called on-board snapshot (OBS) that is built-in as software. The OBS can take a malfunction or other such event as its

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trigger to extract time-series data about engine behavior (snapshot data) that has been collected over a certain period of time preceding the trigger and retain that snapshot in the ECU (Fig. 1). However, the present configuration faces issues such as the following. The first is that the trigger condition that is the starting point for retaining snapshot data in the ECU has to be written into the software in advance. As a result, the present configuration cannot be used except for analysis of malfunctions that were already known and recognized at the time the software was developed, and its applications are therefore limited. The second is that implementation of this functionality requires the buffer that records engine behavior to have relatively large memory capacity. Increasing the memory capacity contributes to increased ECU cost, and this means that new trigger conditions cannot readily be defined and further snapshot data added every time there is an increase in the phenomena for analysis. Given these circumstances, it would be desirable for the OBS to be capable of handling analysis of a variety of phenomena without increasing the memory capacity.

Another factor is that in the present configuration, snapshot data can only be read using a diagnostic tool. Consequently, carrying out troubleshooting using snapshot data necessarily requires the user to go to a dealer. If replacement parts are needed, users must return to the dealer, so there is a time burden on the user. It would be a great advantage for users if snapshot data could be read before users go to the dealer, so that the diagnosis could be made in advance and the repair completed with one visit to the dealer.

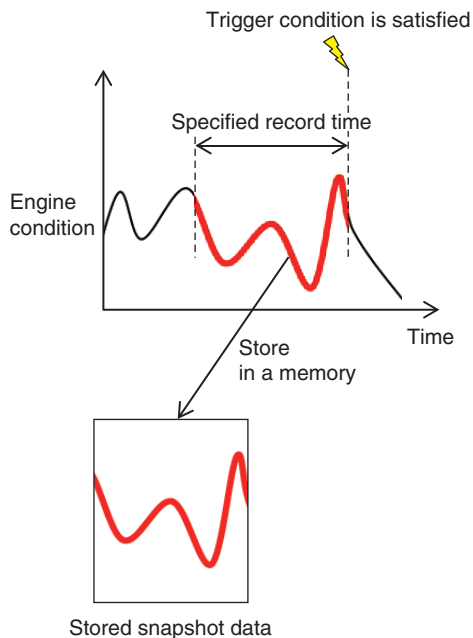


Fig. 1 Conceptual image of drive recorder function

3. Development Goals

The development goals are summarized below.

- (1) To create an OBS that enables later modification of a trigger condition expression by means of a diagnostic tool
- (2) To devise a configuration that enables the snapshot data retained in the ECU to be read by a data server external to the vehicle using a wireless network (Fig. 2)

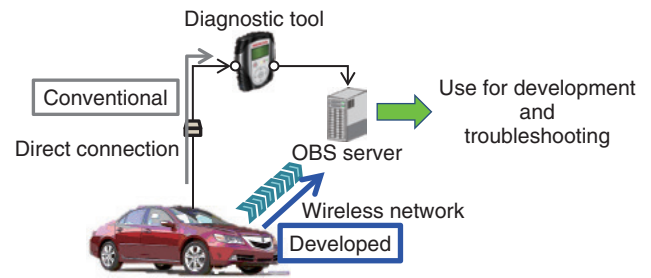


Fig. 2 How snapshot data is collected

4. OBS Configuration that Enables Modification of Trigger Condition Expressions

In order to acquire useful snapshot data by means of OBS, it is important to be able to create detailed trigger condition expressions. In a conventional OBS, the trigger condition expression is written into the software in advance in order to enable definition of a conditional expression that is optimal for grasping the phenomenon. Even when defining a trigger condition expression from a diagnostic tool, a configuration that enables defining a trigger condition expression in detail equivalent to the existing OBS is needed. The configuration proposed in this paper enables modification of the trigger condition expression by means of the diagnostic tool, and this therefore involves having the component elements of a number of conditional expressions built into the software in advance. Then one of those component elements can be selected and populated with variables, threshold value, equal sign, unequal sign, and so on, from a diagnostic tool. This generates the desired trigger condition expression. Combining a number of these component elements can create an even more complex conditional expression. An outline of the generation of trigger condition expressions using a diagnostic tool is shown in Fig. 3. The next section will explain the component elements of those trigger condition expressions.

4.1. Configuration of a Trigger Condition Expression

Figure 4 shows the overall trigger condition configuration. Trigger condition expressions are configured from conditional expressions 1 to 6, and the occurrence

of phenomena satisfying each conditional expression determines the timing for snapshot data to be held in the ECU. Conditional expressions 1 to 6 are configured variously from the first and second conditional expressions, and one each of Expression Type 1 to Type 4 can be selected for the first and second conditional expressions. Expression Type 1 to Expression Type 4 are operation

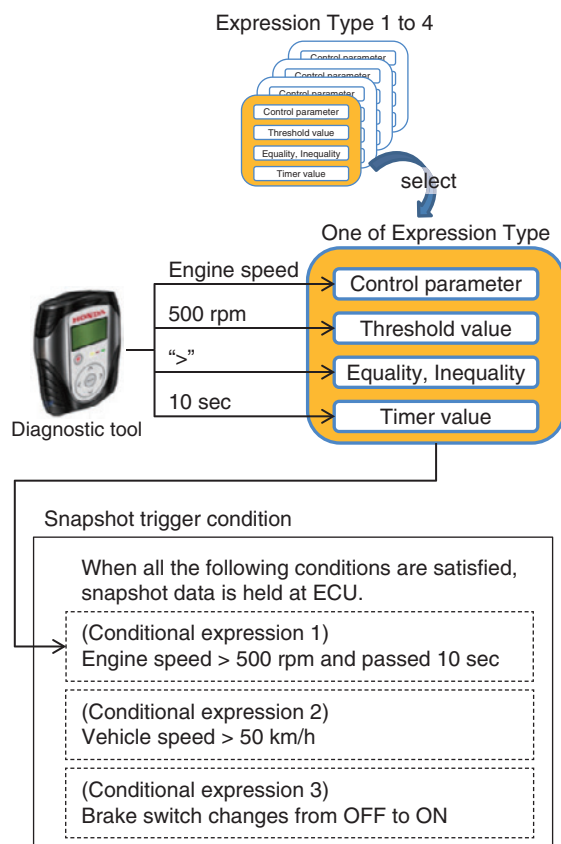


Fig. 3 How to set up trigger condition using diagnostic tool

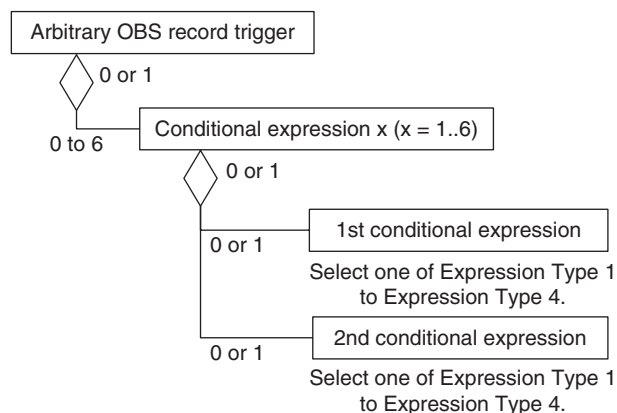


Fig. 4 Entire configuration of arbitrarily selectable OBS record trigger condition

Table 1 Expression type setting

How to judge	Conditional expression	Example of setting
Expression Type 1		
Parameter and threshold	Parameter □ Threshold	Current engine speed > 0 rpm
Expression Type 2		
Each of parameters	Parameter1 □ Parameter2	Current engine torque > Target engine torque
Absolute	Parameter1 - Parameter2 □ Threshold	Current engine speed - Target engine speed ≥ 100 rpm
Expression Type 3		
Parameter edge	Parameter edge (Up edge or down edge)	Brake switch changes from OFF to ON
Expression Type 4		
Many parameters by logical decision	Many parameters logical judgment (Judged by logical decision)	Satisfy any of the conditions below (logical decision = "or") Perform transmission control, air conditioning control, or meter control

* □ is equality or inequality

expressions that use equal signs, unequal signs, or logical operators. Execution of the first and second conditional expressions is then determined in accordance with the selected expression type. The number of conditional expressions and the degree of detail of the configurable items were decided with reference to known phenomena.

4.1.1. Definition of expression types

The items that can be defined as Expression Type 1 to Expression Type 4 are shown in Table 1. The defined content of each expression type is shown below.

- (1) Expression Type 1: Makes conditional judgment according to the relationship between the control parameter and the threshold value. The relationship between the control parameter and the threshold value is judged by an equal sign or unequal sign. For example, this type will be defined when an engine speed greater than 0 rpm is the trigger condition.
- (2) Expression Type 2: Makes conditional judgment according to the relationship between control parameters. The conditional judgment can be made by two methods. The first judges the relationship between control parameters by an equal sign or unequal sign. For example, this type will be defined when an increase in engine torque beyond a target engine torque is the trigger condition. The second makes the conditional judgment by the absolute value of the difference between control parameters and by the threshold value. The relationship between the absolute value and the threshold value is judged by an equal sign or unequal sign. For example, this type will be defined when the difference between the engine speed and the target engine speed reaching 100 rpm or more is the trigger condition.
- (3) Expression Type 3: Makes conditional judgment by when the control parameter passes above or below the threshold value. The control parameter can be defined as passing down from above the threshold value to a level below it or as passing up from below the threshold value

Table 2 Relation setting of expressions

How to judge	Condition	Example of setting
Relation of 1st conditional expression and 2nd conditional expression		
Logical decision	And	Engine speed > 0 rpm or Vehicle speed > 0 km/h (Example of setting that condition is "or")
	Or	
	Xor	
Decision order	None	Brake switch changes from OFF to ON under the condition of "Accelerator pedal > 0 %" (Example of setting that condition is "1st conditional expression to 2nd")
	1st conditional expression to 2nd	
	2nd conditional expression to 1st	
Relation of conditional expression x (x = 1 to 6)		
Logical decision	And	Satisfy all conditions of the below (logical decision = "AND") Conditional expression 1 and Conditional expression 2 and ... and Conditional expression 6
	Or	
Decision timer	Decision delay timer of OBS trigger	When 10 sec pass after "logical decision," OBS trigger condition is satisfied.

to a level above it; either can be selected. For example, this type will be defined when the brake switch changing from OFF to ON is the trigger condition.

- (4) Expression Type 4: Makes conditional judgment by the logical sum or logical product of multiple control parameters. For example, this type will be defined when the trigger condition occurs during the implementation of transmission control, the implementation of air conditioning control, or the implementation of meter control.

In addition to triggering by the time of occurrence of a phenomenon, triggering by the number of times a phenomenon occurs has also been enabled for each expression type. This is to enable the prevention of mistaken recognition of a trigger condition as well as to allow evaluation by the number of times or the frequency of occurrence of a phenomenon.

4.1.2. Definition of relationships between conditional expressions

The items that can be defined as relationships between the various conditional expressions are shown in Table 2. For conditional expressions 1 to 6, logical decisions between conditional expressions are enabled. The relationship between the first and second conditional expressions allows for logical decisions between conditional expressions as well as for definition of the order in which conditional expressions are satisfied. This allows for the capture of phenomena that are limited, such as those that occur under certain conditions. The configuration also allows the timing for retention of snapshot data to be delayed by a defined time from the point when the trigger condition is satisfied. This enables retention of snapshot data that shows the behavior of the control parameter after the trigger condition

has been satisfied, and also allows additional freedom in defining conditions.

4.2. Results from Confirmation of Operation

Figure 5 shows the results for confirmation of operation when snapshot data is acquired through a trigger condition defined using a diagnostic tool. As a configuration example, a conditional expression was defined so that the trigger condition occurs when the vehicle is moving at 30 km/h or faster and when the accelerator pedal is released and then the brake pedal is pressed. As a result, the snapshot data was successfully acquired by means of the defined trigger condition.

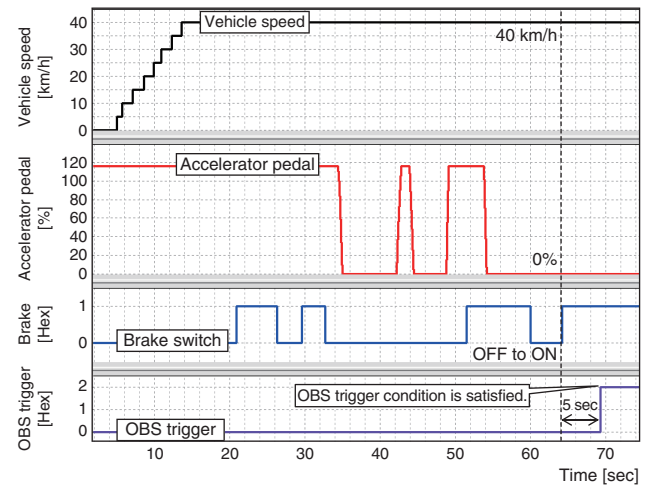


Fig. 5 Results of OBS trigger set up by diagnostic tool

5. Snapshot Data Collection Technique Using a Wireless Network

In order to transmit snapshot data to a data server that is external to the vehicle, wireless network functionality is needed. Already-existing functions of the display audio (DA) unit are used for that wireless network functionality. The ECU and DA unit are connected by wire over the controller area network (CAN). Figure 6 summarizes the configuration of the ECU and peripheral equipment. The CAN is connected with a number of units other than the ECU and DA unit, so it is unable to transmit large amounts of data like the snapshot data, which amounts to several kilobytes, all at one time. Therefore the system is configured to send the snapshot data by divided transmission and put it back together in the DA unit. Furthermore, transmission from the ECU to the DA unit is handled by simplex transmission in order to limit the bus load increase on CAN communication lines due to the added snapshot data transmission. The next section will explain the technique for transmitting snapshot data from the ECU to the DA unit.

5.1. Divided Transmission Technique

Communication from the ECU to the DA unit is conducted on the CAN. CAN communications are capable of handling eight data bytes per frame.

Snapshot data sent by divided transmission will then be reconstructed on the DA unit end, and this involves the possibility that noise or other such extraneous signals will be applied to the communication line, resulting in the loss of transmitted data. This is countered by dividing the transmission into header frames and data frames and guaranteeing the transmitted data.

The header frames are used to transmit the data size, checksum, and chunk number of the snapshot data due to be transmitted. The data size and checksum are used to guarantee the integrity of the snapshot data when it is reconstituted. Chunk numbers enable identification of multiple items of snapshot data on the DA unit end. Chunk numbers are allocated to items of snapshot data in order of their retention in the ECU. In the DA unit, the snapshot data and chunk numbers are strung together for management, enabling recognition of additions to or deletions from snapshot data sent by the ECU. In this way, the DA unit will add to, retain, or delete snapshot data being held in the unit as requested by the ECU. Figure 7 shows an example of snapshot data and chunk numbers strung together. This

example shows a new chunk number being allocated for the snapshot data being held in the ECU when the OBS trigger condition has occurred four times. The OBS shown in this example also updates its snapshot data every time the trigger condition occurs, and the snapshot data held in the ECU up to that point is erased. Consequently, the chunk number that had been allocated to the old snapshot data is erased each time the OBS trigger condition occurs.

The data frames are used to transmit the divided snapshot data in six-byte units. When this is done, continuous numbers are assigned as frame counters to guarantee the continuity of the snapshot data. Figure 8 shows the situation when the trigger condition occurs while snapshot data is being held as Chunk 0, so the transmission data is changed when new snapshot data is added and held.

The technique proposed in this paper uses simplex transmission to send snapshot data from the ECU to the DA unit, so the ECU cannot know how much of the snapshot data has been received by the DA unit. Therefore the system was configured to repeat the transmission of snapshot data.

5.2. Guarantee of Data by Rewind Transmission

The ECU and the DA unit use different timing for start-up and shutdown. The ECU has a power source retention function so that the unit can remain operational by ECU

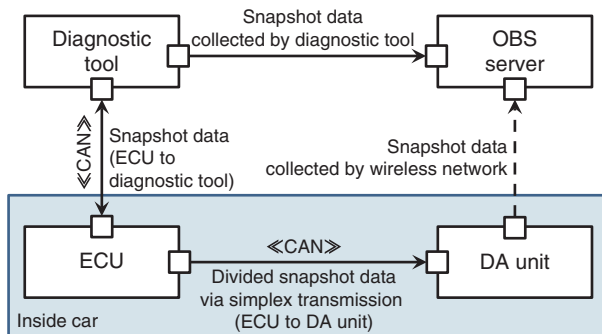


Fig. 6 Entire configuration of system

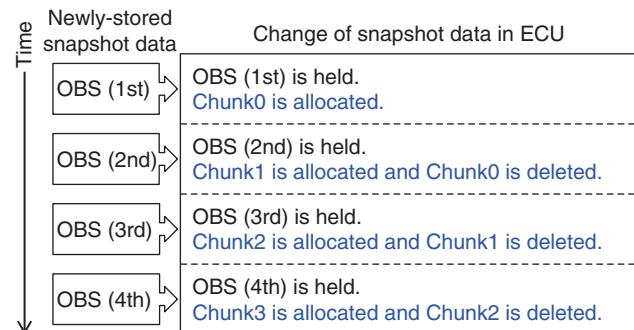


Fig. 7 How to allocate Chunk No. at snapshot

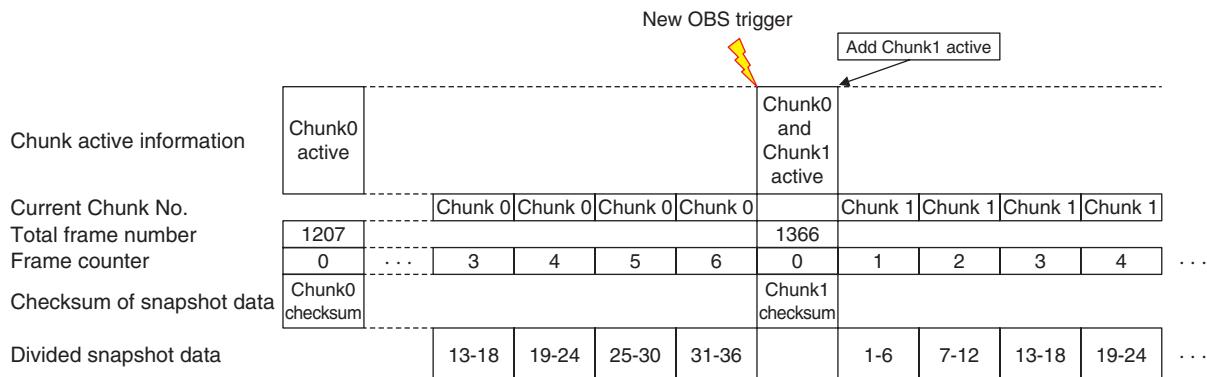


Fig. 8 CAN data management in divided transmission

request even after the ignition has been switched OFF. The DA unit, on the other hand, shuts down immediately after the ignition is switched OFF. The same also applies while the engine is being cranked during start-up, when the DA unit alone shuts down. In this case, the DA unit is unable to receive any data even if the ECU has transmitted snapshot data, so data omission occurs. Therefore, as indicated above, in cases when the DA unit may be shut down because the power supply is cut off due to ignition switch operation, data omission is prevented by causing the frame counter to be rewound by a prescribed number of frames when the DA unit is restarted, and that snapshot data is retransmitted. Figure 9 shows an example of the rewind transmission operation. In the example operation, a DA unit reset is detected while the fifth frame is being transmitted. This example shows the operation of rewind transmission after the restart of the DA unit has been completed, causing retransmission from the fourth frame.

5.3. Results from Confirmation of Operation

Figure 10 shows the results from confirmation of operation when snapshot data held in the ECU is sent to the DA unit by divided transmission. The monitoring results from the CAN communication line were compared with the snapshot data read directly from the ECU by a diagnostic tool. The two are identical, providing confirmation that

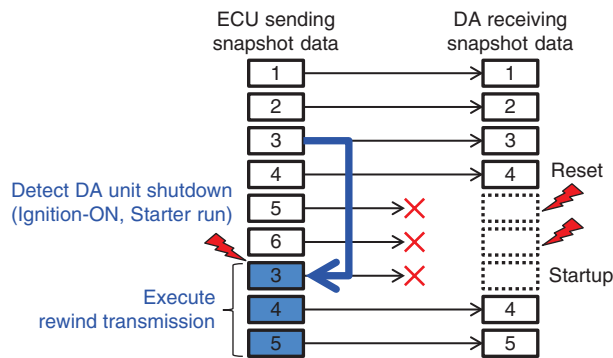


Fig. 9 Rewind transmission

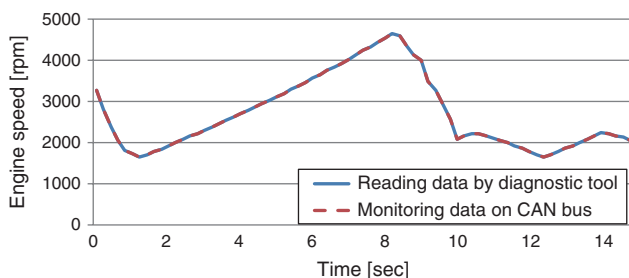


Fig. 10 Result of comparison of data being read by diagnostic tool and being monitored on CAN bus

divided transmission of snapshot data held in the ECU is taking place successfully. Figure 11 shows the results from confirmation of operation when the power supply is cut off due to ignition switch operation. Here the transmission data guarantee by means of rewind transmission was confirmed. It was confirmed that when the ECU detected an ignition operation, the frame counter was rewound from 125 back to 108 and the snapshot data was retransmitted. There is a rewind limit value of 108 on the frame counter during rewind transmission, and this limit is imposed to prevent the frame counter from being rewound more than necessary by successive ignition operations.

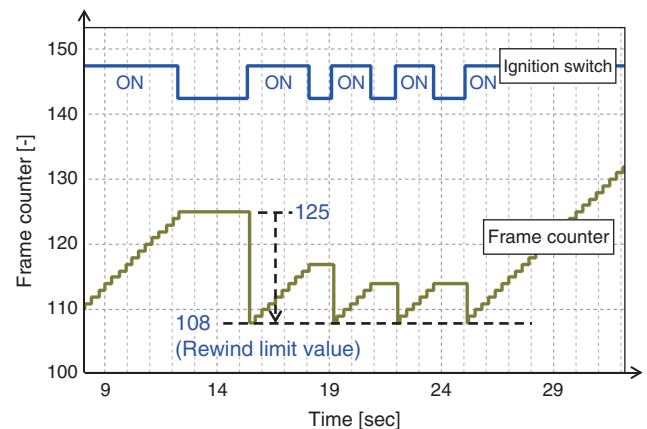


Fig. 11 Result of rewind transmission

6. Conclusion

The following functions were created to extend the drive recorder functions of the in-vehicle ECU.

- (1) An OBS function was created to enable later changes to be made to trigger condition expressions using a diagnostic tool. In order to enable the generation of conditional expressions capable of recording the desired phenomenon, conditional judgment of absolute values, conditional judgment by parameter edge, and other such expressions in addition to conditional judgment of a control parameter and threshold value, were made usable as trigger condition expressions.
- (2) A system was configured with the capability for transferring snapshot data to an external server by means of the wireless network functionality of the DA unit. Transmission from the ECU to the DA unit was achieved using simplex CAN communication. The system was made capable of handling large volumes of data by sending the snapshot data using divided transmission. Measures were taken to perform rewind transmission so that the transmission of snapshot data would be completed even if the DA unit were shut down by ignition switch or other such operation.

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Development of Headlight System with Cost Advantageous Design Using Light Emitting Diodes

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ABSTRACT

Recently, it is widely noticed that replacing conventional incandescence lights with light emitting diodes as light sources is beneficial in terms of their low power consumption, longer life and larger degree of freedom in designing. That is also the case in automobile industry and light emitting diodes are increasingly used as light sources. Applying light emitting diodes to light sources of the headlights, which consume a large amount of electric power, is highly advantageous for overall reduction of consumed energy in a vehicle resulting in a good fuel economy. Moreover, if light emitting diodes are applied to headlights of motorcycles sold in a large number in affordable price range, a significant contribution is expected to the reduction of the total amount of carbon dioxide emission. However, up to the present, the use of light emitting diodes for headlights of motorcycles has been limited to only certain models in high price range. This is mainly because the headlight systems using high power light emitting diodes and their driver units are expensive. Based on these backgrounds, we adopted a configuration with a multiple use of medium intensity light emitting diodes. In addition, heat dissipation configuration that fulfills the thermal requirements was devised without using a heat sink that was a causal factor of high cost. The cost was further reduced through the employment of a single constant current regulation circuit. It was made possible by the serial connection of high-beam and low-beam light sources. This development made it possible to employ headlights using light emitting diode for motorcycles in low price ranges as well.

1. Introduction

Light Emitting Diodes (LEDs) are drawing attention these days because of the various advantages, compared to incandescence light sources, such as small power consumption, long lives and a large degree of freedom in exterior designing and structural designing. In addition, they discharge little amount of hazardous chemical substances when recycled.

Lighting appliances using LEDs are getting widely spread. The amount of shipment of LED lighting devices is increasing with the rise of energy saving consciousness strongly enhanced after the disaster of the Great East Japan Earthquake. With that trend, the price of LED has been reducing and is getting into a status of the vast use (Fig. 1)⁽¹⁾.

Because of the same advantages mentioned above, LED light sources are getting a wide use in automobile industry as well through applications to lighting devices, indicators for alert and/or display and lightings in cabin. Recently, LED light sources are extensively applied to the lighting devices. Among those, headlights especially consume a large power. Accordingly, adoption of LED light sources to headlights significantly contributes to a reduction of the

power consumption. Thus, it results in a large contribution to the reduction of total consumed power of a vehicle improving the fuel economy as a consequence. A large contribution to the reduction of the global CO₂ emission is anticipated if the application of LED light sources is expanded to be applicable to motorcycles sold in a large number in a range of reasonable price. In the first place, headlights using LED light sources

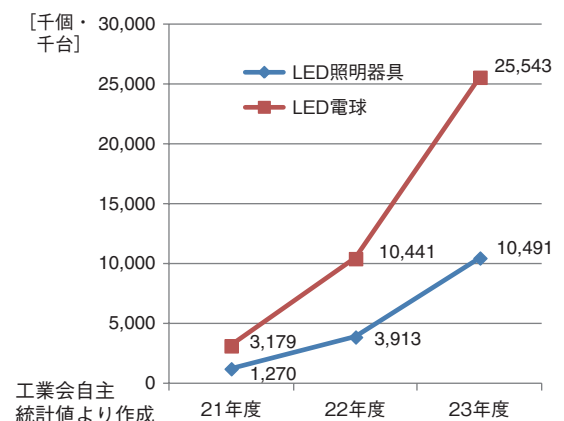


Fig. 1 Numbers of shipments of LED products

* Motorcycle R&D Center

were applied to automobiles in 2007, and the first application to a motorcycle was in 2012. However, a conventional LED headlight system has an issue of high cost because the components, such as a heat sink and a driver circuit, are necessary to be added to a conventional incandescent lamp based system. That cost increase is illustrated in Fig. 2 showing the case that a conventional LED headlight is applied to a low priced range commuter type motorcycle.

As shown in the figure, the cost of a LED headlight system is approximately four times larger than that of an incandescent lamp based system, and its application to a commuter type motorcycle seems extremely challenging. To resolve this issue, an examination of possibilities to reduce the cost of a LED light source system and the driver, which were especially costly, was conducted. To dissipate the heat generated by LED, the addition of a heat sink is needed and is the primary cause of the high cost of the light source system. The heat dissipation using a heat sink is inevitable in a system applying conventional technologies because of large power consumption by a LED. Consequently, it was tried in our development to eliminate the heat sink for reducing the cost of LED headlight system.

The second reason for the high cost of the LED light source system was that it was necessary to have a separate control circuit for each of the low beam (Lo) and the high beam (Hi). In this development, it was tried to reduce the cost of LED headlight system by simplifying the control circuits with a change of the electrical connections of LEDs for the high beam and the low beam.

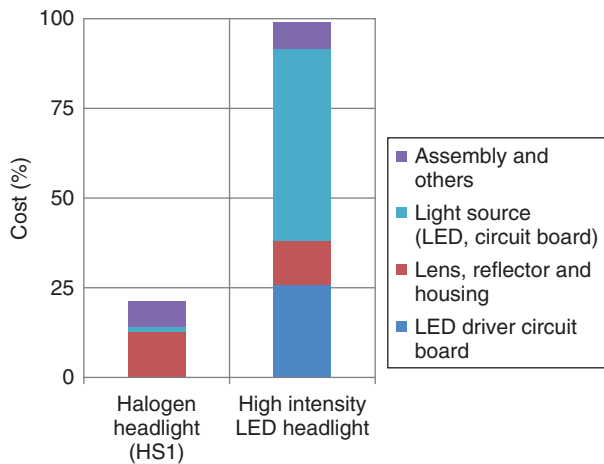


Fig. 2 Cost constituents of a halogen headlight system and a conventional LED headlight

2. Study of Feasibility of LED Headlights without Heat Sinks

2.1. Study of Potential for Use of High Intensity LEDs

First, the research considered the potential for the reduction of the heat sinks in headlights using conventional

Table 1 Rated values of performances for high intensity LED and halogen light bulb

Specification	High intensity LED (PHILIPS/ALTION) ^{*(1)}	Halogen (HS1)
Luminous flux	800 lm	825 lm (High)
Rated voltage	13.7 V	13.2 V
Rated current	1.0 A	2.65 A
Rated power	13.7 W	35 W

^{*(1)} The performance as of products in 2010

high intensity LEDs for automotive use. Tests were conducted using HS1 bulbs, which are used extensively in low-cost two-wheeled vehicles for markets in developing countries (commuters), and high intensity LEDs, both of which provide the same level of luminous flux. Table 1 shows a performance comparison of high intensity LEDs and HS1 bulbs.

In order to study whether heat dissipation would be possible without the use of heat sinks, high intensity LEDs were mounted on glass epoxy substrates (Flame Retardant Type 4: FR4), and the relationship between the LED current and the temperature of the LED joint sections (T_j temperature) was measured (Fig. 3). Substrates of 130 mm in width and 50 mm in depth were used for both high beam and low beam LEDs to produce a size able to be positioned within an incandescent bulb headlight. The substrates were two-sided, coated with a copper foil of 35 μm in thickness. The surface area of the copper foil was identical on both sides of the substrates, and was 14,300 mm^2 in total for both sides. The copper foil was run through through-holes in order to help ensure heat conduction between the foil on each of the sides of the substrates. Ambient temperature was set at the upper limit for the temperature of the use environment for automotive lights. For the measurement of T_j temperatures, the temperature of the solder connection on the cathode sides of the LED chips (T_s) was measured using thermocouples, and the amount of heat from T_s to T_j was calculated by adding the power impressed on the LED (LED forward

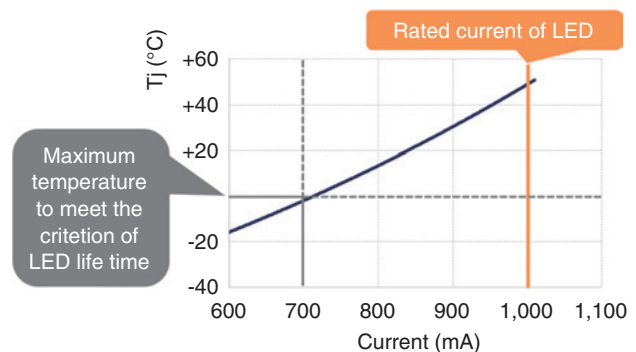


Fig. 3 Characteristic of high intensity LED under the heat dissipation condition without heat sink

Table 2 Rated values of performances for high intensity LED and medium level intensity LED

Specification	Medium intensity LED	High intensity LED
Luminous flux	200 lm	800 lm
Rated voltage	3.0 V	13.7 V
Rated current	700 mA	1.0 A
Rated power	2.2 W	13.7 W

voltage x operating current) to heat resistance inside the LED.

When the drive current is larger than 700 mA, T_j of high intensity LEDs exceeds the maximum operating temperature that can guarantee the life time requirement, which is determined by intensity deterioration characteristics. Consequently, it was verified that the heat dissipation requirement could not be met without a heat sink. These results demonstrated that when high intensity LEDs were employed, it would not be possible to realize the functions of a headlight without the use of heat sinks.

2.2. Study of Feasibility of Application of Medium Intensity LEDs

As indicated in the preceding section, it would not be possible to employ high intensity LEDs without using heat sinks. The potential for the use of multiple medium intensity LEDs instead of high intensity LEDs and the realization of heat dissipation performance by means of a dispersed arrangement of the LEDs (the heat sources) was, therefore, examined. Table 2 and Fig. 4 show representative rated performance values for medium intensity LEDs.

While high intensity LEDs are exclusively used as light sources for automotive headlights, medium intensity LEDs are employed as light sources in a wide variety of consumer applications in addition to their use in

automotive daylight running lamps. As such, they are manufactured in higher quantities than high intensity LEDs, and their cost is being reduced. Because of this, based on consideration of the cost of individual LEDs, the use of multiple medium intensity LEDs could reduce the cost of the light source when compared to the use of high intensity LEDs. Figure 5 shows the relationship between luminous flux and cost for high intensity and medium intensity LEDs.

Luminous flux when high beam is used is approximately 800 lm, and the cost of realizing this level of brightness using medium intensity LEDs is approximately half that when a high intensity LED is employed. It is necessary to use four medium intensity LEDs in order to realize a luminous flux of 800 lm. Two medium intensity LEDs are lit for low beam; by activating a further two LEDs in addition to the low beam light sources when using high beam, it would be possible to obtain a luminous flux equivalent to that of an HS1 bulb. In addition, the rated power of a medium intensity LED is 2.2 W, less than one-sixth the rated power of a high intensity LED. Therefore, it would be possible to realize adequate heat dissipation using a small substrate when four medium intensity LEDs were employed.

Next, the potential for heat dissipation without the use of heat sinks when medium intensity LEDs were employed was examined. Four FR4 substrates with different copper foil area to mount the medium intensity LEDs, were measured for each of T_j temperature. In the above test, T_j of LED is confirmed the copper foil area less than the temperature that can guarantee the life time requirement, which is determined by intensity deterioration characteristics. The substrates were FR4 two-sided substrates. The thickness of the heat-dissipating copper foil was 35 μm , and the foil was the same size on both sides of the substrates. The copper foil was run through through-holes to help ensure heat conduction between the two sides of the foil. The method described above was employed for the measurement of the T_j temperature.

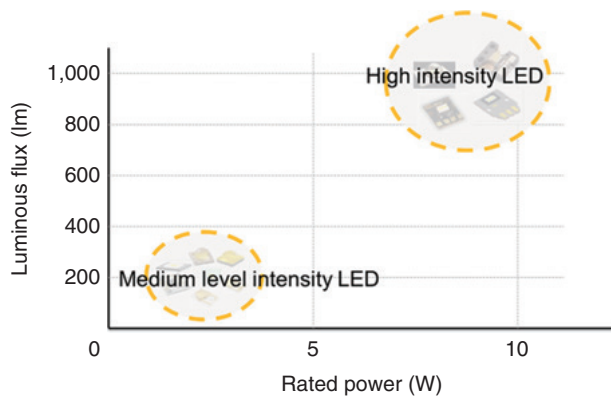


Fig. 4 General ranges in the diagram of rated power and luminous flux for high intensity LEDs and medium level intensity LEDs

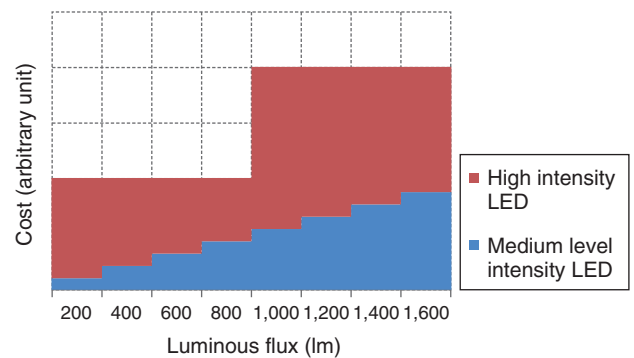


Fig. 5 Relationship between luminous flux amplitude and cost for high intensity LED and medium level intensity LED

Figures 6 and 7 show images of substrates mounted with medium intensity LEDs.

The current flowing to the LEDs was 700 mA, and the ambient temperature was set at the upper limit of the temperature of the use environment of the lights. Fig. 8 shows the relationship between the LED T_j and the surface area of the copper foil on the substrate.

The results indicated that if it was possible to obtain a total surface area of 2,000 mm² (total for front and rear) for the heat-dissipating copper foil for each medium intensity

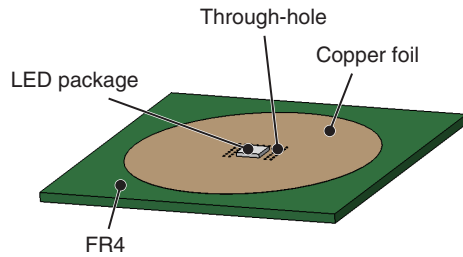


Fig. 6 Schematic view of onboard medium level intensity LED

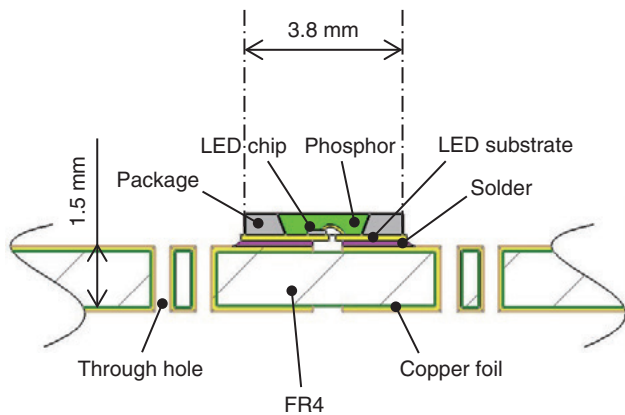


Fig. 7 Circuit board mounted with LED of medium level intensity (cross-sectional view)

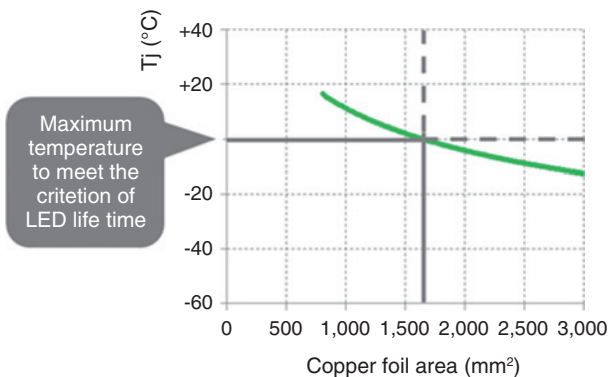


Fig. 8 Heat dissipation characteristic of a medium level intensity LED without heat sink

LED (power: 2.2 W), it would be possible to realize a light without the use of heat sinks. In addition, it was possible to use substrates of 130 mm in width and 50 mm or less in depth for both low beam and high beam. This size is within the size employed in the headlights of commuter models. These results demonstrated that it would be possible to fulfill headlight functions without the use of heat sinks by employing multiple medium intensity LEDs.

3. Study of Feasibility of High Beam/Low Beam Series Connection Activation Circuit

The activation circuits of conventional LED headlights use 12 V batteries as power sources; the LED light source and a high beam circuit provided with a constant-current regulator circuit and a similarly equipped low beam circuit are connected in parallel. Figure 9 shows LED headlight activation circuits connected in parallel.

By contrast with a series connection, when a parallel connection is employed, variations in the value of the current flowing to each row of LEDs occur, and the current flowing fluctuates when switching from activating one row of LEDs to activating two rows of LEDs. This makes it necessary to provide each row of LEDs with a constant-current regulator connected in parallel. In the case of a series connection, there are no variations in the current flowing to each LED and the current flowing is constant. A series connection thus presents the advantage of making it possible to use only one constant-current regulator. However, because V_f is high in the case of a series connection, it is necessary to supply a high voltage, and therefore to address issues including the method of switching between low beam and high beam circuits and of responding to LED malfunctions. Table 3 compares parallel and series connections.

3.1. Method of Realization of High-voltage Drive without Booster Circuit

The maximum V_f of the medium intensity LEDs discussed in the previous section was 3.5 V, while a voltage of 14 V or higher is necessary for activating the LEDs when two low

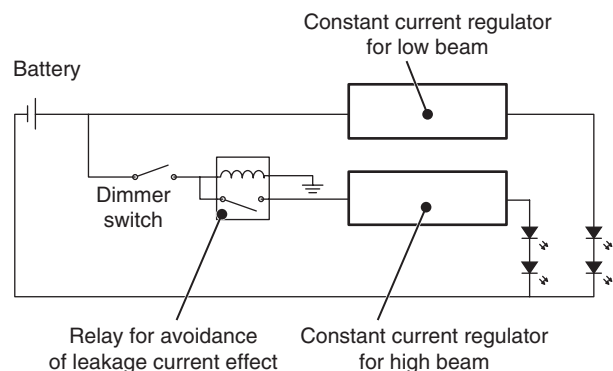


Fig. 9 Schematic circuit diagram for turning on the conventional headlights

Table 3 Comparison between parallel and series circuit connections

Wiring	Parallel connection	Series connection
Equivalent circuit		
Current variation and associated measures	Separate current regulations are necessary because unbalanced current supply occurs from the difference in V_f of those LEDs if one common regulation circuit is applied for providing currents to both of the LEDs for low and high beams.	The same magnitude of current flows through both of low and high beam LEDs.
Constant current circuit	Two (necessary for each line)	One
Total drive current	Large total current is needed for supplying two lines. (1,400 mA)	Current is the same as when driving one LED and unchanged with the number of LEDs. (700 mA)
Drive voltage	Driven by relatively low voltage with a small number of LEDs connected in series on each line. (The voltage is deliverable by using only a down converter.)	V_f becomes high in association with the number of LEDs.
High/Low alternation	By placing on/off switch onto the high beam circuit line, high and low beams alternation is possible.	Placing on/off switch onto the series-connected line works only for turning on or off for both beams at the same time.
When one LED fails in open mode	The other beam with unflawed LED can be turned on.	Both beams cannot be turned on.

beam LEDs and two high beam LEDs are connected in series. Because of this, it is necessary to use a booster circuit when employing a battery as the power source. It was therefore decided to use an ACG, which have long been extensively used in the incandescent bulb headlights of commuter models, as a power source and regulate negative voltage half-waves in order to make it possible to employ the type of circuit that supplies 12 V to incandescent bulb headlights.

Conventional incandescent bulb headlight activation circuits control the voltage impressed on the bulb via the effective voltage of the ACG AC negative voltage half-waves.

By outputting the thyristor (SCR) timing signal (Trig) with consideration of the discrepancy between the preset voltage and the results of calculation of the effective voltage, it is possible to control the period for the supply of power and obtain a constant effective voltage. Figures 10 and 11 show circuits for incandescent bulb headlights that apply negative voltage half-wave activation.

In the case of an LED, constant-current control is necessary. To realize this, the specifications were modified against the incandescent bulb headlight system circuit to make it possible to monitor the current flowing to the LED and control the period of power supply to a thyristor. The use of ACG negative voltage half-waves for constant-current

control would produce concerns over flickering of the LED. Unlike incandescent bulb headlight system, LEDs do not display an afterglow, and because of this flickering due to pulsating current tends to be more conspicuous in LEDs than in incandescent bulbs. The research team decided to attempt to control this flickering by means of the standard method

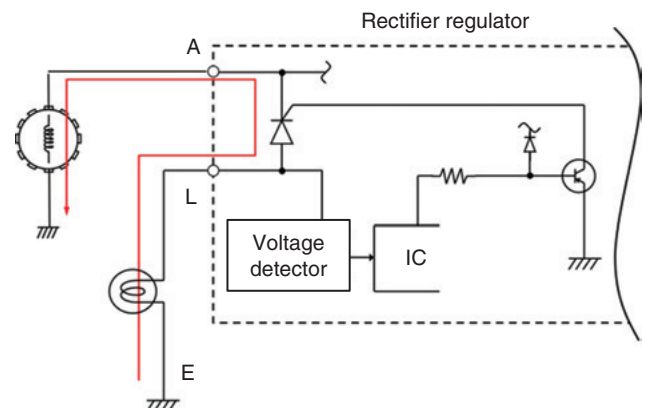


Fig. 10 Circuit diagram of halogen headlamp driver applying negative voltage half wave activation type

of employing a capacitor in order to smooth the pulsating current, but this presented the twin issues of determining the necessary capacitance of the capacitor for control of flickering and the development of a method of controlling voltage to below the withstand voltage of the capacitor.

In order to determine the necessary capacitance of the capacitor, it was first necessary to determine a benchmark for the allowable level of flickering. The present research aimed to realize a level of flickering equivalent to or lower than that realized by the ACG negative voltage half-wave activation method employed for conventional incandescent bulb headlights.

The results of tests to realize a level of flickering equivalent to that of a conventional incandescent bulb headlight showed that LED flickering could be controlled to an equivalent or lower level at ripple currents of 300 mA or below. The results of tests of ripple current with changes in the capacitance of the capacitor showed that at 2,250 μF and above, the ripple current was 300 mA or below, but below 2,250 μF , ripple current increased rapidly. Taking variations of $\pm 20\%$ and an assumed level of capacitor degradation of -20% into consideration, a figure of 4,800 μF was set as the necessary capacitance to help ensure that capacitance did not fall below 2,250 μF . Figure 12 shows the ripple current characteristic in relation to the capacitance of the capacitor.

Because no current would flow to the LEDs when the LED headlights were turned OFF, the voltage from the ACG would continue to rise, overshooting the withstand voltage of the capacitor and resulting in its malfunctioning.

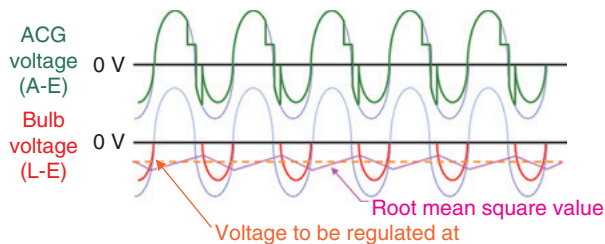


Fig. 11 Waveforms of halogen headlamp driver applying negative voltage half wave activation type

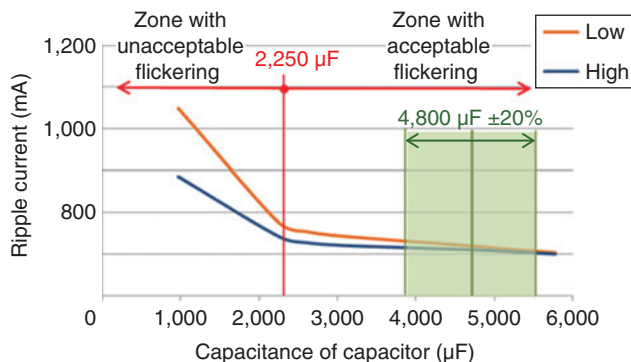


Fig. 12 Ripple currents to capacitance

To respond to this, a benchmark voltage lower than the rated voltage of the capacitor was set, and a control circuit was added that would output a timing signal to reduce the amplitude of thyristor power and adjust the voltage to below the benchmark voltage when voltage increased in excess of the benchmark. Because a capacitor with a rated voltage of 25 V was selected, the benchmark voltage was set at 21 V, taking variations in capacitor temperature characteristics and other factors into consideration. Figures 13 and 14 show the constant-current control circuit with the added capacitor.

During the negative current cycle, the thyristor is ON, and the electrolytic capacitor accumulates potential at the same time as power flows to the LEDs. During the positive current cycle, discharge current flows from the electrolytic capacitor to the LEDs via the current detection circuit.

The current detection section monitors the current flowing to the LEDs. At the same time, the voltage detection section monitors the voltage at both ends of the electrolytic capacitor. If any of these figures exceed benchmark values, Trig is output to reduce the amplitude of the power supply to the thyristor; if any are lower than benchmark values,

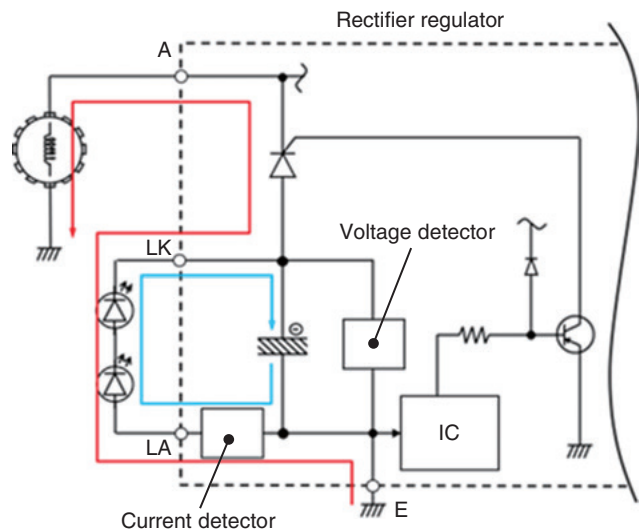


Fig. 13 Circuit diagram adopted with capacitor

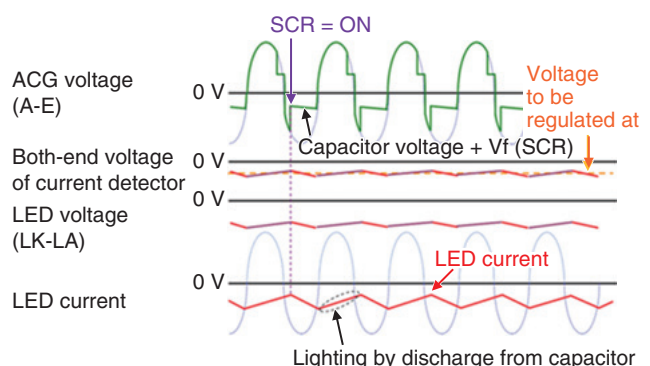


Fig. 14 Waveforms in the circuit adopting capacitor

Trig is output to increase the amplitude of power supply to the thyristor. When current is flowing to the LEDs, current is monitored and constant-current control is employed as the method of output control. When no current is flowing to the LEDs due to a disconnected wire or other factor, the voltage at both ends of the electrolytic capacitor is monitored, and constant-voltage control is employed as the output control method.

3.2. Method of Switching between High Beam and Low Beam using Series Circuits

With regard to the form of LED activation, when the headlights are used on low beam, only the two LEDs on the low beam side are activated; when the headlights are switched to high beam, the two LEDs on the low beam side and the two LEDs on the high beam side are activated simultaneously. In other words, the LEDs on the low beam side are always activated, and switching between low beam and high beam is effected by activating or deactivating the LEDs on the high beam side. Therefore, the bypass line was provided from the middle part of the low beam LEDs and the high beam LEDs in parallel with the high beam LEDs. Alternation circuit of low and high beams is carried out by dimmer switch on the bypass line. Figure 15 shows the circuit that switches between low beam and high beam.

To prevent mistaken activation of the LEDs on the high beam side when the dimmer switch is infiltrated by water, LED headlights using conventional parallel connections are provided with waterproof switches, or they use non-waterproof switches and employ a relay to remove leak current or incorporate a leak current detection circuit in the driver. Any of these measures results in increased cost. In the case of the circuit employed in the developed system, even if the dimmer switch leaks when the high beam is not activated, the circuit will not produce mistaken activation of high beam. In addition, if a leak occurs when high beam is activated, the brightness of the LEDs is dimmed because the current on the high beam side decreases by the amount of current flowing to the bypass circuit, but because the current flowing due to the leak is miniscule, the effect cannot be seen by the naked eye.

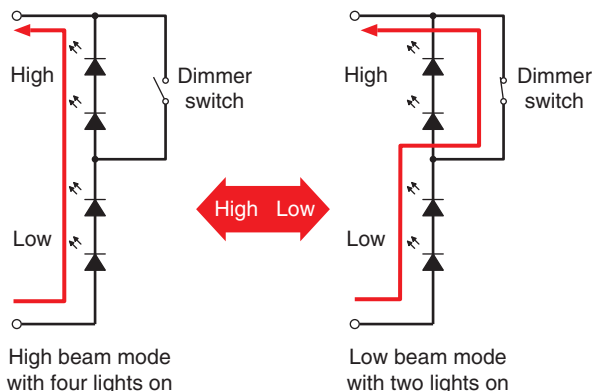


Fig. 15 Alternation circuit between low and high beams

The application of the developed circuit, therefore, makes it possible to reduce the use of countermeasures for dimmer switch leaks, which have conventionally been necessary. However, the use of the method did newly necessitate the application of a countermeasure against rush current occurring when switching from high beam to low beam.

When switching from high beam (four LEDs) to low beam (two LEDs), the capacitor maintains V_f for four LEDs. This results in a rush current when switching to two LEDs. To respond to this phenomenon, a transistor was added to the configuration and a rush current limit resistance was set, and a limiting circuit was employed that produces a current via a resistance only when a rush current occurs. At the normal 0.7 A of constant current control, the base current flows to the transistor Q1, and Q1 is ON; in this state, no current flows to the resistance Rs2 (Fig. 16).

When high beam is switched to low beam, if a current of 1.0 A or greater flows, the voltage between terminals Rs3 increases, and the voltage of Dr1 and Dr2 becomes lower than that of Q1 and Rs3. Because of this, the base current stops flowing to Q1, and Q1 switches OFF. As a result, current flows to resistance Rs2, and the rush current is restricted (Fig. 17).

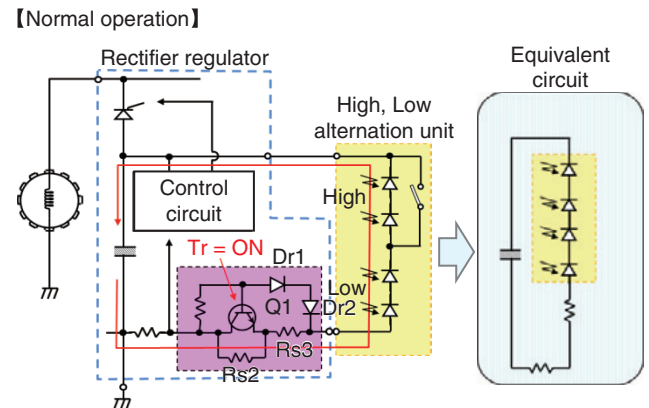


Fig. 16 Current route when normal operation

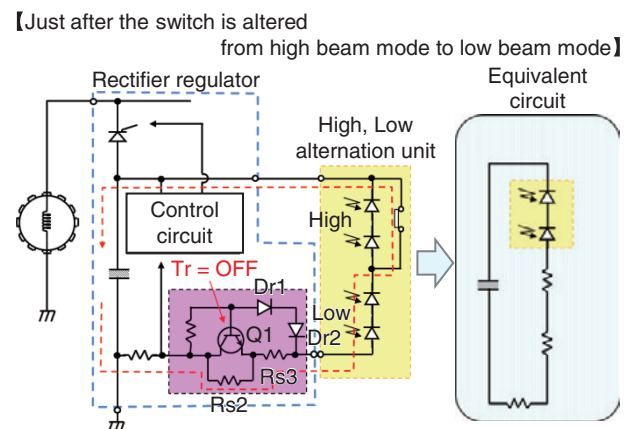


Fig. 17 Current route when rush current occurs

When the voltage of the electrolytic capacitor, CREG, decreases and current drops below 1.0 A, Q1 switches ON, and normal control is resumed.

The employment of this circuit has made it possible to control rush current, which is normally about 2.4 A, to below the rated current for the LEDs (Fig. 18).

3.3. Study of Method of Response to LED Malfunction

To ensure that the vehicle can continue to be operated even when the low beam or high beam circuit is not functioning, in normal headlights it is possible to switch, via the dimmer switch, to the beam that is functioning.

In the case of this system, when high beam is not functioning, it is possible to switch to low beam via the dimmer switch. Figure 19 shows the situation when high beam is not functioning.

However, in the present system, when low beam is not functioning, it is not possible to switch to high beam using the dimmer switch. This represented a new issue presented by this system. In response, a configuration was adopted in which a bypass circuit provided with a Zener diode and a thyristor was connected in parallel with the low beam side; when an increase in voltage between the regulator output lines is detected when low beam is not functioning, the thyristor goes into operation and power is sent to the bypass circuit, causing current to flow to the high beam

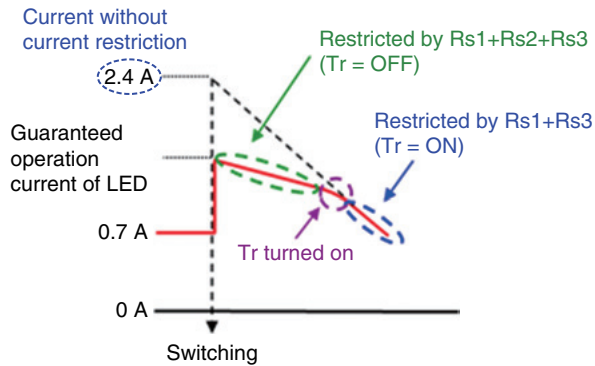


Fig. 18 Current reduction effect by rush current restriction circuit

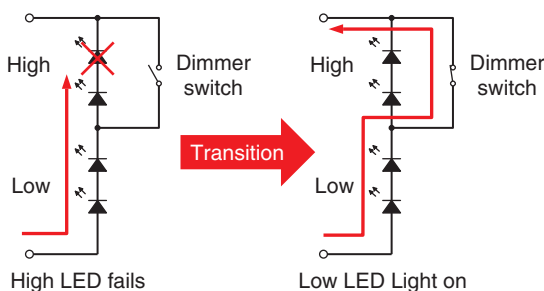


Fig. 19 Change of the current route when a LED for high beam brakes

side (Fig. 20).

The application of this measure has made it possible to employ a switch to activate high beam even when low beam is not functioning.

The development of the new technologies discussed above helped to enable the realization of activation circuits that connect high beam and low beam in series.

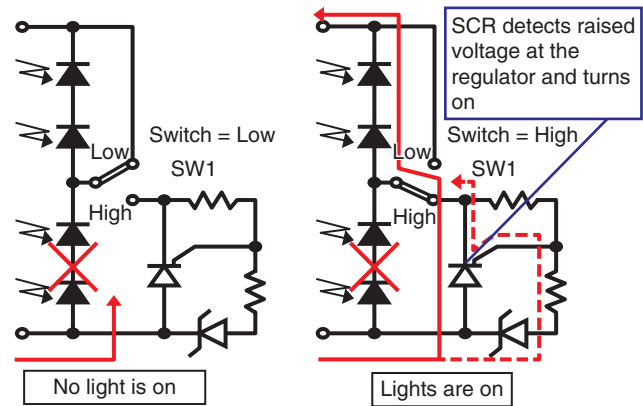


Fig. 20 Change of current route when a low beam LED brakes

4. Conclusion

LED headlights able to be employed in low-cost scooters and motorcycles have been developed. The following technologies were realized through this development.

- (1) The mounting of medium intensity LEDs on a substrate in a dispersed configuration made it possible to realize headlights that did not employ heat sinks.
- (2) The use of ACG half-wave voltage as the drive voltage for the LEDs made it possible to connect four or more LEDs in series without the use of a booster circuit.
- (3) The connection of LEDs by capacitors of appropriate capacitance made it possible to reduce the flickering resulting from ACG half-wave voltage to an equivalent level to that displayed by incandescent bulb headlights or below.
- (4) The use of a bypass circuit connected in parallel to the high beam LEDs and the control of the transmission of power to the bypass circuit via the dimmer switch made it possible to switch between high and low beams.
- (5) The use of a current reduction circuit connected in series with the LEDs made it possible to reduce the rush current generated when high beam is switched to low beam to within the acceptable current range for the LEDs.
- (6) A malfunction detection circuit, connected in parallel to the low beam circuit, has been employed as a response to malfunctions on the low beam side; this made it

possible to switch manually to high beam when LED circuits malfunction on the low beam side.

The application of these technologies has controlled the cost of LED headlights to 1.2 times that of conventional incandescent bulb headlight system. This development has made it possible to employ LED headlights in commuter scooters and motorcycles for developing countries, and can be expected to contribute to the reduction of total CO₂ emissions from motorcycles and scooters in the future.

Reference

- (1) http://www.meti.go.jp/committee/summary/0004310/pdf/018_04_00.pdf

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Development of ACG Using Regulator Rectifier with Phase Control

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ABSTRACT

To get free from the risks that arise from price variations of rare-earth metals, an alternative current generator for motorcycles was developed using conventional ferrite magnet while keeping the same amount of electricity generation as that of using rare-earth metal. For the application of ferrite magnet to a motorcycle, the way of having a larger size cannot be allowed because of the increases of the mass and moment of inertia associated with that. Accordingly, in our development, the increase of electricity generation was realized by changing the current control from regulated short-circuit rectifier method to phase shifting method with a precise control of the effective range of phase shifting. For that purpose, newly developed configuration was implemented to the sensor for phase control to have it under permissible temperature range against resulting high installation temperature. Through those measures, it was achieved by using ferrite magnet to generate a compatible amount of electricity generation to that of using rare-earth metals without changing the dimensions of the generator.

1. Introduction

The price of rare earth metals started to go up since 2010 and it is still under the risk of price fluctuations. With these circumstances, it has become an urgent request for currently used materials in alternating current generators (ACGs) in motorcycles to replace them with materials free from rare earth metals. One of the practical methods to substitute them is an adoption of ACG using ferrite magnets. However, compared to ACGs using magnets with rare earth metals, the electric power generation is small. Consequently, with conventional control method, the amount of power generation cannot meet the requirement, especially, when the rotation speed is slow. To increase the electric power generation, making ACG in larger dimensions is a commonly applied method. However, that increases the mass and the moment of inertia. However, it is difficult to apply that method to motorcycles that severely require light weight and small size. Accordingly, in our development, the control method for electrical power generation was changed from a regulator rectifier method, using short-circuiting control, to a phase control method. By changing the control method, the power generation at low rotation speed was ensured and the dimensions of the ACG were kept almost the same as those of ACG using magnets containing rare earth metals. In this paper, the technologies that enabled this

development will be described. One of those is the phase control method to increase the power generation, which has been applied to a system in a motorcycle for the first time. Another is the sensing method to detect the positions of magnetic poles that endure the increased heat generation associated with the increase of the power generation.

2. Regulated Rectifier with Phase Control

In motorcycles, a regulated rectifier with short-circuiting control method had been commonly used. In that system, the charging voltage was regulated by the charging current while varying the proportion of time between a full wave rectification period and a short-circuiting period (Fig. 1). On the other hand, in the system with a regulated rectifier by phase control, the voltage delivered from the battery is applied to create the induced voltage in ACG. In addition, the phase of applied voltage is varied to control the generated voltage making the output current to be regulated in an almost flat direct current. By using this method, a larger amount of power generation is attainable compared with the system applying a short-circuiting control (Figs. 2 and 3).

The diagram of the equivalent circuit of a single-phase ACG is shown in Fig. 4. In the diagram, the left side illustrates a circuit of an alternating current generator with

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the induced voltage of E and the inductance of L . The right side of it illustrates an alternating voltage power source, with the output voltage of V , which is composed of a battery and an inverter. As a control method, phase control is applied. The target current level I can be obtained by changing the phase of the output voltage V in reference to the phase of the induced voltage E .

Next, the behavior of the current I will be explained when the phase of the voltage V is varied on condition that the frequency of E is the same as that of V . Based on the voltage equation of the equivalent circuit, the current is derived as down below. Where the angular frequency is defined as ω .

$$\dot{E} = j\omega L \dot{I} + \dot{V} \quad (1)$$

$$\dot{I} = \frac{\dot{E} - \dot{V}}{j\omega L} \quad (2)$$

In the Eq. (2), the current I can be varied by changing the phase of V while ω , L and E are maintained to the same values. When it is illustrated by vector diagram, it is shown as in Fig. 5. As you see in the diagram, the amplitude and the phase of the current I changes according to the variations of the phase of V which is defined in reference to

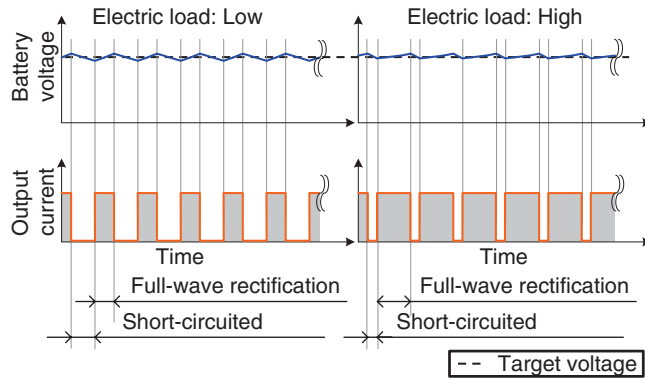


Fig. 1 Schematic illustrations of charging currents under short-circuit type control in different load conditions

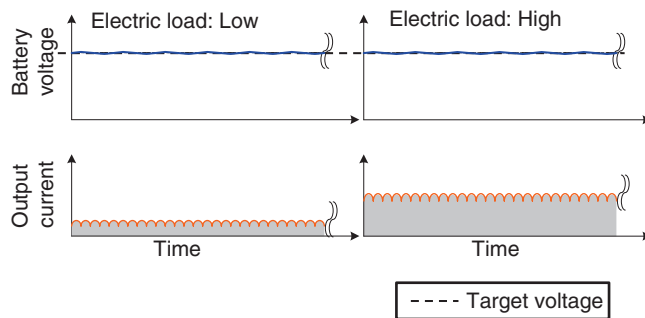


Fig. 2 Schematic illustrations of charging currents under phase control in different load conditions

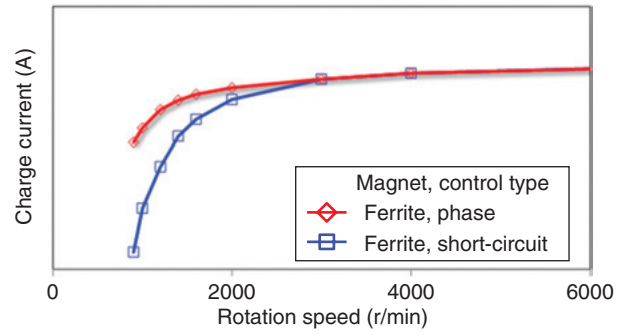


Fig. 3 Characteristics of charge currents under different types of control

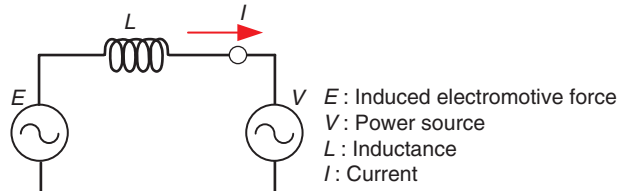


Fig. 4 Circuit composed of two AC power sources and inductance

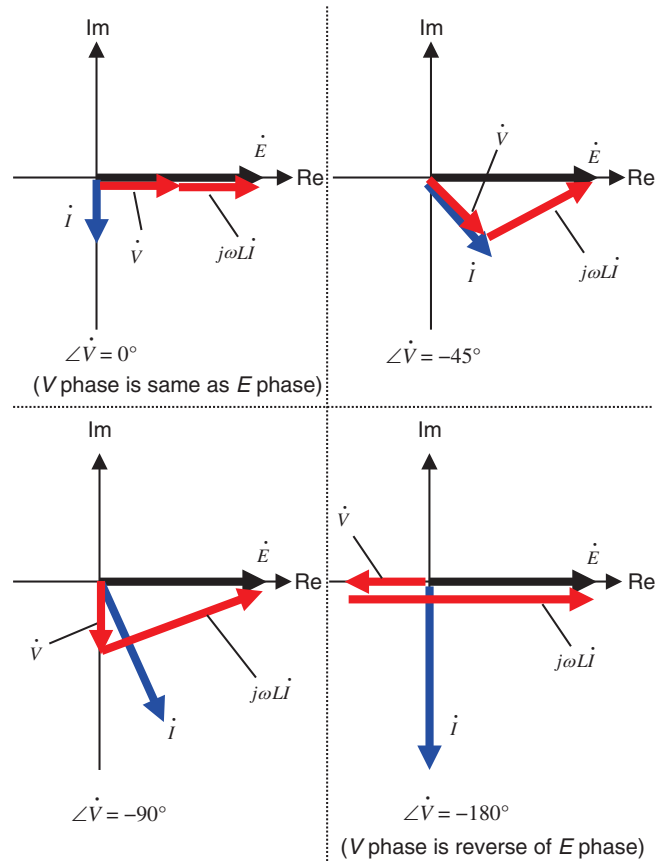


Fig. 5 Vector diagrams with varied phases of supply voltage of V

the phase of E (Fig. 5)⁽¹⁾⁻⁽³⁾.

Accordingly, it is possible to control the current by phase control method by changing the phase of the supplied voltage V . In the actual circuitry to be implemented, a measure to detect the phase of induced voltage E or the angular position of a magnet pole is necessary to determine the phase of the supplied voltage V . Moreover, the resistance of generator coils and the power factor in association with V and I should be taken into consideration as well. Therefore, descriptions that appear in the actual equation are more complicated than the ones described here.

3. Phase Control to Increase Power Generation

It is generally understood, when a phase control is applied, that the selection of the phase range to be controlled has a significant impact on the characteristics of the output power. In our development, it was made possible to yield a larger amount of power generation compared to the short-circuiting method by expanding the range of phase control toward the phase-delaying direction. In Fig. 6, the characteristics of the output current are shown when the phase of the voltage applied from the battery is varied in reference to that of the induced voltage. As the figure shows, around the phase difference of 0° , it has such characteristics that the output current decreases when the phase is shifted toward phase-advancing direction (to the right in the figure), and it increases when the phase is shifted toward phase-delaying direction (to the left in the figure). Utilizing these characteristics, a feedback control is implemented to regulate the output voltage at the predetermined level. The output current is 22.5 A at the phase difference of -68 degrees. From that point, when the phase difference is shifted toward more delayed phase values, the line current of the ACG still increases accordingly. However, the output current begins to decline from that point and keeps decreasing after that. In this

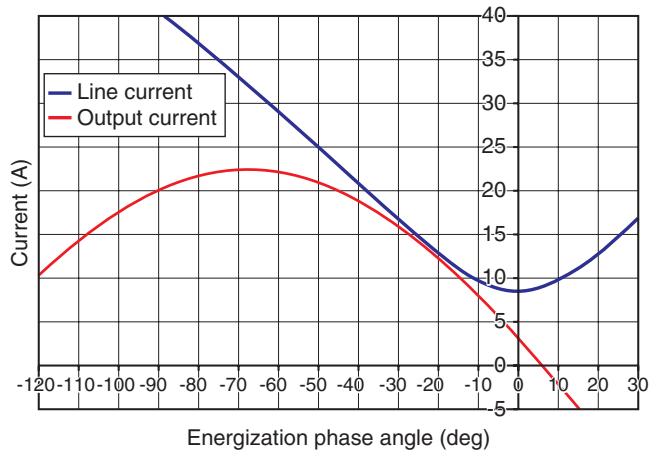


Fig. 6 Characteristics of charging currents to the phase of line current

region, the control status falls into positive feedback. Accordingly, in this region, the generated power declines, and the fluctuation of heat generation by the ACG and/or an unstable status of the control system are likely to happen. To avoid these situations, the phase region in which the shifted phase points to be designated for the control should be restricted within an appropriate range. Furthermore, to enable that control, the information of angular positions that can be used as reference points of the control, which is either of the phase of the induced voltage or the angular positions of magnet poles, is inevitably needed.

4. Developed Method to Detect Rotational Position of Magnet Poles to Cope with Increased Heat Generation

There are several methods to detect a reference position for the system control with high accuracy. One of the most common methods is to install a Hall Effect sensor between coils of the stator and detect the rotational positions of the magnetic poles. When the power generation is increased at a low revolution speed, the temperature of the coils may exceed 200°C , where the heat resistant temperature of Hall Effect sensor is 150°C . Accordingly, if a Hall Effect sensor is applied, it cannot meet the temperature requirement (Figs. 7 and 8).

Consequently, an investigation on the possibility to

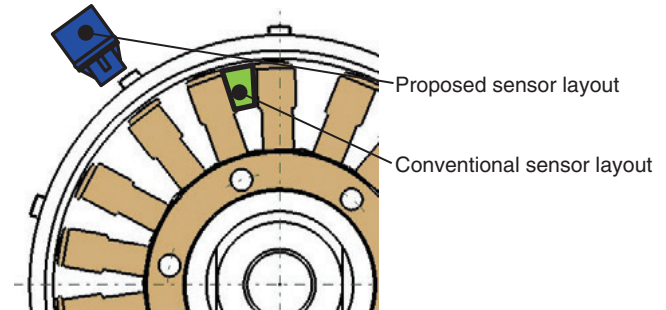


Fig. 7 Comparison of sensor configurations between in-stator location and out-of-flywheel location

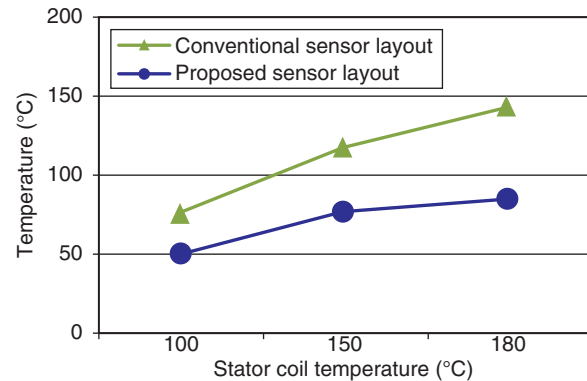


Fig. 8 Comparison of sensor temperatures

Table 1 Comparison of accuracies of detection angles

Sensor layout	Proposed layout		Conventional layout
	Before correction	After correction	
Detection error angle (°)	±43.5°	±4°	±3°

develop a new sensing method to detect magnetic poles had been conducted.

For conducting the investigation, four requirements had been set as follows:

- (1) The design change associated with the engine shape should be minimal.
- (2) The sensor currently mass produced should be commonly applicable.
- (3) The sensor should be located where it has the least chance to be damaged by a vehicle tip over.
- (4) Angular position sensing accuracy should be within ±10°.

After thorough investigations on various methods, it was decided to attempt a method, in which a protrusion was provided on the perimeter of the flywheel with the same angular position of a magnet pole and a phase of the induced voltage was detected by a single Hall Effect sensor (Fig. 7). The advantage of this method is that only one sensor is needed and can be selectively located where the temperature is low (Fig. 8). However, if no extra measures are implemented, the angular position error of a magnetic pole is as large as ±43° or more, and the accuracy requirement cannot be met (Table 1). This is primarily because the mechanical errors of several parts, such as ACG and engine coverings, are accumulated. Accordingly, some error compensation technique is necessary to adopt this sensing method (Fig. 9).

When a full wave rectification is applied, there is a predetermined relationship among the phases of each line currents in ACG and the phase of the induced voltage, and

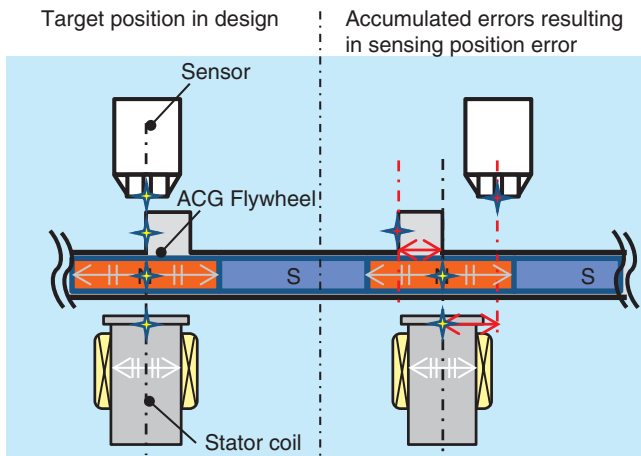


Fig. 9 Source of errors affecting detection angle accuracy of out-of-flywheel type sensor configuration

that relationship varies depending on the frequency. To cope with aforementioned accuracy issue, this relationship had been noticed. The line currents passing through the coils are generated by the induced voltage caused in the stator coils while the flywheel is rotating. Therefore, predetermined phase differences are occurred among the line currents and the induced voltage depending on the frequency of the inducing voltage and the total resistance in the line the charging current goes through. In the equivalent circuit shown in Fig. 10, the induced voltage E of ACG is described as:

Where:

$$\dot{E} = (j\omega L + R)\dot{I}$$

L : Inductance of the stator coil

R : Load resistance of the circuit

$$\dot{I} = \frac{\dot{E}}{j\omega L + R}$$

The phase difference θ in this condition is given as:

$$\theta = \tan^{-1} \frac{\omega L}{R}$$

Next, the wave forms appear in the circuit and their phase differences (Fig. 11). In the figure, (α) the output of the Hall effect sensor (the output of magnetic pole sensing), (β) the induced voltage and (γ) the line current are shown respectively. Under those wave forms, phase differences are

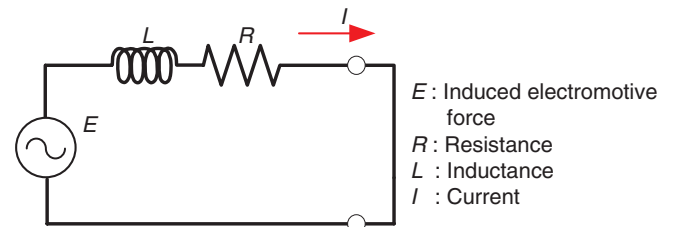


Fig. 10 Equivalent circuit of ACG (single-phase)

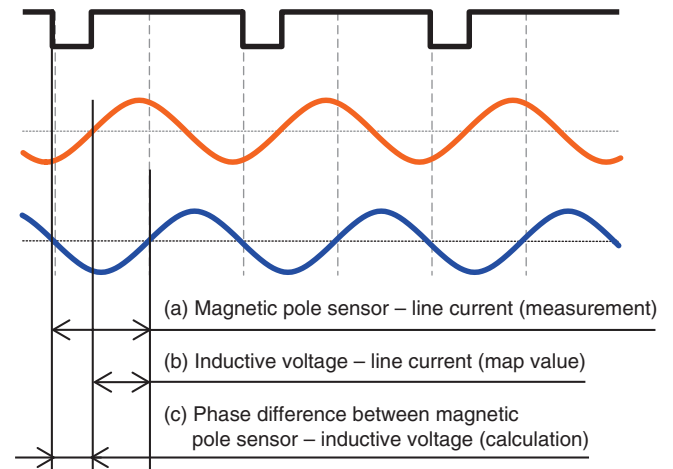


Fig. 11 Timing chart illustrating error compensation

shown, i.e. (a): between (α) and (γ), (b): between (β) and (γ), (c): between (α) and (β), respectively. The phase difference (c) is calculated using (a) and (b). This phase difference (c) is used as an argument in the function to yield the output current control.

Meanwhile, as shown in Fig. 12, in the equivalent circuit that is representing the system to be applied to an actual vehicle, the load resistance R_2 varies depending on the changes of the total electrical load of the devices in a vehicle. Consequently, compensation of the amount of the phase shift was carried out based on the measured value of the output voltage between the terminals of the regulated rectifier. The result after compensation is shown in Table 1. The error after compensation was reduced to $\pm 4^\circ$ for the intended phase variation range towards phase-delaying direction. Thus, the accuracy was enhanced to meet the requirement.

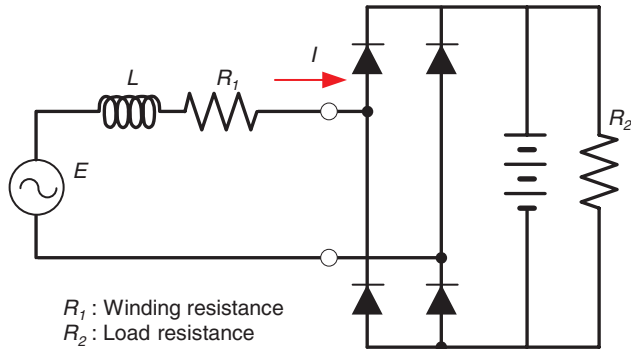


Fig. 12 Equivalent circuit of total charging system applied to the production design (single-phase)

5. Validation of Power Enhancement by Phase Control System

The enhancement of the output current by the regulated rectifier controlled by phase control method was verified. ACGs used in the tests were the one made of magnets containing rare-earth metals and the one made of ferrite magnets. The control methods were regulated rectifier with short-circuiting method and that with phase controlling method. The combinations of those ACGs and control methods are shown in Table 2. According to these combinations, measurements of the output current characteristics were conducted and the results were compared to each other. Table 3 shows the measurement conditions and Fig. 13 shows the measurement results.

Under the measurement conditions applied in the tests conducted this time, the output current yielded by phase control method was larger, across the entire range of rotational speed, than that yielded by short-circuiting control method (1).

Table 2 Combinations of ACG and regulated rectifier

Combination		Short-circuit (1)	Short-circuit (2)	Phase control
ACG	Outer diameter	$\phi 132.5$	$\phi 132.5$	
	Magnet type	Rare-earth magnet	Ferrite magnet	
Regulated rectifier	Control method	Short-circuit control		Phase control

Table 3 Test conditions

ACG temperature	Stator coil temperature 120°C
Ambient atmosphere temperature	Room temperature
Test equipment	Motor bench
Test circuit	

In the low rotational speed range of 3000 r/min or less, the output current was larger in the one with phase control method than the one with short-circuiting method (2). In particular, at the rotational speed of 1000 r/min, which is the speed when idling, the output current was 2.3 times larger than the case controlled by short-circuiting method (2). In the high speed range of 3000 r/min or above, as the graph shows, no significant difference in the output currents was noticed between short-circuiting method using rare-earth contained magnets and phase control method using ferrite magnets. Based on these results, it was made possible to substitute ferrite for rare-earth contained material as ACG magnet material. Thus, the system applicable to motorcycles was successfully realized.

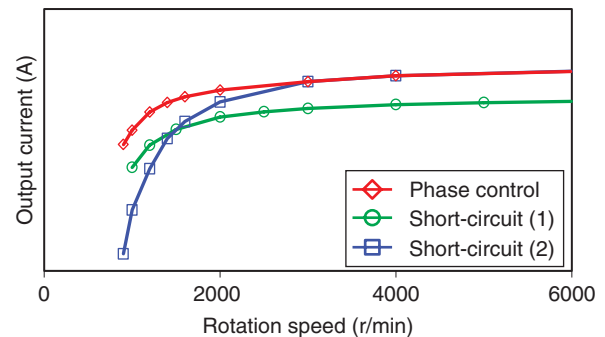


Fig. 13 Characteristics of output current to rotation speed

6. Conclusions

To realize an ACG system using ferrite magnets that is applicable to motorcycles, phase control method was applied.

In the development, the following technologies were established:

- 1) Phase range restriction method for phase shift control to effectively increase the output power while avoiding instability.
- 2) Sensing method to detect angular positions of the magnet poles that is durable under a large heat condition caused by increased power generation.

Through this development, it was made possible to fulfill the requirements for ACGs used in motorcycles by using ferrite magnets without applying rare-earth containing materials to the magnets. As a consequence, it was made possible to get away from the risks caused by price variations of rare-earth metal containing magnets and that brought about a stable cost for ACG manufacturing. The ACGs that employ aforementioned phase-controlled regulated rectifier are already applied to motorcycles on the market. It is highly expected for this ACG to be applied to much more motorcycle models in the future.

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Actual Proof Experiment of Electric Wheelchair “Monpal” for Enhancing Elderly QOL

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ABSTRACT

In August 2010, Honda and Kumamoto Prefecture concluded a comprehensive agreement concerning proof experiments of next-generation personal mobility. In accordance with that agreement, electric carts were provided on loan to elderly people and an evaluation was made of how the resulting augmentation of their mobility changed their quality of life.

Using the Medical Outcomes Study 36-Item Short-Form as an index for evaluating quality of life, changes in the subjective state of health of the experimental subjects were verified. Their life-space mobility was evaluated using the Life-Space Assessment. In order to reinforce those evaluations, the Activities Monitoring and Evaluation System was also used to carry out evaluation of everyday bodily activity.

The results indicated a tendency for the use of electric carts to expand life-space mobility and contribute to enhancement of overall sense of health, activity, and other such aspects of quality of life.

The following will report on these proof experiment results.

1. Introduction

In August 2010, Honda concluded the “Comprehensive Agreement Regarding the Electric Vehicle Testing Program for Next-Generation Personal Mobility Products” with Kumamoto Prefecture with a view to realizing the joy and freedom of mobility as well as a sustainable society where people can enjoy life. Honda then conducted proof experiments until March 2014.

The purpose of the experiments was to contribute to examination of concepts of future personal mobility that would enhance the quality of life (QOL) of elderly people by means of personal mobility utilizing electrical energy, and that by extension would contribute to enhancement of community QOL⁽¹⁾ (Fig. 1).

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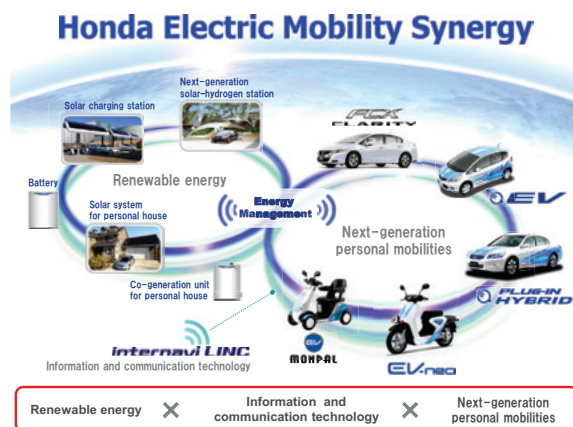


Fig. 1 Honda electric mobility synergy

2. Purpose of Social Proof Experiments Using Electric Carts

Honda has been marketing the Monpal electric cart as a device to assist elderly people when they go outside their homes. However, the Nursing Care Insurance Law that came into effect in 2000 requires the certification of need for nursing care for people to be eligible to use these on a rental basis, and shipments have been trending downward for this and other reasons (Fig. 2). As things stand at present, the fact that dependence on devices of this kind can result in further deterioration of bodily functions, and the scarcity of environments where people can feel at ease using such devices, are among the factors that have perhaps kept the recognition and active use of electric carts from becoming fully accepted in society.

Meanwhile, Kumamoto Prefecture aims to realize a society whose members can enjoy long life, and was interested in clarifying the impact of electric cart use on elderly people on the basis of QOL indicators. Concluding this comprehensive agreement concerning proof experiments of the next generation of personal mobility, therefore, the prefecture took the opportunity to form an Electric Cart Working Group centered primarily at the Japanese Red Cross Society's Kumamoto Health Care Center and involving collaboration by government, industry, and academia. This group has been a forum for active and extended discussion of new ways of using electric carts in order for elderly people to maintain as high a QOL as possible in their lives in local communities (Fig. 3).

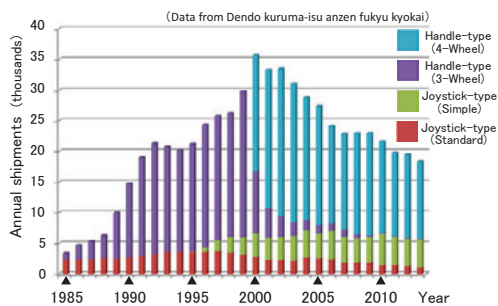


Fig. 2 Annual shipments of electric wheelchair

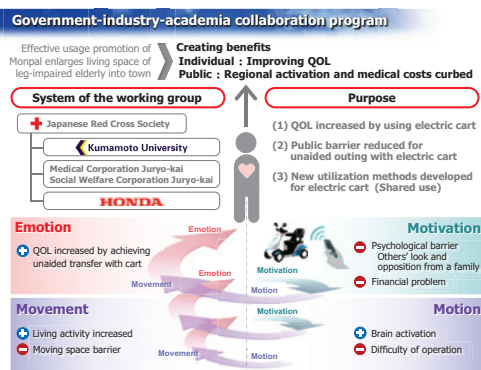


Fig. 3 Objectives of working group with government-industry-academia collaboration program

3. Overview of Proof Experiment

Proof experiments were held in which elderly people who have no experience in using electric carts were given the loan of a Monpal to assist in their everyday movements. This was done for the purpose of verifying the changes that such use brings to those elderly people's lives. A number of elder care facilities with differing lifestyle patterns were chosen as demonstration fields for the proof experiment, and surveys and analysis were conducted regarding changes in users' lives, range of mobility, and QOL before and after using an electric cart, as well as the circumstances of their electric cart use^{(2), (3)}. The experiments described below were conducted with the approval of Honda's Bioethics Committee.

3.1. Demonstration Field

Elder care facilities were selected as demonstration fields according to these two levels of criteria for bodily function and capacity for activity:

- (1) Nursing care facilities that are residences for people who require nursing care on an everyday basis
- (2) Assisted-living facilities with services for elderly residents capable of living independently

3.1.1. Demonstration field A (model of nursing care facility)

The elderly people who reside in nursing care facilities are either people whose care condition requires nursing care services under the Nursing Care Insurance Law or those certified as requiring nursing care because their condition requires assistance for daily living. Many of the people who receive this certification have diminished bodily function and in most cases they require the wheelchairs, walkers, or other such devices owned by nursing care facilities even for their everyday movement. These people have a more restricted range of mobility than most normally healthy people, and their opportunities for mobility are also more limited.

It appears likely, however, that even these people certified as requiring nursing care may be able to expand the range of their mobility and increase the frequency of their movement if they have electric carts that assist safe movement. Proof experiments were therefore conducted in the shared use of electric carts at nursing care facilities for the elderly, such as special nursing homes for the elderly located in the western part of Kumamoto City. This was done for the purpose of verifying a variety of changes in QOL before and after the use of electric carts by elderly people who receive the services of nursing care facilities.

3.1.2. Demonstration field B (model of assisted-living facility for the elderly)

Society is aging rapidly, the shift to nuclear families is progressing, and there are growing numbers of elderly people living alone or in households consisting only of

husband and wife. The national government has therefore been promoting the supply of residences for elderly people that have barrier-free construction and that provide services coordinated with nursing care services and healthcare services as measures to assure stable residences for the elderly. The elderly people who use these assisted-living facilities for the elderly have a greater degree of independence than those who reside in nursing care facilities, and most of them are able to carry on their daily living without assistance from others.

With advancing age, however, their physical abilities gradually deteriorate, and as they find it increasingly challenging to walk for extended periods of time or over long distances, they come to require aid in going outside their residences, assistance in traveling to healthcare appointments, and other such services. Even if they come to require these services, and even if they are able to make use of them, the elderly people who live in facilities with services for elderly residents may still be able to continue their independent lives if electric carts that support their safe mobility are available. As a result, they may also be able to shorten the period when they require aid in going outside their residences and assistance in traveling to healthcare appointments. Proof experiments were therefore conducted in assisted-living facilities for the elderly located in the eastern part of Kumamoto City for the purpose of verifying a variety of changes in QOL before and after the use of electric carts by residents of assisted-living facilities for the elderly (Table 1).

3.2. QOL Evaluation Tools

The following evaluation tools were used in the two fields of the proof experiment for the purpose of verifying changes in electric cart users' lives (daily activities), range of mobility, QOL, and other such factors before and after use.

3.2.1. Methods for evaluating living activities

(1) Bodily Activity Evaluation

The Activities Monitoring and Evaluation System (A-MES), which monitors daily activities, was used for evaluation of bodily activity. The A-MES records data using two acceleration sensors affixed to the experimental subject's torso and thigh. Analysis of the data enables evaluation of the following activity states (Table 2, Fig. 4).

- Activity states over 24-hour period (reclining, sitting, standing, driving electric cart, walking)
- Reclining states (reclining on back, reclining on right side, reclining on left side, reclining on front)
- Number of times changed posture (stand up, sit up, number of times turned over while sleeping)
- Total time of each activity and maximum sustained time
- Percentage of time occupied by each activity state in one-hour period

A-MES is used in the medical and nursing care fields to track daily activities. The data is accumulated in a logger

Table 1 Forms of use in two different testing fields

	Ownership form	User	Utilization area
Field-A Nursing-care services	Care facility	Group	Living area
Field-B Assisted-living facility for elderly	Care facility	Personal	Living area

Table 2 General specification of A-MES

General specifications of the Data Logger	
Sampling period	0.2 sec constant
Recording time	≥ 24 hours
Power source	size AA battery x 1
Size	85 mm x 75 mm x 25 mm
Data	Sampling time, 6 sensor data items (12 bit/data), Measuring time

over an extended period of time, allowing monitoring of the everyday (24-hour) activity states of experimental subjects. In the proof experiments, bodily activity was tracked under the two patterns of days when electric carts were used and days when they were not used, and the differences in daily activities between the two were evaluated.

(2) Life-Space Assessment

The Life-Space Assessment (LSA) is defined as the product of the distance traveled in everyday life, the frequency of that travel, and the degree of independence of that travel. It is an index for evaluating mobility within the spatial expanse of people's lives. The distance traveled takes an individual's bedroom as the point of origin for movement used in evaluating life-space, and the life-space is represented in the following five stages from the bedroom to outside the town limits. The evaluation is made by assigning scores from zero to 120 points.

Life-Space 0: Bedroom

Life-Space 1: Home interior

Life-Space 2: Outside (very close to home)

Life-Space 3: Neighborhood

Life-Space 4: Town

Life-Space 5: Unlimited (outside town)

For the proof experiments, analysis was made of the LSA values from the one-month period before use of electric carts and the one-month period during use of electric carts.

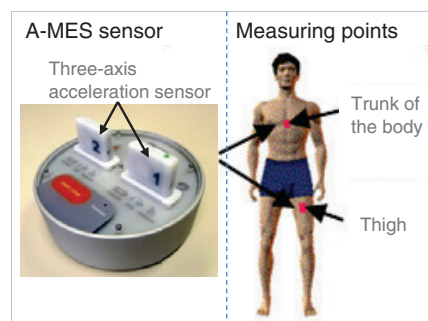


Fig. 4 Sensor and measuring points of A-MES

Table 3 General specification of GPS data logger unit

Size (LxWxH)	Communicator device	101.5 x 139.2 x 47.8
	Antenna	20.0 x 35.0 x 60.0
	GPS	φ 61.0 x 19.5
Total weight	1.8 kg	
Sampling time	1 sec (const.) 5 minutes of FOMA transmitting period	
Loading point	Under seat of MONPAL	
Sampling data	GPS NMEA0183 Velocity, Accelerator position Steering angle, Battery condition	

(3) Measurement of Range of Activity

A GPS data logger equipped with communications functionality was manufactured to record the Monpal operating state and driving operation status. These loggers were mounted on the Monpals.

The Monpal operating state and driving operation status together with GPS data were sampled at one-second intervals and recorded in a file. Distinguished by Monpal unit number and date, these files were transferred to the server over a mobile phone line at approximately one-minute intervals for accumulation and storage.

Software for the verification of stored data was also developed (Table 3, Fig. 5, Fig. 6). It accumulates and

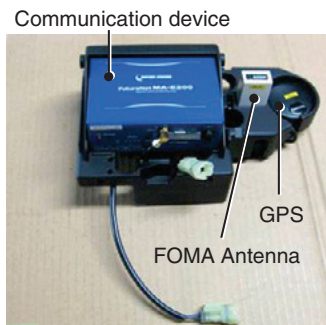
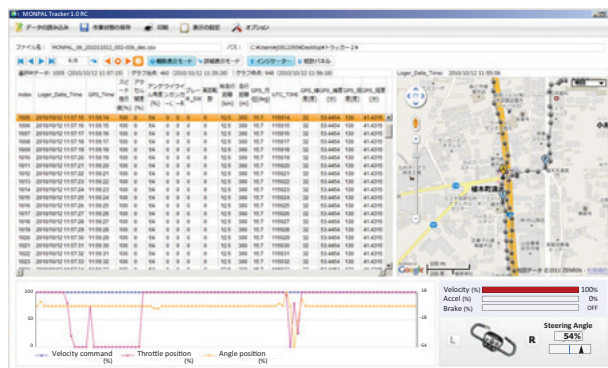


Fig. 5 External view of GPS data logger unit



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Fig. 6 View of Sampling data on PC screen

Table 4 Subscales defined in SF-36™

Subscale items	Abbr.	Scoring reference	
		Worst condition	Best condition
Physical functioning	PF	Impossible to take a bath or change clothes	All physical activity possible
Role physical	RP	Experience trouble with ordinary work	Experience no trouble with ordinary work
Bodily pain	BP	Ordinary work disturbed by severe physical pain	Ordinary work not disturbed at all without physical pain
General health	GH	Health condition getting worse	Good health condition sustained
Vitality	VT	Fully exhausted	Full of vigor
Social functioning	SF	Friendships with families, friends or acquaintance deadily disturbed by some physical or mental impairments	Friendship with families, friends or acquaintance not disturbed by any physical or mental impairments
Role emotional	RE	Problem with work or other activities due to mental reasons	No problem with work or other activities due to mental reasons
Mental health	MH	Always feel depressed with nervous temperament	Always feel calm and happy

(relating to a health condition in the past month)

analyzes Monpal data, including its movement track, the operating status of the accelerator, turn indicators, steering wheel angle, and so on, the vehicle speed, the battery state of charge and voltage, and the motor current.

3.2.3. Methods for evaluating QOL

The Medical Outcomes Study 36-Item Short-Form (SF-36™), which is an evaluation index for health-related quality of life (HRQOL), was used in evaluating changes in QOL due to the use of electric carts. Measures of HRQOL are generally classified under two types: generic measures and disease-specific measures^{(4), (5)}. The SF-36™ is classified as a generic measure, and has the advantage of being able to evaluate QOL without regard to an individual's illness or whether or not the individual has a health disorder. SF-36™ evaluation is made up of eight subscales. Table 4 shows explanations of the scoring for those measures. The survey used self-administrated response forms with questions on 36 items surveying state of health over the month preceding the time of the survey.

3.3. Proof Experiment Results and Discussion

Environments for Monpal use were developed in the proof experiment fields and the following results were obtained with regard to the daily activities of electric cart users before and after use, their range of mobility, changes in their QOL, and the circumstances of electric cart use.

3.3.1. Daily activities

Tables 5 and 6 show the results from monitoring two people wearing A-MES sensors who used electric carts at nursing care facilities. Their daily activities were monitored on days when an electric cart was used and days when one was not used. In order to rule out differences due to different time periods of daily activity on days when electric carts were used and days when they were not, those time periods on both days during

Table 5 Movement status of subject A in Field A

State/Posture	Without Monpal		With Monpal	
	Accumulated Time	Continuous Max. Time	Accumulated Time	Continuous Max. Time
Walking	02:44:57	00:03:03	04:06:04	00:05:50
Standing	00:46:22	00:04:24	01:11:38	00:02:04
Sitting	02:38:16	00:30:53	03:03:30	00:17:13
Recumbent	06:12:40	01:30:01	04:00:43	01:31:59
Total Time	12:22:16	-- : -- : --	12:21:56	-- : -- : --

Table 6 Movement status of subject B in Field A

State/Posture	Without Monpal		With Monpal	
	Accumulated Time	Continuous Max. Time	Accumulated Time	Continuous Max. Time
Walking	00:36:16	00:06:00	01:05:08	00:02:15
Standing	01:03:03	00:06:50	00:45:24	00:04:19
Sitting	03:04:28	00:13:14	02:55:36	00:24:37
Recumbent	02:32:43	00:32:52	02:30:07	00:31:14
Total Time	07:16:32	-- : -- : --	07:16:16	-- : -- : --

which accurate measurement of data had taken place were isolated for evaluation.

For experimental subject A, the periods of time evaluated on the day when an electric cart was used showed more time spent walking (by 1 hour and 21 minutes), standing (by 26 minutes), and sitting (by 25 minutes) than on the day when an electric cart was not used. On the other hand, time spent reclining was reduced (by 2 hours and 12 minutes). The number of times actions were performed per day showed an increase, with movements from sitting to standing and from standing to sitting nearly doubling from 32 times to 61 times.

For experimental subject B, daily activity times were concentrated in the afternoon, and the periods of time evaluated were shorter than for experimental subject A. Walking time had increased by 29 minutes. The number of times actions were performed per day also showed an increase, with sitting-standing movements nearly doubling from 16 times to 31 times.

Although the electric carts provide users with a convenient mobility, this also becomes a replacement for walking. Therefore some people expressed concern that this would reduce opportunities for walking and lead to diminished muscle strength in their legs. This concern was also found expressed here and there on the proof experiment questionnaires.

Because of the increased risk that diminished motor functions or disabilities will lead to the need for nursing care, efforts to prevent “locomotive syndrome” have been proposed. Consciousness-raising efforts are being made so that elderly people will maintain the habit of walking as much as possible and not lose their ability to walk. The possibility that easy availability of electric cart use may

Table 7 LSA scores and usage frequency of subjects

Subject No.	Life-Space Score <Before>	Life-Space Score <After>	Usage Frequency
1	120.0	102.0	B
2	84.0	24.0	B
3	49.5	63.0	S
4	102.0	120.0	A
5	66.0	84.0	S
6	120.0	—	—
7	84.0	84.0	S
8	120.0	63.0	A
9	120.0	63.0	B
10	22.5	54.0	S
11	120.0	120.0	A
12	18.0	—	—
13	19.5	—	—

go counter to such efforts is probably the reason for those expressed concerns.

The present proof experiments, however, indicate that electric cart use does not simply become a replacement for walking that reduces walking time, but rather that it increases opportunities for mobility. Apart from the two examples shown here, it was also found with all the experimental subjects that more time was spent walking and less time reclining on days when electric carts were used than on days when they were not used. This indicates that electric cart use tends to increase the activities of independent walking and sitting that accompany mobility.

3.3.2. LSA evaluation results

Table 7 shows the life-space scores and frequency of electric cart use in 13 cases among the experimental subjects who used electric carts in field A and were surveyed before and after use. The frequency of electric cart use is shown as S for use several times a week, A for use once a week, and B for use less than once a week.

People who had higher LSA scores before using electric carts tended to show a lower frequency of electric cart use. Conversely, people who had lower LSA scores tended to show a higher frequency of electric cart use. When changes in LSA scores were matched against frequency of electric cart use, it was found that four people had lower LSA scores after electric cart adoption than before, four people had higher scores, and two people showed no change. The four experimental subjects who showed greater frequency of electric cart use were found to have increases in their LSA scores.

3.3.3. Changes in QOL

The SF-36™ results for experimental subjects in field A before and after using electric carts were derived by norm-based scoring (NBS) based on national standard

values for Japan in each of the measures scored. Figure 7 shows the average values in the eight measures for before and after use.

In field A, scores for physical functioning and bodily pain were lower than national standard values by a large margin. Scores for general health, vitality, social functioning, and mental health were generally at national standard values.

The measures of “role physical” everyday role functionality, “role emotional” everyday role functionality, and mental health were found to have risen from before the use of electric carts to after.

3.3.4. Verification in assisted-living facilities for the elderly

Results of proof experiments at nursing care facilities indicate that greater increases in QOL can be anticipated for people who are more capable of operating an electric cart on their own and who have an environment that allows for greater freedom of operation and mobility.

Elderly people who live in assisted-living facilities for the elderly were given Monpals on loan, the effects were verified, and the receptivity to use was confirmed. Figure 8⁽⁶⁾ shows the activity of an experimental subject in field B.

Before his Monpal use, this experimental subject had no choice but to use taxis for mobility within his living area, and he felt stress from being unable to go out immediately whenever he wanted, and from keeping taxis waiting. Once he started using a Monpal by himself, he felt a sense of satisfaction at being able to go out more or less every day, even at the height of summer or during a light rain. The facility manager felt that the way the experimental subject who cooperated as an experiment monitor had become emotionally and mentally more receptive was the most pleasing result of this proof experiment, and expressed gratitude for how the Monpal had motivated the experimental subject and brought about such a dramatic change in his life.

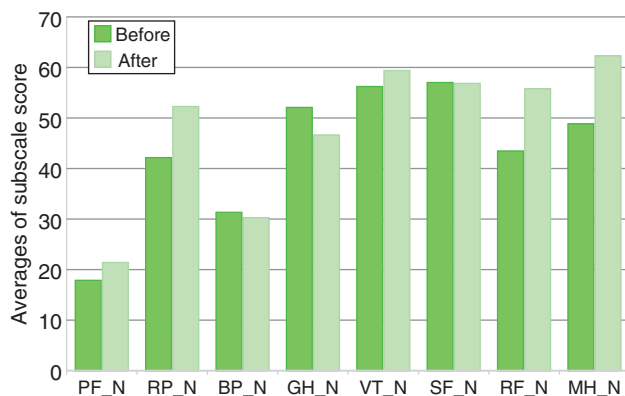


Fig. 7 QOL before-after difference using Monpal in Field A

Active use of the electric cart thus increased the LSA. That in turn was found to have a tendency to contribute to heightened QOL in terms of not only everyday convenience, but also the overall sense of health, vitality, and other such measures.

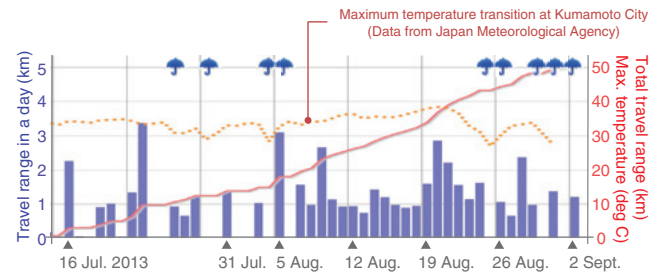
The October 2011 amendment of the Act on Stable Supply of Residences for the Elderly resulted in the establishment of assisted-living facilities for the elderly that offer residents a large degree of freedom in leading their lives, and the supply of such housing within people's living areas has increased. It was inferred, therefore, that such residences have greater need for electric carts.



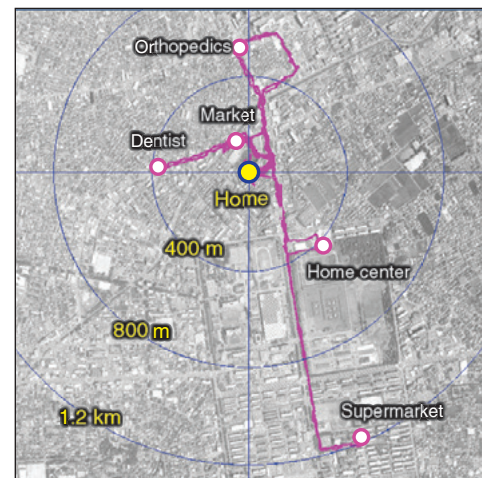
Subject: Mr. K

- Age 86
- Care need level 1: Legs impaired
- Occupancy date : Jun. 2013
- Method of moving around while outside the home: Taxi (almost every day, sometimes twice a day)

(a) Profile



(b) Monpal usage throughout the testing period



The recorded movement locus and circular polar coordinates are aligned with the corresponding section of geospatial photograph from the site (<http://maps.gsi.go.jp/maplibSearch.do>) provided by the Geospatial Information Authority of Japan.

(C) Representative frequent routes of travel

Fig. 8 Survey of subject's travel in Field B

4. Development of Software to Assist People in Going Out Using Electric Carts

Requests were received from demonstration field managers and Monpal user family members for a way to check on the present whereabouts of Monpal users by means of location information obtained using mobile phones. A way was therefore found to do this using Inter Navi, a car navigation service intended for automobiles. This uses a remote monitoring app for smartphones to provide information that supports mobility activity over a wide area and with a high frequency⁽³⁾.

The system was configured to have data generated by the GPS logger used in the proof experiment in collaboration with the Inter Navi server. Figure 9 shows an overview of this system configuration.

The app being provided on this occasion is a Webapp developed using the HTML5 language. This app was adopted because the development man-hours were reduced, the app response speed was increased, and provision of feedback was made easier than before by placing the file with font size and other such settings on the server. The provided app has two functions as described below.

The first is a current position map that shows location information for the Monpal being managed from a base location defined by the facility or family (hereafter, managers). The second is an operation status display (Fig. 10) that allows the Monpal operation status, battery state of

charge, and driving history to be tracked.

The current position map has an additional function that, for example, allows managers to set a destination on the Inter Navi screen. Using that, managers can check the current position by acquiring it from the GPS logger by smartphone. They can register that location with the app so that it is there in advance when they need to go there to pick up the user, and they can use the Inter Navi service to get there.

Questionnaires were administered at facilities that were cooperating with the proof experiment after development of the app had been completed, as well as at the time of the in-town shared use field tests. Managers were asked about how it felt to use the remote monitoring app, and whether using the app gave them a sense of security from remotely monitoring the users. Out of 22 respondents, 19 answered in the affirmative. When asked whether an activity history could serve as an index for health management, nine out of 12 responded in the affirmative. When asked if, in the event that activity history was used as an index for health management, Monpal use could serve to stimulate an increase in frequency of going outside the home, eight out of 12 responded in the affirmative. A comprehensive look at the questionnaire results indicated that the remote monitoring app could serve as a tool to assist with mobility outside the home.

Meanwhile, there was another issue that emerged from the questionnaires. This was the need first of all for an enhanced user interface that would be easy to use even for people who do not, because of their age group, use smartphones on an everyday basis. Measures were also needed to enable people to master the essentially broad applications involved, even in courses on the use of smartphones and apps.

5. Conclusion

As indicated by these proof experiments, greater enhancement of QOL can be anticipated for people who have the capability to operate electric carts on their own and who have an environment that allows them to freely operate the electric carts and be mobile.

For elderly people who find their physical abilities deteriorating and their living area becoming constricted, developing social systems that utilize IT together with personal mobility that allows freedom in operation so as to encourage those elderly people to move outside their homes contributes not only to their individual QOL but also to the formation of a society with higher QOL.

Acknowledgements

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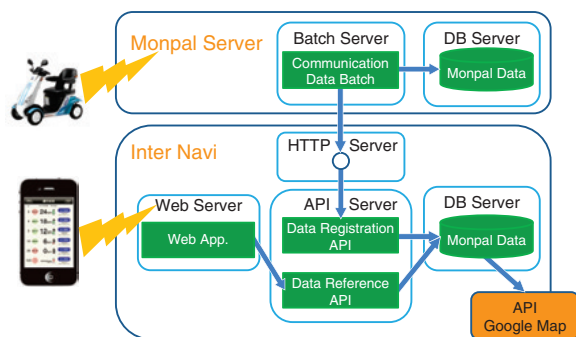


Fig. 9 General diagram of system configuration



©2011 Google-Map date ©2011 ZENRIN

(a) Menu screen (b) Actual location (c) Operation status

Fig. 10 Display of tracking monitor on smart phone

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Research of the Technology for Reducing the Load of Yarding

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ABSTRACT

Satoyama provide a variety of services and are symbolic of the coexistence of people with nature, so their conservation is to be desired. HELLO WOODS' is a facility that Honda maintains as a place for people to experience nature. Here, we perform conservation initiatives and receive benefits from the woods in return.

This research uses HELLO WOODS' as a case study in Satoyama conservation. Technology was developed to reduce the environmental burden of yarding; that is, moving trees after they have been logged (cut down).

This technology uses a small crawler-type power carrier and has an unmanned carrier function, overturn suppression function through sloping areas and loading/unloading function.

An experimental carrier was built and used to confirm that each function worked as required. These functions could reduce the burden created by yarding and help to conserve Satoyama.

1. Introduction

Since ancient times, humans coexisted with the natural world by taking resources from nature in moderation and maintaining sustainable ecosystems. The forests that people maintained for the sake of their livelihoods were referred to as Satoyama. Satoyama provide a number of services: fuel and other resources, biodiversity, disaster reduction, cultivation of water resources, environmental conservation, scenery, and a place for environmental education.

However, since the use of fossil fuels became widespread in the period of high economic growth, people began to leave the Satoyama unmaintained, as they did not feel that the Satoyama's services made them worth maintaining from an economic perspective. The Satoyama gradually changed as a result, forming dark forests thick with brush and filled with bigger trees.

In collaboration with workshop participants, Honda has taken part in Satoyama conservation initiatives at HELLO WOODS', a facility, located within Honda's Twin Ring Motegi, where people can come to experience nature. These initiatives realize Satoyama services by keeping up the cycle of raising trees and then logging them for use. Satoyama are maintained as young, bright forests as shown in Fig. 1, because they are periodically logged. The logged trees are then used as firewood, charcoal, and the like. Conservation tasks include practices that establish the forest like cutting grass and vines as well as harvesting work like tree logging and yarding.

Out of all of these, the most burdensome task is yarding.

The purpose of this research is to reduce the burden of yarding when performed by ordinary persons with little yarding experience. The aim was to establish technology to lower the burden of yarding, using HELLO WOODS' as a case study. If a technology with lower burden were to become widespread, it would allow more people to get involved in conservation initiatives in Satoyama other than HELLO WOODS' and more Satoyama could be conserved.

This paper suggests functions to reduce the burden of yarding, gives an overview of an experimental carrier that the



Fig. 1 Satoyama in HELLO WOODS' (Provided by HELLO WOODS')

* Fundamental Technology Research Center

researchers built in order to meet established requirements, and discusses how the technology and performance were verified.

2. Work Analysis and Targets to Achieve

Yarding refers to transporting harvested trees (i.e. logs) from the logging area to the place where they are collected (called a log yard). For this study, the researchers began by examining the nature of the work and the burden that it creates at HELLO WOODS'.

The log yard at HELLO WOODS' uses a small crawler-type carrier, called Honda Power Carrier. At the logging area, logs are cut into appropriate lengths in a process called bucking. The bucked logs are manually loaded onto the Honda Power Carrier, then a person operates the Honda Power Carrier to make it travel through the logging area and over logging roads, finally unloading the logs at the log yard. Annually, 0.4 ha of Satoyama trees harvested this way at HELLO WOODS' is yarded by repeating the above process again and again.

The researchers' study found that yarding creates three types of burden. The first is that forest roads are traveled over repeatedly in order to carry the logs. As they operate the carrier, human operators have to walk back and forth over sloping logging roads that were built on uneven terrain. The longer the distance, the more time and human strength the process requires. The second burden is that carriers traveling on sloping ground are susceptible to overturning. To help prevent overturning while traveling over the roads, carriers can only be loaded with less than half their maximum capacity of logs, which increases the number of trips required. The third burden is the loading and unloading of heavy logs. Logs weighing between 20 and 35 kg make up about half of this burden by weight. On a questionnaire given at the workshop, many respondents said that loading and unloading logs was the most physically challenging aspect of the work. To alleviate the three burdens above, the objective was to build three functions as shown in Fig. 2: the use of unmanned carriers, overturn suppression, and loading and unloading support. These are described below.

(1) Unmanned carrier

Unmanned carrying allows workers to do other tasks and is very efficient. It also reduces the physical burden on the worker, who no longer needs to walk long distances.

This is done by a carrier that automatically travels a pre-established route as it carries the logs. Because trees in a Satoyama create interference that makes GPS unusable, this was done in two ways. The first is electromagnetic navigation. This approach assumes that the carrier will travel an unchanging route between two log yards. It will be able to do so even in rain or snow. The second approach is visual navigation. This is anticipated when carrying logs from the logging area, which changes every year. With this approach, routes can be changed with minimal work.

(2) Overturn suppression

With the use of overturn suppression, loading the carrier

with many logs for travel through sloping logging areas reduces the number of trips to and from the log yard. It also minimizes the number of detours around sloping areas. These increase work efficiency.

The shape of the crawler's footprint on the ground makes it more unstable from side to side than from front to back. Therefore, this function was designed to reduce the likelihood of overturning to the side. Additionally, Satoyama contain ancient roads referred to as "three-shaku roads," which are just 90 cm wide.

Building wider roads would be environmentally damaging, so this is not an appropriate option if Satoyama conservation is the goal. The researchers therefore worked to suppress overturning to either side while maintaining a size small enough to let the carrier travel over these narrow roads. To this end, the carrier was built with a swing drive mechanism to suppress overturning. This lets the carrier balance its center of gravity as it travels.

(3) Loading and unloading support

A small crane is used to load and unload logs. Although this can reduce the physical burden, operating the crane is complex: ordinary controllers like levers and buttons are used to move the crane in three dimensions (back and forth, up and down, left and right). A person not used to such controllers will work much less efficiently. There is also a risk of accidents if controllers are operated incorrectly.

The function was therefore developed to enable easy operation with an interface that directly manipulates the movement of the logs, and to make it easy for even those unaccustomed to yarding work to load and unload without any great drop in efficiency.

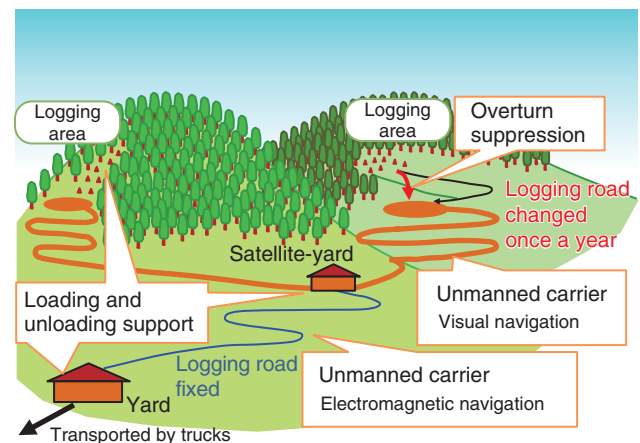


Fig. 2 Three functions for logging in Satoyama

3. Experimental Carrier and Verification Items

This part discusses the experimental carrier used to verify the functions, and the items that were verified.

Table 1 Experimental carrier specifications

	Experimental carrier	Honda Power Carrier HP500
Length	2090 mm	2030 mm
Width (cargo bed)	850 mm	Max. 900 mm
Surface area of the grounding of unilateral crawler belt	180 mm × 694 mm	180 mm × 694 mm
Weight of carrier and max. load	703 kg	542 kg
Max. velocity (forward)	2 km/h	4.3 km/h
Max. angle of rise	20°	15°
Type of drive of crawler	2 Motors	Engine
Power source	Li-battery	Gasoline

3.1. Experimental Carrier

The experimental carrier was based on the Honda Power Carrier HP500. It was given an electric drive system and equipped with mechanisms, sensors, and drive systems for the three functions. It also has a system controller to control all functions. Specifications of the experimental carrier equipped with the three functions are given in Table 1. The maximum velocity while traveling takes into account the speed while yarding in HELLO WOODS'.

Figure 3 is a diagram of the electric system of the experimental carrier with the three functions, and Fig. 4 is a photograph of the experimental carrier that the researchers built.

The crane for loading and unloading support is located next to the cargo bed and has a boom long enough to allow it to clamp onto logs around the bed. While the experimental carrier is traveling, the boom folds up and is stowed at the side of the vehicle. The camera used for visual navigation is located opposite the cargo bed, with an arm

in between, to help prevent it from making contact with the logs. During unmanned carrying, the camera side is in front as the carrier travels.

3.2. Verification Items

To test the unmanned carrier function, it was verified whether the carrier can travel over a test course within the error requirements described below. To test overturn suppression, it was verified whether the carrier can travel the test course while loaded. To test loading and unloading support, it was verified whether the amount of time needed to load and unload with this function satisfies the requirements described below.

Figure 5 shows the test course that was set up to test the unmanned carrier and overturn suppression functions. The course reflects the characteristics of roads used to perform yarding in HELLO WOODS'. A circuit about 50 m long was used to check the unmanned carrier function. A traverse road surface was separately laid out to verify overturn suppression.



Fig. 4 Experimental carrier

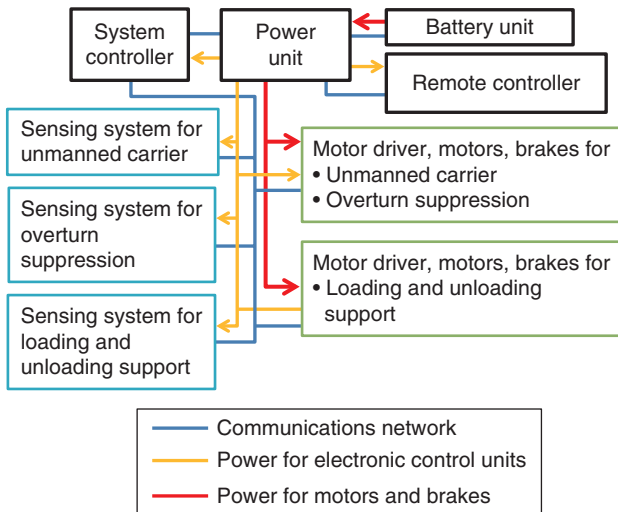


Fig. 3 Electric system of experimental carrier

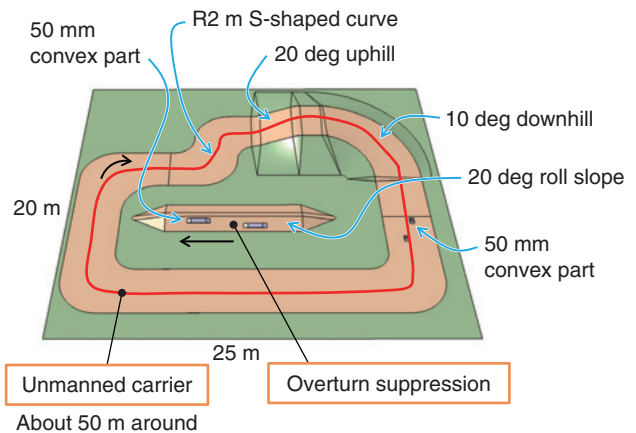


Fig. 5 Test course

4. Major Technologies and Achievements

4.1. Electromagnetic Navigation

The logging road over which the carrier traveled was 900 mm wide, with maximum roll angle of 7° and maximum surface asperity of ±50 mm. These values were based on “three-shaku roads” and the road surface conditions found in HELLO WOODS’. The same conditions were used for testing visual navigation, as described below.

Because the carrier travels over uneven terrain, the sensing system had to work not only with lateral but also vertical positional change between the guide cable and onboard sensors. The usual technique for dealing with positional change, which focuses on lateral positional change (as used in golf carts), is greatly affected by the detection distance to the guide cable in the lateral direction as a result of vertical positional change. For that reason, the experimental carrier is also designed to deal with vertical positional change.

4.1.1. Functional requirements

During unmanned carrying, the crawler, which is 600 mm wide, travels over a road that is 900 mm wide in the straight sections, as shown in Fig. 6. Therefore, the maximum allowable position error during travel is ±150 mm. The minimum radius at corners on the logging road was set at a turning radius (R) of 2 m in the center of the road. At R 2 m points, 1100 mm was set as the logging road width, which is the width that the Honda Power Carrier is able to travel while working conventionally. Table 2 shows the maximum allowable gap between the position of the guide cable and the center of the road; the maximum position estimation error for the experimental carrier in respect to the guide cable; and tracking error. The velocity requirement is the ability to travel at least 2 km/h on straight sections.

4.1.2. Technology achieved

As it traveled, the experimental carrier used its magnetic sensors to detect the magnetic field generated by the guide

Table 2 Required range of position error

No.	Factor of position error from center of road	Required range of position error from center of road [mm]	
		Straight road	R2 m curved road
1	Gap of laid cable and center of road	±50	±120
2	Position estimation (Included in No.3)	±60	Not setting
3	Trajectory tracking control	±100	±130
Lateral margin (No.1+No.3)		±150	±250

cable laid down the middle of the logging road, thus estimating its own position. The carrier stopped when it detected a stop position, which was created by placing a magnetic field shield board over the guide cable.

The carrier’s magnetism detection system consisted of two magnetism sensors, one vertical and one horizontal, whose axes were perpendicular to each other. This arrangement allowed the system to detect the distance to the guide wire in both the lateral and vertical directions. This configuration is called a cross sensor module.

The guide cable contained transmitters that produced the same current pattern repeatedly at regular cycles. Each time this current pattern occurred, an induced electromotive voltage peak induced in the coil in the magnetic sensor was detected. Combined vector V_P of induced electromotive voltage peak as detected by the vertical sensor (V_{VP}) and induced electromotive voltage peak as detected by the horizontal sensor (V_{HP}) is inversely proportional to distance from guide cable (r) and proportional to the peak of first-order differentiation of current, as in Eq. (1), as Ampere’s law makes clear. Here, V_{VP} and V_{HP} are the values shown in Eq. (2), and horizontal distance y and height z are derived as in Eq. (3). The value of constant C as used in Eqs. (1) through (3) was identified by experimentation. The two experimental carriers built showed some magnetic field distortion owing to variability in the metal of the vehicles, so detection results were not the same. Therefore, C was identified so that the amount of error in detection distance would be the same in both carriers.

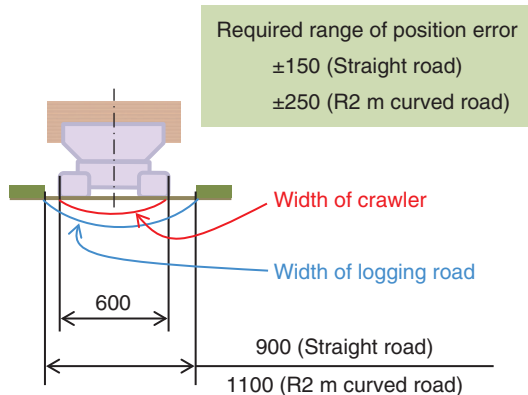


Fig. 6 Width of carrier and logging road

$$V_P = \frac{C}{r}, \quad C = \frac{\mu NS}{2\pi} \cdot \left(\frac{di}{dt} \right)_{\text{peak}} \quad (1)$$

$$\begin{cases} V_{VP} = \frac{C}{r} \cdot \frac{y}{\sqrt{y^2 + z^2}} = \frac{Cy}{y^2 + z^2} \\ V_{HP} = \frac{C}{r} \cdot \frac{z}{\sqrt{y^2 + z^2}} = \frac{Cz}{y^2 + z^2} \end{cases} \quad (2)$$

$$\begin{cases} y = \frac{CV_{VP}}{V_{VP}^2 + V_{HP}^2} \\ z = \frac{CV_{HP}}{V_{VP}^2 + V_{HP}^2} \end{cases} \quad (3)$$

Cross sensor modules were affixed to the front and back of the carriers as shown in Fig. 7 to control travel. Each module provided y , the horizontal distance between the guide cable and vehicle center; and φ , the angle between the guide cable and vehicle. The turning velocity Ω_c^{ref} was given and forward velocity V_c^{ref} was set at a uniform value to calculate the lateral crawler velocity.

The carrier automatically stopped when the value of detected height z from Eq. (3) was detected as exceeding an established threshold value. This occurred when the magnetic field reaching the cross sensor module was weakened by a magnetic field shield board, as shown in Fig. 8.

4.1.3. Verification results

Table 3 lists error factors associated with cross sensor modules when they are mounted on carriers and the maximum error as measured during testing of properties.

Table 3 Tolerances measured about each factor

No.	Factor of position estimation error	Error estimate [mm]
1	Slope of cross sensor module (roll 10 deg, pitch 10 deg, yaw 20 deg)	± 12
2	Electromagnetic strain (max measured value of 2 carrier-bodies and 4 sensors)	± 28
3	Measurement error in calibration	± 5
4	Electromagnetic noise	± 4
5	AD convert and arithmetic error	± 2
6	Others	± 3

Table 4 Position error of automatic traveling

	Straight road [mm]	R2 m curved road [mm]
Required range of position error	± 100	± 130
Test result	± 35	± 43
Consider a production tolerance of carrier and sensor	± 63	± 71

The maximum amount of error of mounted cross sensor modules was ± 54 mm, which is the sum of all errors.

The carriers were able to travel over the test course with this technique. Figure 9 shows a carrier traveling with navigation by electromagnetic navigation. Because the vehicle was traveling on the same course as used with visual navigation, visual navigation marks as explained in the next section were placed along the course. The amount of error during trajectory tracking control was found by using a ruler to measure the distance between the crawler track and guide cable and converting. As Table 4 shows, traveling results satisfied the allowed error requirements indicated in Table 2, No. 3. The carriers even satisfied the requirements when magnetic distortion caused by vehicle variability is considered.

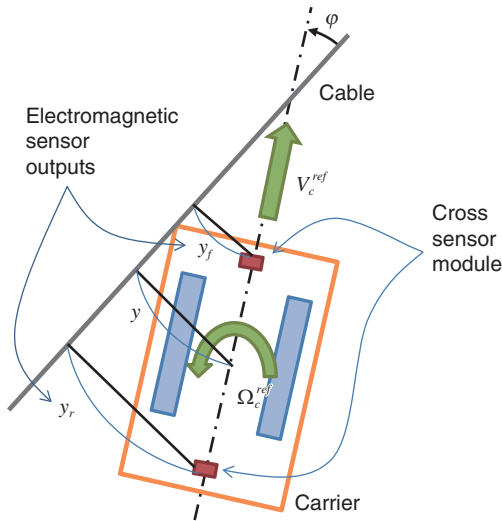


Fig. 7 Position of carrier and sensor output

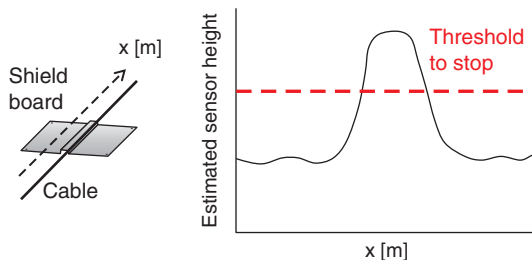


Fig. 8 Automatic stop by shielding magnetic field



Fig. 9 Automatic traveling by electromagnetic navigation

4.2. Visual Navigation

From sunrise to sundown, and throughout the four seasons, the optical environment of the Satoyama will vary, as will the condition of the plants that provide landmarks. Therefore, it is a challenge to achieve very robust position estimation. For that reason, the technique used was to set artificial marks around the course to help ensure that the carrier reliably detects its position; that is, its position in respect to those marks. Additionally, automatic traveling by teaching playback was used to enable the carrier to travel any trajectory: ordinary travel, stopping, switchbacks, and so on.

4.2.1. Functional requirements

The traveling precision requirements in respect to road width were the same as with electromagnetic navigation. Table 5 shows the maximum error allowed for each factor. Allowed errors during teaching travel were decided based on the operability of the experimental carriers. Additionally, position was estimated both during teaching travel and trajectory tracking control, and therefore the visual system position errors of the two, as in the table below, are added together, making double that amount.

4.2.2. Technology achieved

In order to achieve stable estimates of position, this technique combines results of position estimation using visual sensors with results of position estimation with internal sensors.

The locations of marks for estimating position by visual sensor were first tentatively decided based on camera angle of view and the form of the course. Then, the experimental carrier was allowed to travel the course, and as it did so the researchers confirmed which positions it was able to detect, and they adopted those positions. Estimating position with visual sensors requires that at least two mark positions are detected at all times. As Fig. 9 shows, marks were placed alternately on the left and right sides of the road in straight lines with intervals of about 0.7 m. At the curves, they were placed on the outer side at intervals of about 0.9 m. Retroreflective material was applied to the marks at a certain rate in the long direction. The infrared beam from a projector was reflected toward the camera at high intensity.

The visual sensor was a stereo camera using a difference camera⁽¹⁾, which made it possible to separate light from the projector from light in the environment. As a result, the system was able to extract the mark image in a short period of time, using only light from the projector. To enhance the intensity of reflected light, it is necessary to reduce the distance between projector and camera. One projector was placed on each side to correspond to the left and right cameras. Stereo cameras can offer enhanced precision when they have longer baselines, and in this case, the length was set at 0.3 m, the farthest distance they could be placed apart on the carrier.

The major processes that happen when estimating

Table 5 Required range of position error

No.	Factor of position error from center of road	Required range of position error from center of road [mm]	
		Straight road	R2 m curved road
1	Operation by user in teaching phase	±50	±100
2	Position estimation in teaching phase (Included in No.4)	±25	±25
3	Position estimation in playback phase (Included in No.4)	±25	±25
4	Trajectory tracking control	±100	±150
Lateral margin (No.1+No.4)		±150	±250

Table 6 Features of position estimation by each sensor

	Processing Time	Noise	Drift
Position estimation by visual recognition	Large	Large	Small
Position estimation by inner sensors	Small	Small	Large

position with visual sensors are: (1) reading the image, (2) detecting the marks, (3) performing stereo operations, (4) finding the uncorrected position, (5) correcting the position, and (6) outputting the corrected position.

Marks are detected by the visual sensors, which are used in combination with the technique of calculating position. Acceleration and angular velocity sensors and a crawler velocity detector (i.e. internal sensors) are also used, then position is estimated by integration. Table 6 shows features of position estimation by each type of sensor. The table suggests that visual sensors offer better position estimation in the low-frequency range while internal sensors do better

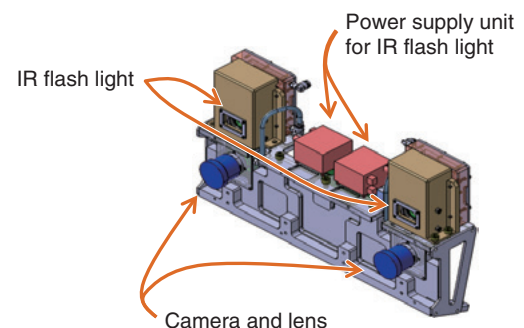


Fig. 10 Stereo difference camera unit

in the high-frequency range. To take advantage of these features, the position estimation system designed here uses a low-pass filter on carrier position as found by the visual sensors and a high-pass filter on carrier position as found by the internal sensors, and combines the two. This is illustrated in Fig. 11. The result is stable position estimation.

During trajectory tracking control, crawler velocity during teaching travel is used as a feedforward term, while the deviation between travel trajectory during teaching travel and current position is used as a feedback term, to calculate velocity command values for the left and right crawlers.

4.2.3. Verification results

First, the precision of the visual system's position detection was evaluated. Because the system is both a teaching and trajectory tracking control system, tracking precision in respect to the teaching trajectory is required, but absolute locational precision is not important. For that reason, the visual system is evaluated according to the variance in detected position (i.e. the visual system position error) when the carrier travels the same trajectory. Moreover, this variance is attributable to variance in visual sensor output.

Four visual system output variables are used to verify precision: X, Y, Z, and θ_z . θ_x and θ_y , which are not used for control purposes, are excluded. Thus, the amount of displacement was checked by setting the camera system upon an X - Y - Z - θ_z table as shown in Fig. 12, and moving/rotating the table as the reflective marks were being detected. Figure 13 shows the visual system position error on the Y axis when there has been camera displacement along the Y axis at the furthest position on the X axis at which detection is assumed to occur. These results show

that, under the strictest conditions, the visual system position error (3σ) is ± 7.7 mm, meeting the pre-established requirement of ± 25 mm.

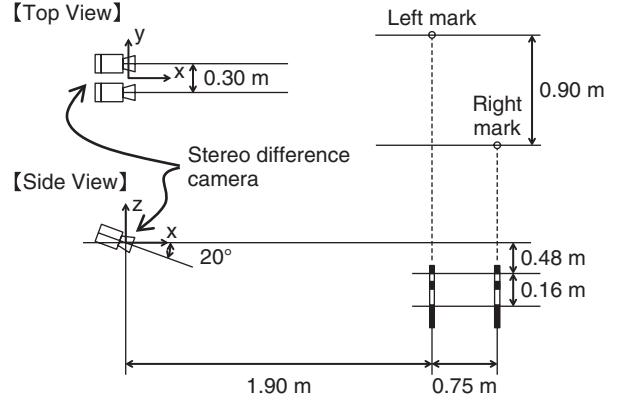


Fig. 12 Bench for measurement of locational error of visual recognition

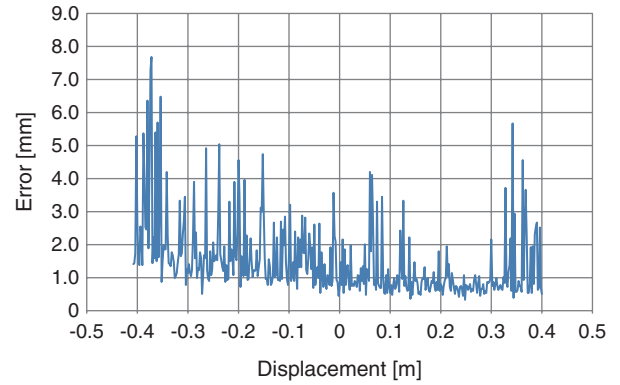


Fig. 13 Locational error of visual recognition

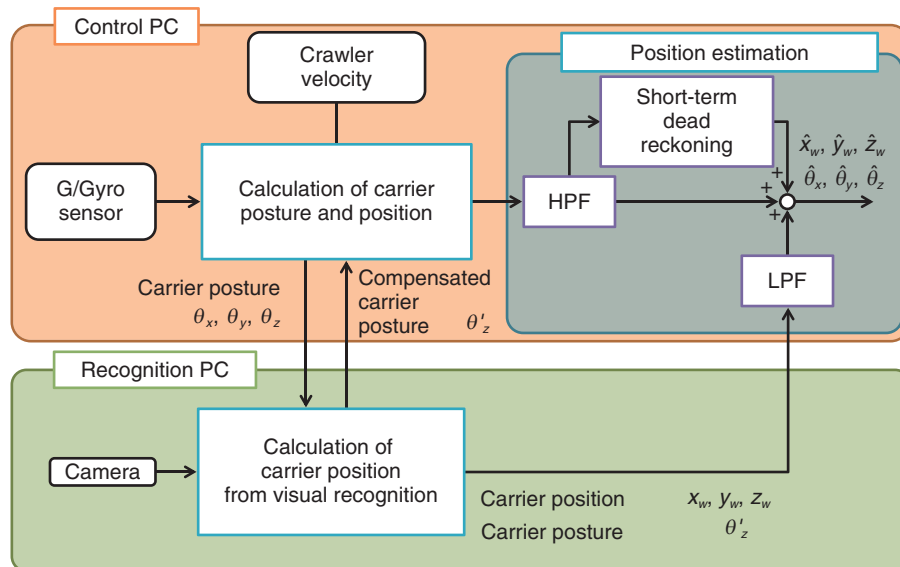


Fig. 11 Process of integration position estimation

Table 7 Position error of automatic traveling distance from teaching orbit

	Straight road [mm]	R2 m curved road [mm]
Required accuracy	± 100	± 150
Test result	± 15	± 40

The carriers were able to travel over the test course with this technique. Table 7 shows the deviation from the teaching trajectory during trajectory tracking control. The results showed that the carrier satisfied the allowed error requirements indicated in Table 5, No. 4.

4.3. Overturn Suppression

The overturn suppression technology assumes that the carrier will mainly travel through the logging area. The maximum slope for the carrier to travel in the logging area was set at 20° . It was assumed that on slopes of greater than 20° , workers would roll the bucked logs until they come to a 20° slope.

4.3.1. Functional requirements

The functional requirement was that the carrier be able to travel, while loaded, on road surfaces with asperity of ± 50 mm maximum on slopes with a maximum roll angle of 20° .

4.3.2. Technology achieved

For the sake of attitudinal stability, the carrier consists of two parts: the chassis and cargo bed. A lateral swing drive is activated to maintain balance in the center of gravity. A slope sensor affixed to the cargo bed detects the cargo bed's roll angle. Feedback control is used so that the roll angle goes to 0° , that is, horizontal.

To maintain balance in the center of gravity between left and right and ensure travel stability, the swing drive mechanism's center of rotation has to be close to the road surface. As Fig. 14 shows, when there is a high center of rotation, the center of gravity in the cargo bed does not

change very much. Even if swing drive is activated, the zero moment point (ZMP) is likely to go beyond the tread as in (1) so that the overturn suppression function does not work. The ZMP is the point over the road surface where the horizontal component of the combined moment of inertia and gravity generated by motion around that point is zero. In (2), even if the ZMP is within the treads, there is a difference in the amount of grip force between left and right, making it a challenge for the carrier to move straight ahead. In (3), the cargo is susceptible to collapsing as a result of the axis of rotation swinging left and right.

Thus, the experimental carrier was built as in Fig. 15 with a multi-joint mechanism and an arched rail to keep the center of rotation low. As a result, the virtual center of rotation within the swinging axis was 90 mm from the road surface.

4.3.3. Verification results

This technique made it possible for the carrier to travel 1.5 km/h on a road with 50 mm bumps and roll angle of 20° . Figure 16 shows the upper-side crawler traveling over a 50 mm bump on a 20° slope.

ZMP was used to evaluate attitude stability. Figure 17 shows a model of the ratio of ZMP on tread during travel. The experimental carrier's tread was set at 420 mm, which is the distance between the longitudinal centers of the left and right crawlers. When the ZMP is at the center of one of the crawlers, the ZMP's positional ratio y_{ZMP} is 1.

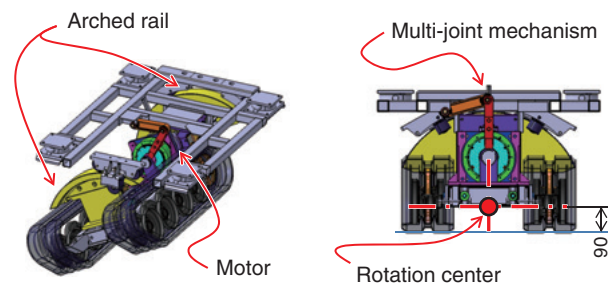


Fig. 15 Swinging mechanism with arched rails

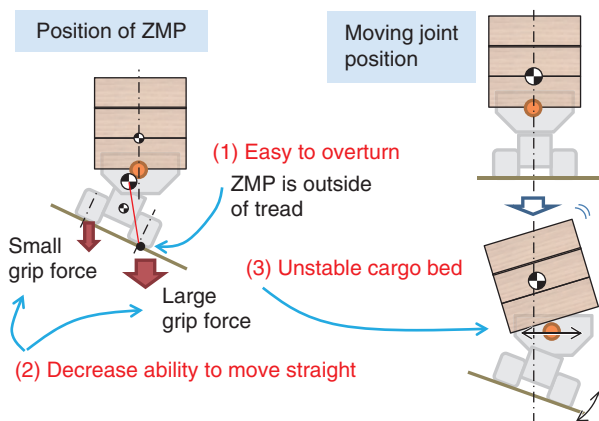


Fig. 14 Harmful effect of high position of joint



Fig. 16 Traveling on slope using overturn suppression

Figure 18 shows travel data from the experimental carrier with overturn suppression function together with results of simulation using vehicle parameters assuming that the vehicle does not have this function. In the case of the carrier with overturn suppression, the ZMP stays within the tread range, indicating that there is sufficient stability. The carrier without overturn suppression could possibly overturn because the ZMP fluctuates beyond the tread range.

4.4. Loading and Unloading Support

For the purpose of this study, the maximum log weight was set at 35 kg, because the survey results indicated that logs weighing 35 kg or less make up 80% of the total weight of logs loaded and unloaded. Also based on survey results, log length was set at 70 cm. Logs weighing more than 35 kg were to be bucked to shorter lengths to keep their weight at 35 kg or below. The requirement for slope of roads on which the carrier would work was set at a maximum of 20°.

4.4.1. Functional requirements

A requirement was set for loading and unloading time, because one objective of this function is easy operation.

Results of the workshop survey indicated that the average time required to load or unload a log is 13 seconds. In consideration of the fact that other objectives are to alleviate burden and help prevent any great loss of work efficiency, the requirement for allowable loading and unloading time was set at 20 seconds per log. Moreover, because the other two functions enable efficiencies during transportation work,

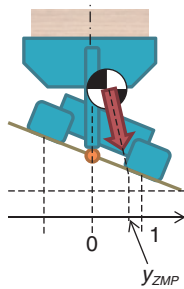


Fig. 17 Ratio of ZMP on tread

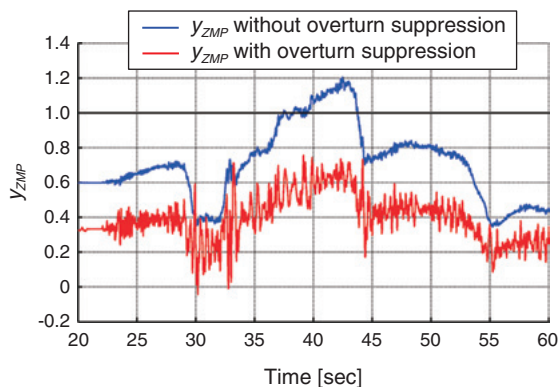


Fig. 18 ZMP on traveling on slope

it is still possible to achieve greater efficiency overall, even if there is some loss of efficiency as a result of this function.

4.4.2. Technology achieved

Loading and unloading with the small crane are performed on slopes, so the boom has to be able to turn and move up and down. A motor was provided for each of these movements. Reeling the wire in and out is also done by means of a motor.

A stable hold can be maintained if the tip of the boom supporting the wire follows a grip held by the operator, staying over it. Data on the wire's inclination is input and the boom position is controlled to track the grip so that the boom follows the grip and the wire hangs straight down. A method that refers to the velocity and force at the grip would not be appropriate here, because twisting of the wire makes it challenging to determine the attitude around the yaw of the grip. Moreover, with a method that refers to the force of the wire on the boom tip, gravitational force cannot be separated from force generated by user operation of the equipment when using it on a slope. Therefore, two components of the relative angle with the wire and the vertical direction (i.e., pitch axis and roll axis) are taken as input values for following control. The boom's pitch axis target angle is calculated based on the relative angle of the pitch axis, while the boom's yaw axis target angle is calculated based on the relative angle of the roll axis, and thus there is feedback control. At the same time, the amount of wire reeled out is controlled in conjunction with the boom pitch drive so that the grip is at a constant height. Additionally, the system is designed so that following control only occurs when the operator pushes a button on the grip. This helps prevent unintended activation of the boom. The grip also has a controller to move the boom up and down, which is a way of reeling the wire in and out independent of following.

The mechanism for sensing the inclination of the wire is shown in Fig. 19. It was designed so that the wire would form a tangent in relation to the pulley at all

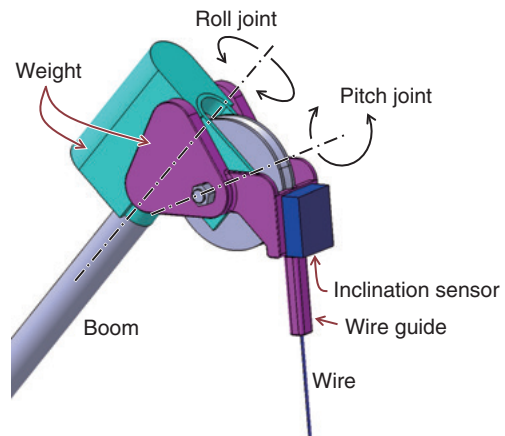


Fig. 19 Guide mechanism for sensing inclination of wire

times so that the inclination of the wire could be detected with two degrees of freedom and the impact of the wire's tension could be reduced. Moreover, to reduce self-induced vibration by the pendulum element resulting from the mass of the wire guide and inclination sensor, weight was allocated to each axis so that the center of gravity was positioned close to the axis of rotation.

Furthermore, since the crane was to hold logs 70 cm long, the range over which logs can be picked up was extended 400 mm beyond the cargo bed perimeter, and the boom length was set at 2020 mm, as shown in Figs. 20 and 21.

4.4.3. Verification results

This technique made it possible to load and unload logs through direct operation. Figure 22 shows an operator performing the work with the crane.

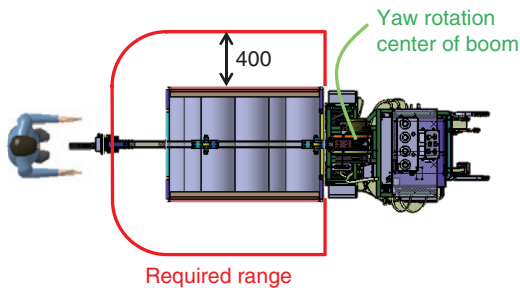


Fig. 20 Required range for picking up logs

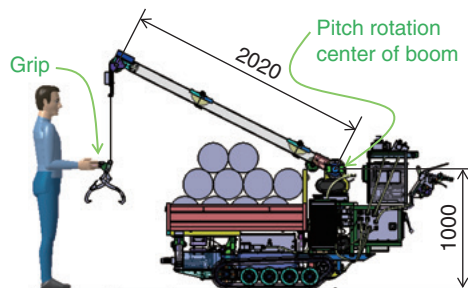


Fig. 21 Crane design of loading and unloading support



Fig. 22 Loading and unloading support

Additionally, in order to determine how well this function performs, the researchers found the shortest possible time needed to load and unload. The prescribed actions of loading and unloading are as described below and shown in Fig. 23. (a) As the work begins, four logs are on the ground around the carrier, (b) the logs are loaded into the cargo bed, and (c) the logs are placed side by side next to the carrier. For both the loading and unloading stages, the work was divided into four steps and the time necessary for each was found: (1) move the grip to the log, (2) clamp onto the log, (3) move the log to the desired place, and (4) release the clamp on the log. For verification, four individuals each performed these tasks two times, and their time was taken.

The shortest sum of time needed to perform all the steps during loading was 17 seconds, which was also the shortest sum of time needed to perform all the steps during unloading. This clears the requirement of 20 seconds.

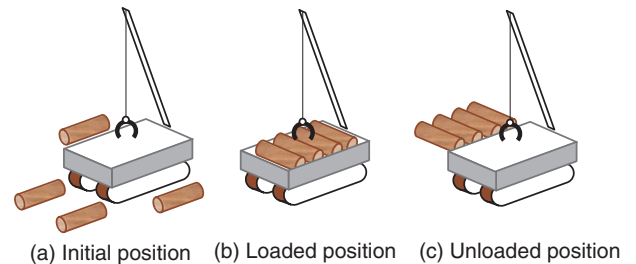


Fig. 23 Steps for measurement time of loading and unloading

5. Expected Benefits

The above functions and the requirements that they meet should reduce the burden of yarding work.

The researchers calculated the total work time (from start to finish of yarding work) and the worker hours (found by multiplying the number of workers with their work time) when the three functions were used. The calculation assumed that the work would be done by two workers and one carrier. The logging site was on 0.4 ha of sloping ground. The carrier traveled 2 km/h from logging area to log yard over a road 300 m long each way. The carrier made repeated trips back and forth. The time needed to perform each job and the amount carried were set based on the workshop survey, then calculations were made that considered the loss of efficiency owing to loading and unloading support. A carrier with the three functions is predicted to reduce total work time by 44% and total worker hours by 51% compared to a conventional carrier.

Moreover, total travel distance of the carrier over the logging road was 303 km with the conventional technique. The unmanned carrier therefore greatly reduces the physical burden on workers, who now do not need to walk that

distance. Even loading and unloading support does not greatly increase work time, but it does reduce the physical burden during loading and unloading work.

6. Conclusion

Using HELLO WOODS' as a case study, the researchers proposed three functions—use of an unmanned carrier, overturn suppression, and loading and unloading support—to conserve Satoyama and reduce the burden of yarding. Based on the HELLO WOODS' case study, they confirmed that the experimental carrier they developed met its requirements. Following is an overview and a description of the major achievements of each function.

(1) Unmanned carrier

When using electromagnetic navigation, equipping a carrier with a cross sensor module capable of dealing with uneven terrain, together with a guide cable on the road surface, allowed the carrier to travel and stop automatically.

When using visual navigation, a system equipped with a stereo difference camera together with marks around the course made it possible for the vehicle to travel by teaching playback.

(2) Overturn suppression

By using an arched rail to effectively stabilize attitude, the researchers achieved an attitude stabilization mechanism that controls the tilt of the cargo bed.

(3) Loading and unloading support

To make crane operation easy, the researchers built a mechanism that detects wire inclination and an activation control system that keeps the wire vertical at all times.

A test course was laid out for this research and used to find the basic performance of each function. Actual yarding sites present complex environments, so it is predicted that various issues will occur. Verification of whether the configuration and requirements associated with each function are appropriate will have to be done at actual yarding sites.

Acknowledgments

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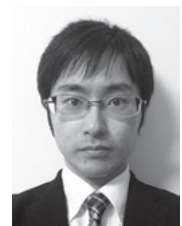
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Particles Wear-Out Behavior of Reciprocating Engine Crankshaft During the Initial Running-in Operation

Kenji MATSUMOTO*

ABSTRACT

Reciprocating engines are popular in automobile and small airplane applications, and their reliability relies on the operating life of the crankshaft journal bearings.

Traditionally, reciprocating engines have been designed based on an assumed journal wear rate, which is calculated on the basis of the maximum load, maximum velocity, average project area and maximum oil temperature over the entire sliding surface of a journal bearing. A prediction of journal wear rate suggests that engine parts have some allowances to carry loads. From the perspective of energy conservation, it is desirable to minimize, if not eliminate, such gap. However there have been few attempts to examine the real loads on engine journals. Therefore it may be worthwhile to examine engine parts for excessive margins incorporated in the conventional design of reciprocating engines.

This research is intended to propose a method for measuring the load and the pressure distribution on the journal bearing surface with the intention of modernizing the engine design on the basis of tribological data rather than assumption. From this study, the reliability of engine bearings will increase if the wear particles generated during the initial running-in operation.

1. Introduction

As reciprocating engines have been used for almost a century, automobile engine manufacturers have accumulated a lot of experience and know-how related to engine design. For this reason, reciprocating engines have been designed on the basis of past experience and such established practices have been accepted without question.

The wear of the metal journal bearings in a reciprocating engine is one of the most important and critical issues which determine the reliability and product life of engines. Therefore it is important to study both the pressure distribution of oil films on journals, which carry loads, and their wear. In the past, there was no technology to successfully measure the pressure distribution of oil films on metal journals while engine in a moving vehicle is running⁽¹⁾⁻⁽³⁾. Therefore the author have developed a thin film sensor to measure the load distribution on metal journals⁽⁴⁾⁻⁽⁸⁾.

This study consists of three experiments. The first experiment was the measurement of the load on journals in a general aviation reciprocating engine using newly developed thin film sensors. The second was the measurement of the wear of the journal bearing using a

simulation test apparatus whose load distribution was controlled by servo valves to simulate the data obtained by the first experiment. The third was the measurement of the wear of a general aviation engine journal bearing for comparison with the data obtained in the second experiment.

It has been known from our experience that both wear patterns and wear rates differ for Start-stop driving conditions and Steady-state driving conditions. But there has been no study, within our knowledge, that identifies the wear patterns and wear rates under Start-stop driving conditions and Steady-state driving conditions independently, because wear particles generated under Start-stop driving conditions are carried over to the Steady-state driving stage and those particles cause excessive wear unless each test is conducted independently. Therefore this research was conducted in two stages. The number of wear particles was measured during Start-stop operation first, and then the tested engine was overhauled and the wear condition was inspected. After all the parts had been cleaned and inspected, the engine was reassembled and the number of wear particles was measured during Steady-state operation. These two-stage tests made it possible to distinguish the wear patterns and wear rates under Start-stop

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driving conditions from those under Steady-state driving conditions.

The first experiment was reported at the SAE World Congress & Exhibition held in Detroit in April 2009⁽⁹⁾, and then further experiments were continued. This paper is a revised version of the report based on the newly obtained data. Since I and my co-author presented the first report about the methods at the SAE World Congress in 2009⁽⁹⁾, the measurement techniques for obtaining pressure distribution on journal bearings have been improved. This paper provides an overview of our test and measurement system with additional test data.

2. First Experiment: Measurement of Pressure Distribution of Oil Film

2.1. Construction of Newly-Developed Sensor

The leads of conventional sensors are connected to pressure sensing surfaces. However, the leads of our new sensor are attached directly to metal side. The sensor has five pressure sensing points, each 0.8 mm in diameter. The five points are arranged in the radial direction. This structure makes it possible to measure the load distribution on a journal bearing on the metal part with the same width. An external view of the thin-film sensor attached to a crankshaft journal for the experiment is shown in Fig. 1.

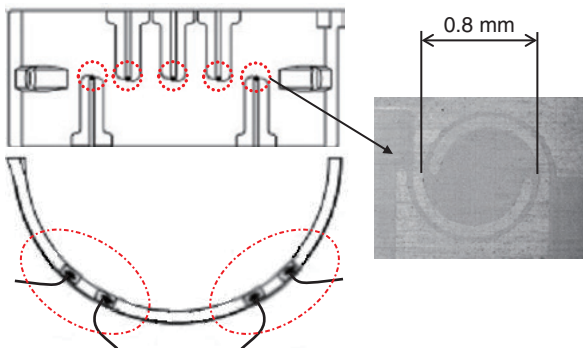
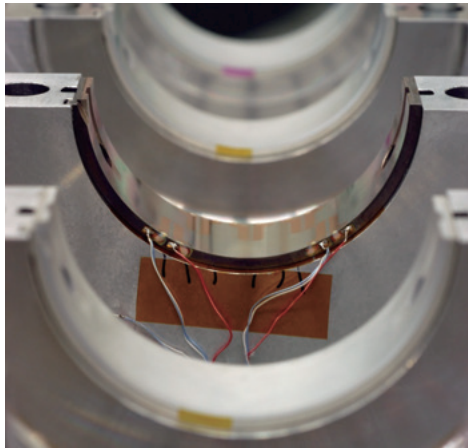


Fig. 1 External view of thin-film sensors

The sensor is made of three layers: an insulation layer, a sensor layer, and an insulation layer on the lining. A cross-section is shown in Fig. 2.

For the calibration of the sensor, the change in its electric resistance was measured under various hydraulic pressures which were uniformly applied to the bearing surface in an autoclave. The temperature dependency was also characterized by varying oil temperature. Functions were curve-fitted to both pressure and temperature characteristics to convert the measured signal to physical quantities, and bearing load was obtained.

2.2. Pressure Measurement in Engine

A water-cooled horizontally-opposed four-cylinder general aviation engine with output of 230-hp was used for the tests. A reduction gear was placed between the engine and the propeller.

The reduction gear had a gear ratio of 1:2.08, which generated 2400 r/m with the propellers in operation. The engine displacement was 3500 cm³. Premium unleaded gasoline for automobiles was used for fuel. The lubricant for the engine was Ultra Mild 10W-30 Honda genuine engine oil. The connecting rod bearings on which oil film pressure was detected were TAIHO KOGYO SA250.

Two thin-film sensors were used for the tests. One was attached to Journal 1 between the case end and Cylinder 1, and the other to Journal 3 between Cylinders 2 and 3, as shown in Fig. 3. The measured loads on the journals at 3000 r/m were compared with the calculated loads.

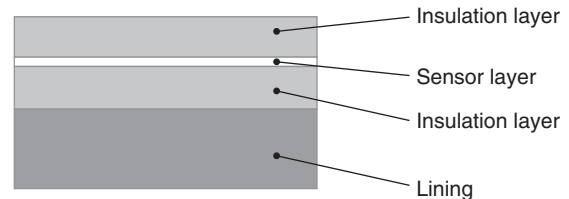


Fig. 2 Thin-film sensor in cross section

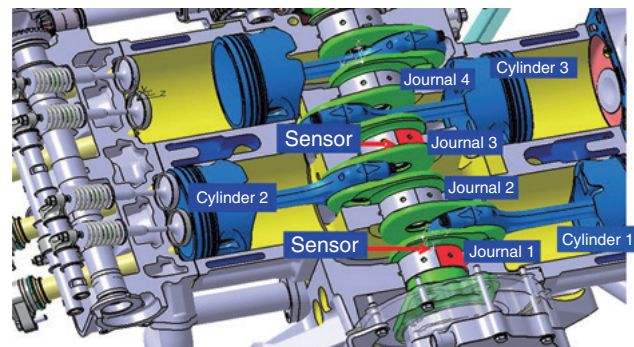


Fig. 3 Locations of thin-film sensors on crankcase

2.3. Measurement Results of Load Distribution on Journal Bearings

Comparisons of the measured loads on bearings and the calculated loads are shown in Figs. 4 and 5.

The calculation of the loads was made on the assumption that the pressure would be carried uniformly by the total surface of the journal bearings. The measured loads on Journals 1 and 3 were less than half of the calculated ones.

The discrepancy may result from two assumptions made in calculations. One is that the rigidity of the bearing support and the rotary parts such as pistons and piston rods was not taken into account when the resultant force of the inertial load and the explosion load on the journal bearings were calculated, and the other is that the rotary shaft was treated as a beam. The measurements indicate that the loads on the bearings were reduced, because the rotary parts such as pistons and piston rods deformed like springs when the explosion load was received by the bearings. The results of

measurement indicate that the size of journal bearings can be reduced by half. This is important to help engine makers reduce not only bearing cost but also the weight of engine.

The shapes of the curves of the measured load are not sharp compared with those of the calculated ones. This is because the loads are spread over the journal bearing surface and because the sensor measures the load at five points in the radial direction, although the calculation shows the peak load only.

The difference in crank angle between the measured peak load and the calculated one for Journal Bearing 1 was large, because Journal Bearing 1 was influenced by the motion of Piston 1 only. On the other hand, the difference in crank angle between the measured peak load and the calculated one for Journal Bearing 3 was small, because Journal Bearing 3 was influenced by the motion of both Pistons 2 and 3.

3. Second Experiment: Wear Simulation Tests of Journal Bearing

3.1. Simulation Test Apparatus

In the past, it was common to examine the wear and the reliability of bearings through tests of a completed engine at the final stage. However, in order to design lightweight engines more efficiently, it is desirable to obtain fundamental data on the wear of journal bearing metal by simulating various loads on the journal bearings of an engine. Therefore a bearing test apparatus that can apply various loads to the journal bearings by servo valves was developed. Figure 6 shows the schematic arrangement of the bearing simulation test apparatus, by which bearing wear was examined using the data obtained by the sensors, which were attached to the bearings of the general aviation engine.

Figure 7 shows the construction of the inside of the test chamber with the thin-film sensors, the rotating shaft, the position of the crankcase journal, and the vibrator base, in which a newly developed high-speed hydraulic servo valve is installed.

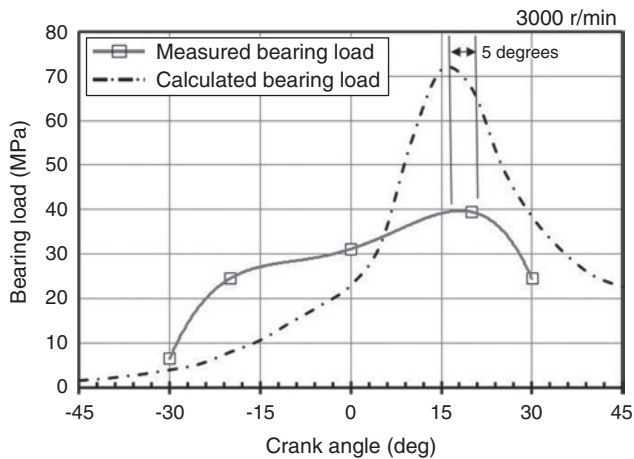


Fig. 4 Relationship between bearing loads and crank angle at peak load of #3 journal bearing

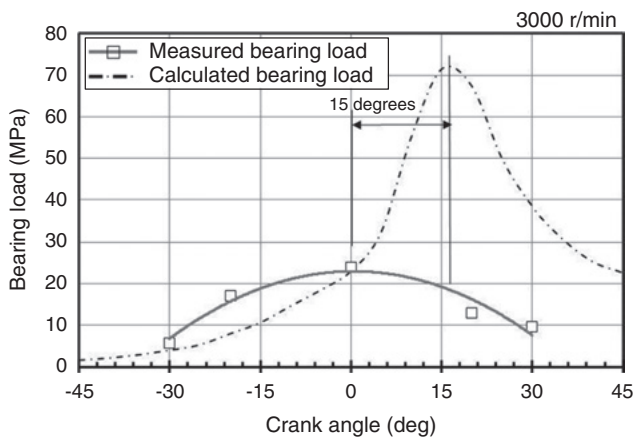


Fig. 5 Relationship between measured bearing load and calculated load and crank angle at peak load of #1 journal bearing

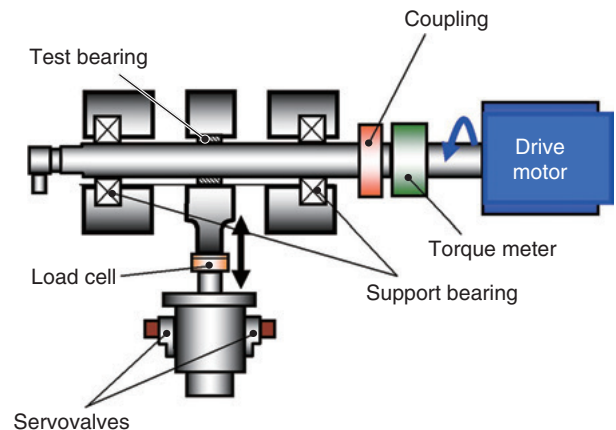


Fig. 6 Schematic arrangement of simulation test apparatus

The data obtained by the first experiment were incorporated into the computer of the simulation test apparatus, and the wear of the metal journals was monitored during the running of the simulation test apparatus. For the tests, the engine firing force and the simulated load on the journal bearing were adjusted to be identical. Figure 8 shows an example of the load on the bearing at 70 MPa.

3.2. Initial Wear and Steady-State Wear

In conventional wear tests, the amount of wear was measured throughout the tests, which included both Start-stop tests and Steady-state operation, and was treated as Steady-state wear. However, it is known that the initial wear during the running-in period is greater than the wear during Steady-state operation. Therefore a long running test was conducted in order to keep the initial wear level within the margin of error.

Figure 9 shows the test period with the smallest influence of initial wear. In existing wear tests, the amount of initial wear tends to exceed that of steady wear.

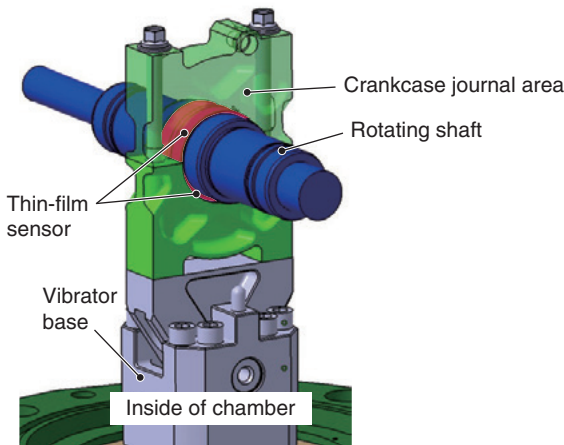


Fig. 7 Inside of chamber of bearing simulation test apparatus

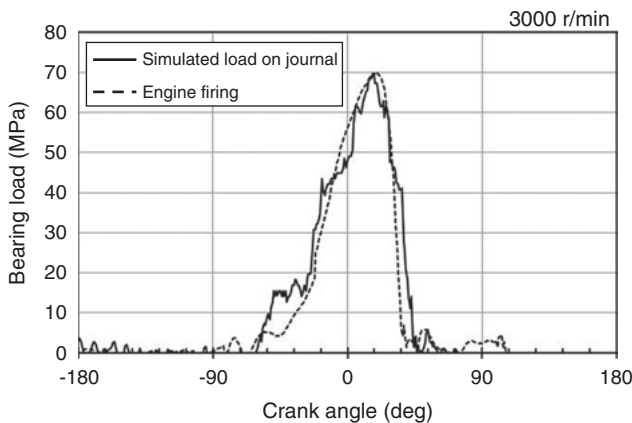


Fig. 8 Conversion data of bearing load value from thin-film sensor measurement data

For this reason, longer and more sufficient wear tests were conducted. That is, Steady wear was measured by dismissing the initial wear as erroneous, and comparing the amount of wear before and after the test.

In our new method, the initial wear test and Steady-state wear test were conducted separately. After measuring the wear amount during the initial wear tests, the metal bearings were removed from the test apparatus and cleaned. Then the bearings were re-fitted to the apparatus for the Steady-state wear test. Consequently, our method not only reduced the initial test time, but also made it possible to verify the amount of wear during Steady-state operation.

An originally developed in-line wear particle counting system enabled the separation of these wear phases. As shown in Fig. 10, a portion of the oil from near the bearings containing wear particles flows into the branch line to the counter. The wear particles cover focused laser beams across the oil line and are detected as intensity deviations on a photo detector, whose outputs are processed and yield the number of particles of different sizes.

The oil sampling and particle counting were conducted every 3 minutes during the test.

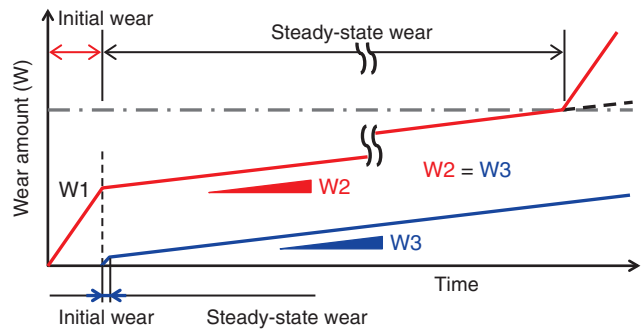


Fig. 9 Test period with small influence of initial wear

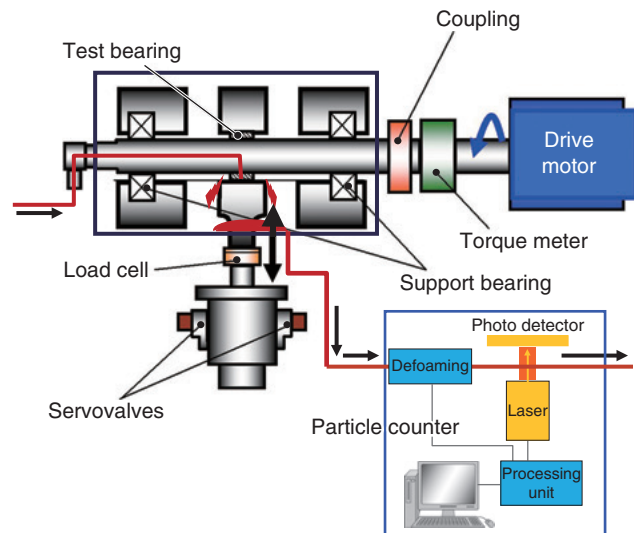


Fig. 10 Oil sampling location

The data were categorized into particle sizes larger than $10\ \mu\text{m}$ and of $10\ \mu\text{m}$ or smaller, and the change in number of particles during the test periods is shown in Figs. 11 and 12.

In the case of the initial wear test, the number of particles $10\ \mu\text{m}$ or smaller increased rapidly as soon as the test started. Then, it decreased as time elapsed until it became constant. But the number of particles larger than $10\ \mu\text{m}$ was almost constant during the initial wear test.

Figure 12 shows that the generation of particles larger than $10\ \mu\text{m}$ or smaller was low and almost constant throughout the steady-state wear test, different from the initial wear test. This suggests that few wear particles are generated in Steady-state wear, after the particles generated by initial wear have been completely removed.

The test results indicate that the wear of bearings is very low during normal operation and the reliability of bearings can be assured as long as the wear metals, which are generated during the initial running, are completely removed before commencement of Steady-state operation.

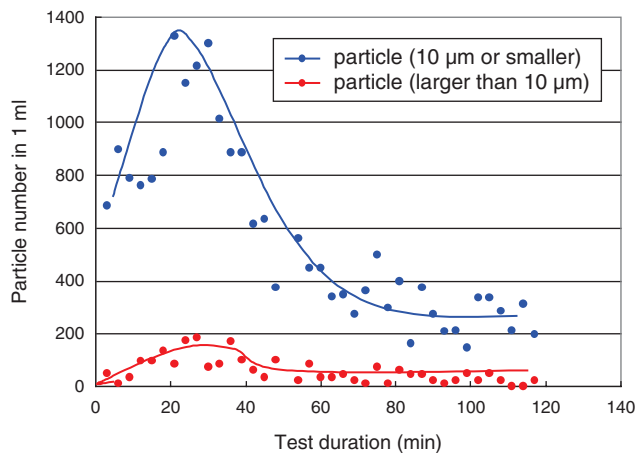


Fig. 11 Generation of initial wear particles

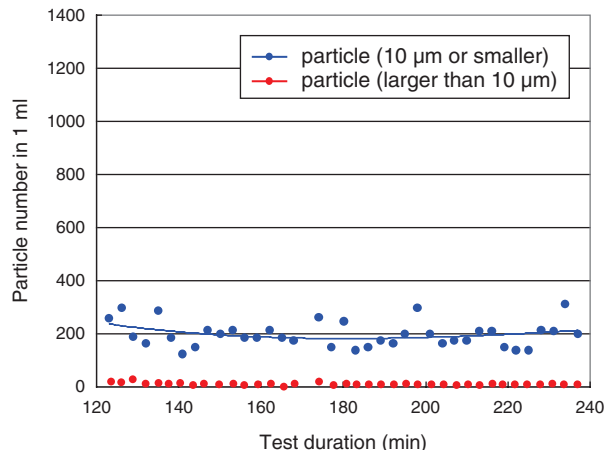


Fig. 12 Generation of Steady-state wear particles

4. Third Experiment: Start-Stop and Steady-State Wear Tests With a General Aviation Engine

4.1. Test Method

Figure 13 shows the flight simulation modes used for the tests. In order to verify the wear data obtained by the simulation test apparatus, confirmation tests were conducted using a general aviation engine, because general aviation engines are operated in simply programmed modes such as “Warm up,” “Take-off,” “Cruise,” “Landing” and “Cool down.” Therefore tests to evaluate the fatigue life of the crankshaft journal bearing were repeatedly conducted in these flight simulation modes.

The tests were carried out based on the flight simulation mode for an aircraft. The main shaft rotational speed and duration for the tests are shown in Fig. 14.

4.2. Results of Start-Stop Wear Test and Steady-State Wear Tests with a General Aviation Engine

After running 2-, 12-, 22- and 32-hour tests (Start-stop tests and Steady-state tests), the condition of the metal was examined under an optical microscope, and the wear of the journal bearing metal was measured with a roughness measurement gauge. The metal was set to the master reference plate of the roughness measurement gauge to measure the same point. The measured cross-sectional curve

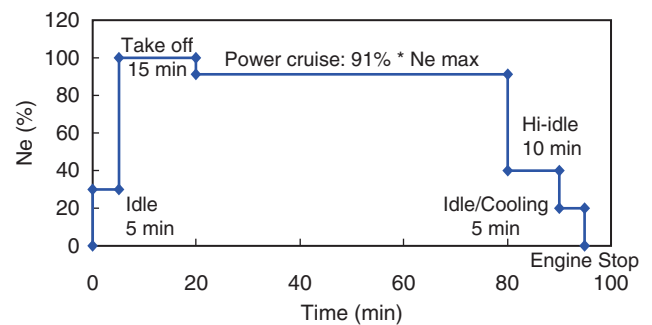


Fig. 13 Flight simulation modes of typical general aviation engine

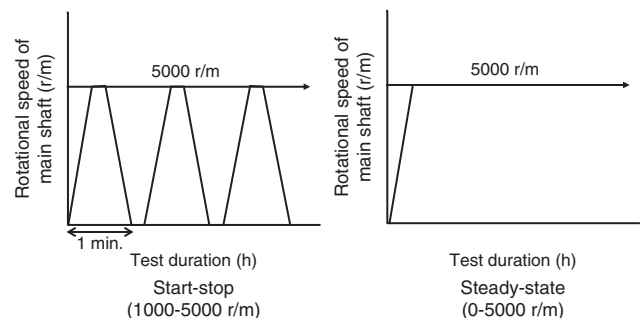


Fig. 14 Running modes

shows the wear at the center of the metal bearing where the wear was greatest.

In steady-state running mode, there was almost no change in the roughness curves before and after tests, while there was a slight change in the roughness curves in the Start-stop running mode showing some progression of wear, as shown in Fig. 15.

The surfaces of the journal bearings after a 32-hour test are shown in Fig. 16.

The photos in Fig. 16 show that the machining patterns were removed by the initial wear. The bearing surface after Steady-state operation was smooth, although that after Start-stop operation had a relatively deep and new groove, which was found after the 32-hour test. These photos indicate that wear during Start-stop operation is greater than that during Steady-state operation.

Figure 17 shows the number of discharged particles during the test in Start-stop running mode, where r/m varied from 0 to 1,000 and in steady-state running mode, where r/m was constant at 5,000.

Compared with steady-state running mode, the Start-stop running mode produced more wear particles from

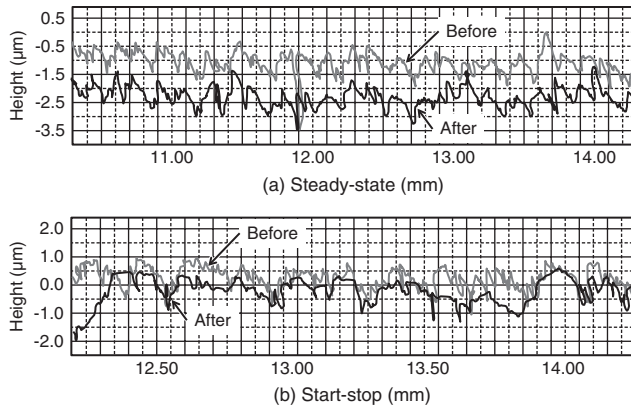


Fig. 15 Roughness curve before and after test

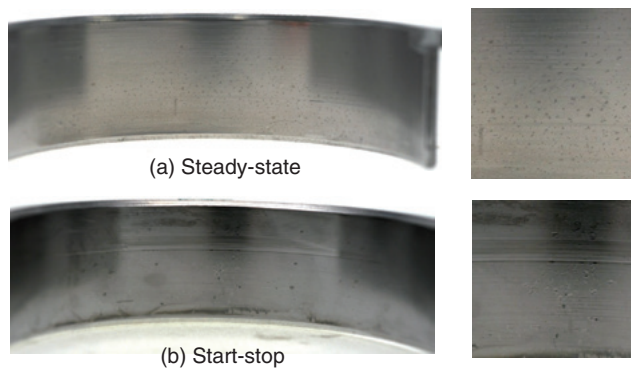


Fig.16 Example of journal metal surfaces at sliding side after 32-hour test

the beginning of the test, and it took a long time until the production of wear particles becomes stable.

In order to better understand wear during Start-stop operation and during steady-state operation, these wear data, which were obtained using the simulation test apparatus, were compared with those from endurance tests of a general aviation engine in a flying mode.

Figure 18 shows the wear prediction curves in three test modes, which were drawn on the basis of the test data.

The squares show the wear during Steady-state operation, the dotted line shows the wear during Start-stop operation, and the circles show the wear of the metal bearings during the endurance tests in a flying mode. Even though the amount of data was not enough to draw any conclusions, it suggests a general tendency that wear during the steady-state running test, which was conducted after removing the wear particles produced during the Start-stop test, is less than that during the actual engine endurance test and the Start-stop running test in that order respectively.

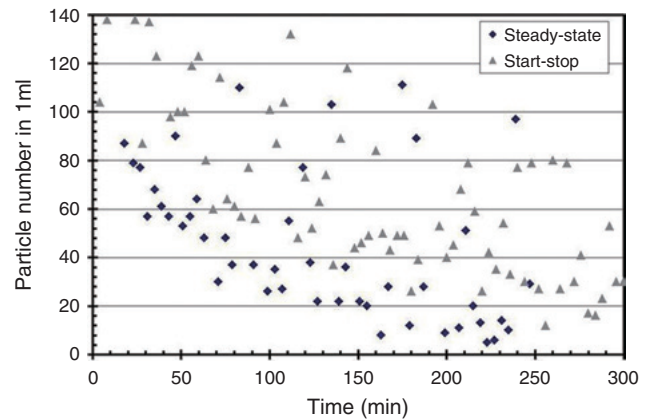


Fig. 17 Generation of particles during start-stop test and steady-state test (Steady-state: 5000 r/m, Start-stop: 0-1000 r/m, 5 min.x100 times)

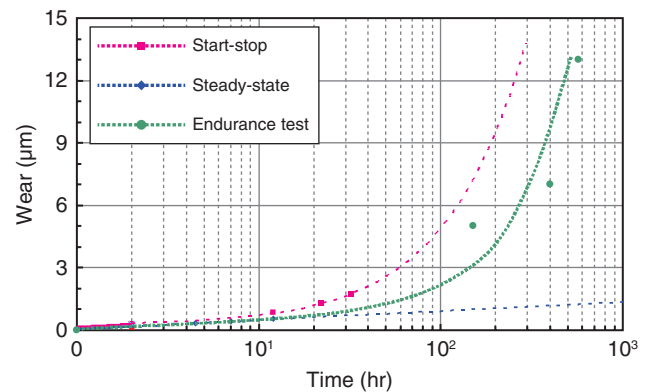


Fig. 18 Comparison of wear amount in three test modes

5. Conclusions

- (1) The journal load was measured in an actual running engine with thin-film sensors and the actual load in an actual engine was ascertained.
- (2) A bearing simulation apparatus made it possible to reproduce the actual load distribution, and wear tests of the metal bearings were able to be conducted.
- (3) The initial wear was differentiated from the Steady-state wear by measuring the generation of wear particles with a particle counter.
- (4) The study suggests that the reliability of engine bearings will increase if the wear particles generated during the initial running-in operation are completely removed.
- (5) The results of measurement of the loads on the journal bearings indicate some possibility of reducing the width of engine bearings.

In this paper, the new approach by the author, whereby initial and steady wear of the journal bearings in aero-plane engine can be divided, showed the validity for higher the accuracy and efficiency of endurance tests. The basic techniques, such as oil film pressure measurement, load simulation test apparatus and in-situ wear particle counting, are also applicable to other parts such as automobile engine bearings and enhance the development efficiency.

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Synthesis of Facet-controlled PtNi Nanoparticles and Evaluation of Performance in PEM Fuel Cell

Ryogo SAKAMOTO*

ABSTRACT

The research discussed in this paper set out to reduce the amount of Pt used in automotive polymer electrolyte fuel cells. Octahedral PtNi nanoparticles supported by carbon black (octahedral PtNi/C), which displays a high level of oxygen reduction reaction activity, was synthesized, and its effect in reducing the amount of Pt employed in an actual fuel cell was evaluated.

Performance tests of a fuel cell using the octahedral PtNi/C as a cathode material showed that Pt mass activity at 0.9 V was 3.4 times that of a market Pt catalyst. These results demonstrate that the octahedral PtNi/C is well suited as a catalyst material, displaying a high level of oxygen reduction reaction activity even in an actual fuel cell, and reducing the amount of Pt used in the cathodes by approximately 70%. The octahedral PtNi/C also displays good durability performance, with a rate of decline in mass activity of 19% after 10,000 0.6-0.9 V potential cycles, against 29% for the market Pt catalyst.

1. Introduction

Fuel cells are electrochemical devices that use hydrogen as fuel and generate electricity through the reaction of hydrogen and oxygen. Because they do not produce CO₂, expectations are high for fuel cells as a power source with minimal environmental impact. Among the numerous characteristics that make polymer electrolyte fuel cells (PEFC) well suited as an automotive power source are their high power conversion efficiency, their high power density, their compactness and low weight, their low operating temperature of approximately 80°C, and their degree of freedom in design. A significant amount of research is therefore being focused on their practical realization.

One of the major issues to be addressed in order to realize the widespread use of fuel cell vehicles (FCV) fitted with PEFC is the reduction of cost. Current PEFC electrode catalysts employ high-cost platinum (Pt) due to its high level of hydrogen oxidation activity and comparative chemical and electrochemical stability. However, Pt displays insufficient activity in relation to the oxygen reduction reaction (ORR), and large amounts of Pt are therefore used in FCV in order to compensate for this, becoming a factor in increased cost. Cathode catalyst materials that display a high level of ORR activity while using minimal Pt are being developed throughout the world in order to address this issue. The use of Pt and transition metal alloys is a

representative approach⁽¹⁾⁻⁽³⁾, but this method only increases ORR activity by around twofold against pure Pt, and therefore has little effect in reducing the amount of Pt. The use of Pt-shell/transition metal-core nanoparticles has been investigated as another approach, and it has been reported that this realizes a higher level of ORR activity than the use of Pt alloy nanoparticles⁽⁴⁾⁻⁽⁷⁾. However, the transition metals employed in the cores of these Pt-shell/transition metal-core nanoparticles elute in the high-oxidation environment of the cathode, and it is believed that this presents issues of durability.

Catalyst activity is known to generally change in response to crystal face orientation, and it is expected that this effect will also characterize Pt catalysts for PEFC. Markovic et al. report that the ORR activity of single-crystal Pt increases in the order {100}<{111}<{110}⁽⁸⁾. Stamenkovic et al. report that the ORR activity of single-crystal Pt₃Ni alloy increases in the order {100}<{110}<{111}, demonstrating a different tendency to Pt⁽⁹⁾. In addition, the ORR activity of Pt₃Ni{111} per specific surface area is the highest, at approximately 10 times that of Pt{111}, indicating that the ORR activity of Pt catalysts is increased through the combination of alloying and the effect of crystal face orientation.

The activity of a catalyst per unit mass is generally expressed as the product of activity per specific surface area and unit area⁽¹⁰⁾. In other words, in order to effectively increase catalyst activity, it is important to increase

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the specific surface area, or to select a material with an inherently high level of activity. Because the use of nanoparticles would make it possible to increase the specific surface area of the catalyst, if a material such as Pt₃Ni{111}, which has an inherently high level of ORR activity, could be produced as nanoparticles, activity per unit of Pt mass would increase, which could be expected to reduce the volume of Pt used in FCV.

Using the liquid-phase chemical reduction method to synthesize nanoparticles, the research team selected poly (diallyldimethylammoniumchloride) (PDDA) as an additive and polyol as a reducing agent and obtained octahedral PtNi nanoparticles supported by carbon black (octahedral PtNi/C) with {111} exposed on the particle surfaces by growing the particles slowly. Reports published by other researchers have indicated that rotating disk electrode (RDE) evaluation of the ORR activity of octahedral PtNi/C shows an high level of mass activity, four to 10 times that of a conventional Pt electrode⁽¹¹⁾⁻⁽¹³⁾. However, there are still no reports concerning the generation performance or durability of octahedral PtNi/C when employed in actual PEFC cells.

The research discussed in this paper applied octahedral PtNi/C in PEFC cells in order to evaluate its effect in reducing the volume of Pt used and its durability. PEFC cells using synthesized octahedral PtNi/C were subjected to generation tests and durability tests using electrical potential cycles. The results showed that the use of octahedral PtNi/C made it possible to reduce the amount of Pt used in the cathodes by approximately 70% against a market Pt catalyst. In addition, electrical potential cycle durability tests showed that the material demonstrated greater durability than a market Pt catalyst. This paper will provide details of this research.

2. Experiments

2.1. Synthesis of Octahedral PtNi Nanoparticles Supported by Carbon Black

The research discussed in this paper employed a simpler method than previously reported to synthesize octahedral PtNi/C⁽¹¹⁾⁻⁽¹³⁾. First, 513 mg of carbon black (Ketjen black ECP-600JD; Lion Corporation), 588 mg of platinum acetylacetonate (Sigma-Aldrich Co. LLC.), 372 mg of nickel acetate tetrahydrate (Sigma-Aldrich Co. LLC.), and 760 μ L of a 35 wt.% PDDA aqueous solution (Sigma-Aldrich Co. LLC.) were added to 50 ml of ethylene glycol (KANTO CHEMICAL CO. INC.). This mixed solution was subjected to argon gas reflux for two hours at 190°C. The products were separated from the solution by filtration, and washed multiple times in hot ethanol, acetone, and hot water. The products were dried adequately at 50°C, producing octahedral PtNi/C.

2.2. Material Characteristics

The synthesized octahedral PtNi/C was subjected to scanning electron microscope (SEM) and transmission

electron microscope (TEM) observation in order to determine the shape and size of octahedral PtNi nanoparticles. The SEM was an HD-2000 (Hitachi High-Technologies corporation), and the TEM was an H-9000 UHR (Hitachi High-Technologies corporation). Inductively coupled plasma atomic emission spectroscopy (ICP-AES) was employed in order to study the atomic composition and the weight concentration of metal of the octahedral PtNi/C. Energy dispersion X-ray spectroscopy (EDX) with particles as the subjects of analysis was applied at the same time as SEM observation in order to study the local atomic composition ratio of the octahedral PtNi nanoparticles.

2.3. Evaluation of ORR Activity Using RDE

A catalyst film for RDE was produced using the following method. Octahedral PtNi/C was added to a mixed solution of a 35 wt.% aqueous solution of ethanol and a 5 wt.% Nafion^(R) solution (Sigma-Aldrich Co. LLC.) and dispersed using ultrasound. 10 μ L of this dispersed fluid was dripped onto a glassy carbon (GC) electrode for RDE use (surface area: 0.196 cm²) and dried slowly at room temperature, forming a catalyst film for RDE. 1.4 μ g of Pt was used for the electrode. A three-neck electrochemical cell, an RDE apparatus (Pine Research Instrumentation), and an SI1287 potentiostat (Solartron analytical) were employed in electrochemical measurements. A saturated-calomel electrode was employed as the reference electrode, with a platinum-black electrode as the counter electrode. However, all the potentials indicated in this paper are based on a reversible hydrogen electrode as the benchmark. The electrochemistry surface area (ECSA) of the octahedral PtNi/C was determined prior to RDE measurements using cyclic voltammetry (CV). A 0.1 M aqueous solution of perchloric acid was employed as the electrolyte following sufficient removal of dissolved oxygen. The range of electrical potentials was set at 0.05-1.05 V. Following 100 cycles at a potential scan rate of 400 mV/s for electrochemical cleaning of the electrodes, CV curves were obtained at a potential scan rate of 100 mV/s. Using the obtained CV curves, the range of electrical potential in which hydrogen desorption occurs (0.05-0.4 V) was integrated in order to determine the electric charge Q_H [C], and ECSA[m²/g-Pt] was found using Eq. (1)⁽¹⁴⁾.

$$ECSA = \frac{Q_H}{2.1 M_{Pt}} \quad (1)$$

Here, M_{Pt} [g] is the amount of Pt employed in the GC electrode.

The oxygen-reduction current obtained by RDE was affected by the activation-controlled current and the diffusion-limited current. It was necessary to remove the effect of the diffusion-limited current from the oxygen-reduction current and focus on the activation-controlled

current only in order to more accurately evaluate catalyst activity. In the present research, a Koutecky-Levich plot was obtained, and the activation-controlled current was isolated. An oxygen-saturated 0.1 M aqueous solution of perchloric acid was used as the electrolyte for RDE measurements. Electrode rotation speeds of 400, 800, 1200, 1600 and 2000 rpm were employed. Electrical potentials from 1.05 to 0.05 were scanned at a scan rate of 10 mV/s. A TEC10E50E catalyst (TANAKA KIKINZOKU KOGYO) was evaluated under the same conditions in order to compare ORR activity with a market Pt nanoparticle catalyst supported by carbon black (Pt/C). The amount of Pt in the electrodes of the market Pt/C at the time of evaluation was 3.9 μg .

2.4. Evaluation of Cell Generation Performance

The membrane-electrode assembly (MEA) used in cell generation tests was produced using the decal method. Octahedral PtNi/C was added to a mixed solution of ion-exchanged water and a 5 wt.% Nafion^(R) solution (Sigma-Aldrich Co. LLC.) and dispersed using ultrasound. This dispersed fluid was sprayed uniformly onto a 30 mm-square PTFE sheet of 100 μm in thickness and dried at 80°C to produce cathode decal sheets. Market Pt/C was employed to form anode decal sheets using the same method. A proton exchange membrane (NR-212; Dupont) was sandwiched between the cathode and anode decal sheets and hot-pressed. The amount of Pt in each electrode was determined by measurement of the difference in the weight of the PTFE sheets before and after the decals were formed. The amount of Pt in the anode and cathode was 0.50 mg/cm² and 0.14 mg/cm², respectively. To provide a comparison, an MEA using a market Pt/C for the cathode was produced using the same method. In this case, the amount of Pt was 0.50 mg/cm² in both the anode and the cathode.

The MEA were fitted in fuel cells (Japan Automobile Research Institute standard cells) together with gas diffusion layers (GDL25BCH; SGL Carbon), and the cells were connected to a fuel cell test system (NF Corporation). Table 1 shows the test results. Cell resistance was measured using the current interruption method, and the values for voltage shown in the current-voltage (I-V) curve have had cell resistance subtracted.

2.5. Evaluation of Durability Using Potential Cycles

Table 2 shows the conditions for durability evaluation tests using potential cycles. Cell potential was varied using a potentiostat (HD-3000; Hokuto Denko corporation). The ECSA and the I-V curve for the cathode were compared before and after the potential cycle in order to study changes in catalyst surface area and cell performance. CV measurements for the calculation of ECSA were conducted with hydrogen flowing to the anode and nitrogen flowing to the cathode, and the anode as a pseudo reference electrode. ECSA was calculated using Eq. (1). Table 1 shows the conditions used for the tests.

Table 1 Conditions for fuel cell test with octahedral PtNi/C as cathode material.

	Anode	Cathode
Cell temperature [°C]	70	
Gas	H ₂	Air
Gas stoichiometric ratio	1.4	1.8
Relative humidity [%]	50	73
Back pressure [kPa]	130	100

Table 2 Conditions for durability test of octahedral PtNi/C by potential cycling.

	Anode	Cathode
Cell temperature [°C]	70	
Gas	H ₂	Air
Gas stoichiometric ratio	1.4	1.8
Relative humidity [%]	100	100
Back pressure [kPa]	130	100
Potential [V]	0.6 - 0.9	
Shape of potential wave	Square	
Potential retention time [sec.]	20	
Cycle number [times]	10,000	

3. Results and Consideration

3.1. Material Characteristics

Figure 1 shows electron micrographs of the synthesized octahedral PtNi/C. The low-magnification SEM image shown in Fig. 1(a) indicates a good dispersion of 10-15 nm octahedral nanoparticles on the carbon black. The high-magnification SEM image shown in Fig. 1(b) indicates that the nanoparticles are not completely octahedral, but are actually truncated octahedrons with their vertices cut off. Figure 1(c) shows a high-resolution TEM image of the octahedral PtNi nanoparticles. In order to examine the orientation of the exposed faces, they were photographed perpendicular to the plane of the page. Figure 1(d) shows a pseudo electron diffraction pattern image obtained by applying fast Fourier transformation to the area enclosed by the square in Fig. 1(c). The diffraction spots from A to F correspond to the exposed faces from A to F in Fig. 1(c). As a result of applying exponents to the diffraction spots, the faces with cut vertices (B and E) were identified as {100} and the other faces (A, C, D and F) were identified as {111}.

This indicated that the exposed faces of the synthesized octahedral PtNi nanoparticles were almost all {111}.

It was considered that two synthesis conditions were essential to obtaining octahedral PtNi/C. One of these was the addition of PDDA. PDDA is a polymer, and because it has a high density of quaternary ammonium cations, which are considered to be adsorption points, it displays strong adsorptivity in relation to metal ions and metal particle surfaces^{(15), (16)}. This property has the following two effects on the particles:

- (1) By increasing the size of the particles, it increases the {111} exposure ratio; and
- (2) By controlling the speed of particle growth, it planarizes the exposed crystal faces.

With regard to (1), by coordinating Pt^{2+} and Ni^{2+} during the formation of particle nuclei in the initial stages of the reaction, the PDDA inhibits reduction to Pt and Ni, minimizing the number of nuclei formed. It is conjectured that as a result, the majority of the precursors are consumed in the growth of the particles, which grow to the comparatively large size of 10–15 nm. Figure 2 shows the relationship between the ratio of each section of the octahedral particle surfaces (the ratio of the number of atoms composing a specific section to the total number of atoms in the exposed surfaces) and the size of the particles, as determined by calculations. As particle size increases, the ratio of {111} becomes higher than corners and edges, until it is approximately 90% at 11 nm. In other words, to help ensure that the majority of octahedral particle surfaces are {111}, it is necessary to increase the size of the particles, and it is considered that PDDA contributes to increasing their size.

With regard to (2), it is conjectured that when the nuclei grow into particles, the PDDA is strongly absorbed into the particle surfaces, and continuous metal precipitation reactions occur slowly and uniformly on the particle surfaces. As a result, {111} with few steps or kinks and planar at the atomic level are exposed, producing octahedral particles with the regular shape shown in Fig. 1.

The second essential synthesis condition is that the surface energy of the {111}PtNi is lower than that of other faces. The exposure ratio of the crystal faces is determined by the speed of growth of the faces, and this is dependent on the magnitude of surface energy. In other words, the

Table 3 Atomic ratio and weight concentration of octahedral PtNi/C as determined by ICP-AES.

	Pt	Ni	C
Atomic ratio [at.%]	62.2	37.8	
Weight concentration [wt.%]	27.5	5.0	67.5

higher the surface energy of the crystal face, the faster its growth, and the exposed area of the face decreases as the particle grows, until it finally disappears. In the case of PtNi alloys, which have a face-centered cubic lattice crystal structure, it has been reported that {111}Pt₃Ni has a lower surface energy and its growth is slower than other crystal faces^{(11), (17), (18)}. In addition, PDDA is selectively adsorbed by {111}PtNi, and this is thought to further reduce the surface energy of {111}PtNi. It is considered that the multiple effects of PDDA discussed above made it possible to obtain octahedral PtNi nanoparticles with large numbers of planar {111} exposed at their surfaces.

Table 3 shows the composition ratio of octahedral PtNi/C measured using ICP-AES. The atomic composition ratio of Pt and Ni in the octahedral PtNi/C was Pt:Ni = 62.2:37.8. The starting atomic composition ratio at the time of synthesis was Pt:Ni = 50:50, meaning that the ratio of Pt was higher in the obtained octahedral PtNi/C than in the

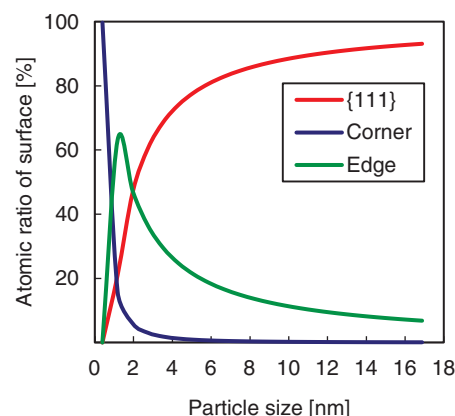


Fig. 2 Calculated relationship of particle size and atomic ratio of {111}, corner, and edge on octahedral nanoparticle surface.

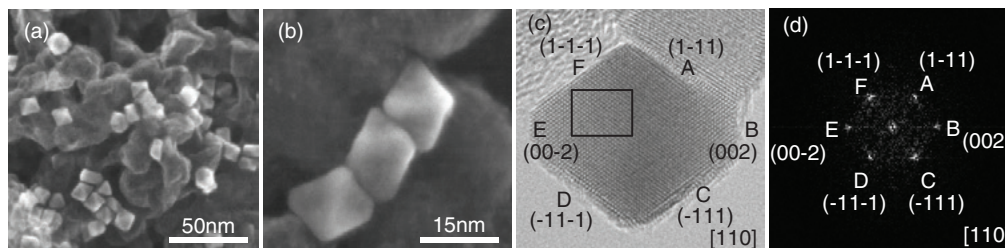
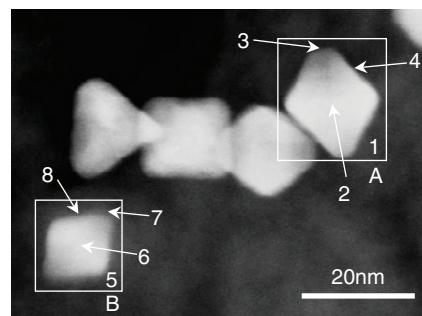


Fig. 1 SEM (a) and (b) and high-resolution TEM (c) images of octahedral PtNi/C. Square shows area image-processed by inverse Fourier transformation to obtain pseudo-electron diffraction pattern (d) of octahedral PtNi nanoparticles.

starting atomic composition. The mass concentration of the metals in the octahedral PtNi/C was Pt: 27.5 wt.% and Ni: 5.0 wt.%, making a total of 32.5 wt.%.

SEM-EDX particle analysis was applied to the octahedral PtNi nanoparticles in order to determine their local atomic composition ratio. Figure 3 shows the results. For Particle A, the composition ratio of the entire particle (Measurement Area 1) was Pt:Ni = 63.8:36.2. This result corresponds well with the ICP-AES results. The composition ratio in Measurement Area 2, in the center of Particle A, was Pt:Ni = 57.3:42.7. The composition ratio in Measurement Area 3, at a corner, was Pt:Ni = 80.7:19.3, and the composition ratio in Measurement Area 4, at an edge, was Pt:Ni = 72.3:27.7. These results indicate that there is variation between composition ratios depending on the area. The composition distribution of Particle B demonstrated the same tendency as that of Particle A. These results indicate that the atomic composition ratio of the octahedral PtNi nanoparticles is not uniform, but that they display a characteristic composition distribution, in which the ratio of Ni is greater in the centers of the particles and the ratio of Pt is greater at the corners and edges of the particles.



Analysis points		Atomic ratio [at.%]	
		Pt	Ni
1	Particle	63.8	36.2
2	Center	57.3	42.7
3	Corner	80.7	19.3
4	Edge	72.3	27.7
5	Particle	67.2	32.8
6	Center	58.1	41.9
7	Corner	80.8	19.2
8	Edge	73.6	26.4

3.2. Evaluation of ORR Activity Using RDE Method

Figure 4(a) shows the CV curves for the octahedral PtNi/C and the market Pt/C. The CV curves of Pt nanoparticles generally show currents associated with

Fig. 3 Dark-field SEM image of octahedral PtNi/C including EDX analysis areas (squares) and points (arrows). Table shows atomic ratio at each analysis point.

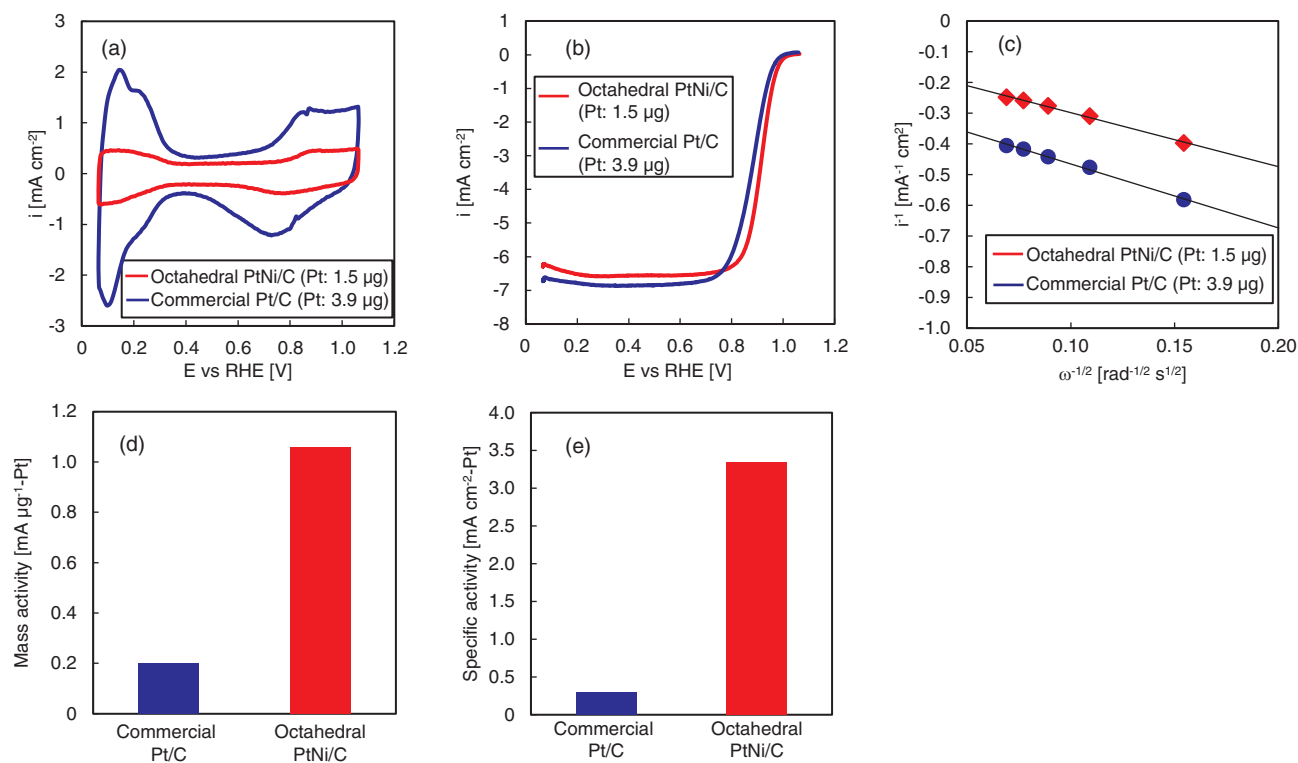


Fig. 4 (a) CV curves, (b) polarization curves and (c) Koutecky-Levich plot for octahedral PtNi/C (Pt: 1.5 µg) and commercial Pt/C (Pt: 3.9 µg) as determined by RDE measurements. Comparison of (d) mass activity and (e) specific activity at 0.90 V between octahedral PtNi/C and commercial Pt/C.

hydrogen adsorption and desorption from 0.05-0.4 V and the formation and reduction of oxides on the surface from 0.7 V onwards. The CV curve for the market Pt/C showed conspicuous peaks at 0.13 V and 0.20 V, but these were not observed for the octahedral PtNi/C. A CV curve with no peaks in the potential range for adsorption and desorption of hydrogen matches well with the reported CV curve for Pt{111} single crystals in 0.1 M perchloric acid⁽¹⁹⁾, suggesting significant exposure of Pt{111} on the surfaces of the octahedral PtNi nanoparticles. In addition, the current flow associated with the formation of oxides on the surfaces from approximately 0.69 V in the market Pt/C has shifted to the higher potential side, from approximately 0.75 V, in the octahedral PtNi/C. This is thought to indicate that the overpotential of the octahedral PtNi/C is high in relation to the formation of oxides on the nanoparticle surfaces, impeding oxide formation, demonstrating that the substance displays a different surface characteristic to conventional Pt catalysts. The ECSA of the octahedral PtNi/C, as determined from hydrogen desorption peaks, was 32 m²/g-Pt, less than half of the figure of 68 m²/g-Pt for the market Pt/C. The average particle diameter for the market Pt/C is 2.3 nm, smaller than that of the octahedral PtNi nanoparticles, and this difference is reflected in the figure for ECSA.

Figures 4(b) and 4(c) respectively show the ORR polarization curve obtained using RDE and a Koutecky-Levich plot for 0.90 V. The intercept current values in the Koutecky-Levich plot are values for oxidation-reduction current with the effect of the diffusion-limited current removed. Figure 4(d) shows these as figures for mass activity specified by the amount of Pt in the electrodes. The mass activity of the octahedral PtNi/C is 5.3 times that of the market Pt/C. These results indicate that by using the octahedral PtNi/C, it is possible to obtain a specific current volume using approximately 81% less Pt as a conventional Pt catalyst. Figure 4(e) shows oxidation-reduction current values specified by ECSA as specific activity. The specific activity of the octahedral PtNi/C was 11.5 times that of

the market Pt/C. This shows that the octahedral PtNi nanoparticles are a catalyst material essentially well suited to ORR.

3.3. Evaluation of Cell Performance

Figure 5(a) shows I-V curves for an MEA using cathodes employing octahedral PtNi/C with 0.14 mg/cm² of Pt and an MEA using cathodes employing a market Pt/C with 0.50 mg/cm² of Pt. The I-V curves are virtually identical, despite the fact that the amount of Pt used in the octahedral PtNi/C is less than 1/3 the amount used in the market Pt/C. Figures 5(b) and 5(c) respectively show a Tafel-plot with mass activity on the horizontal axis and a comparison of mass activity at 0.9 V. Mass activity in the MEA using cathodes employing octahedral PtNi/C is 3.4 times that in the MEA using cathodes employing the market Pt/C. These results indicate that the replacement of the market Pt catalyst by the octahedral PtNi/C in PEFC cathodes makes it possible to reduce the amount of Pt used in the cathodes by 71%, and demonstrate that this significant reduction in the amount of Pt used in the cathodes will also be realized in actual fuel cells.

The 5.3-fold increase in mass activity realized through the use of octahedral PtNi/C as determined by RDE is smaller in actual fuel cells at 3.4-fold. It is considered that one reason for this is the fact that residual PDDA is present on the surfaces of the octahedral PtNi nanoparticles in the MEA, and this impedes the ORR. It is conjectured that the immersion of the electrodes in an aqueous solution for electrochemical cleaning in the RDE method causes the water-soluble PDDA in the electrolyte to elute or decompose, and the octahedral PtNi nanoparticles are evaluated with no PDDA present on their surfaces. In the case of the fuel cell performance tests, it is considered that while the MEA was subjected to a sufficient number of polarization cycles prior to the measurements in order to help enable the highest level of performance, because the environment around the electrode layers is almost exclusively gaseous, the effect in reducing PDDA is minimal, and the cells were measured with a higher quantity

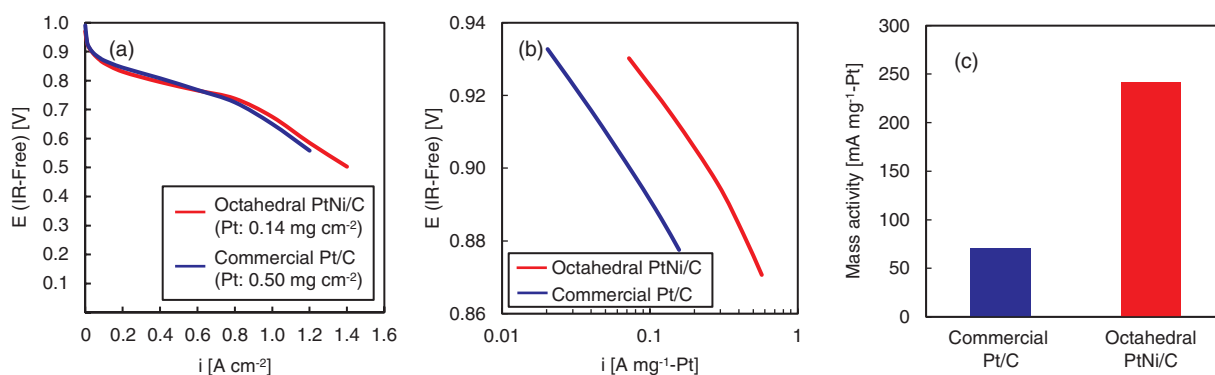


Fig. 5 (a) Polarization curves of PEFC using octahedral PtNi/C and commercial Pt/C for cathodes. (b) Tafel plots for octahedral PtNi/C and commercial Pt/C in fuel cell tests. (c) Comparison of mass activity at 0.9 V for the octahedral PtNi/C and commercial Pt/C.

of PDDA adsorbed into the surfaces of the octahedral PtNi nanoparticles than was the case for RDE evaluation.

3.4. Evaluation of Durability Using Potential Cycles

Figure 6(a) compares I-V curves for a fuel cell with octahedral PtNi/C in the cathodes before and after 10,000 0.6-0.9 V potential cycles. The potential cycles produce no major changes in the I-V curves in any of the current ranges. Figure 6(b) shows changes in mass activity with potential cycles. The rate of decline in mass activity for the octahedral PtNi/C is 19%, lower than the figure of 29% for the market Pt/C. Even after 10,000 0.6-0.9 V potential cycles, the octahedral PtNi/C retains its good performance, displaying 4.1 times the mass activity of the market Pt/C. The results discussed above demonstrate that the octahedral PtNi/C displays a higher level of durability in relation to 0.6-0.9 V potential cycles than the market Pt catalyst.

Figure 6(c) shows changes in ECSA as a result of the 0.6-0.9 V potential cycles. The rate of decline in ECSA was 4% in the octahedral PtNi/C against 28% in the market Pt/C. There are considered to be two reasons for this. One of these is the fact that the octahedral PtNi nanoparticles are large, resulting in less migration and agglomeration of the particles on the carbon black. The other is the fact that the {111} exposed on the surfaces of the nanoparticles has a comparatively high resistance to dissolution, making the particles less prone to Ostwald ripening. The facts that {111} has a higher atomic density than other crystal faces, and that its coordination number is also high, are considered to be the reason for its high resistance to dissolution.

Because the rate of decline in mass activity in the market Pt/C almost exactly corresponds to the rate of decline in ECSA, it is considered that the main factor in its decline in activity is the decline in the surface area of the catalyst. Because there was no correlation between the rate of decline in mass activity and the rate of decline in ECSA in the case of the octahedral PtNi/C, it was judged that a decline in surface area was not the main factor in the decline in activity in this case. Because the reason that octahedral PtNi/C displays a high level of ORR activity

is the large amount of {111}PtNi exposed on the surfaces of the particles, it is conjectured that the cause of the 19% decline in mass activity was the loss of {111}PtNi structures exposed on the particle surfaces due to the potential cycles.

4. Conclusion

The research discussed in this paper set out to reduce the amount of Pt used in automotive polymer electrolyte fuel cells. Octahedral PtNi/C, which displays a high level of oxygen reduction reaction activity, was synthesized, and its effect in reducing the amount of Pt employed in an actual fuel cell was evaluated.

The particles obtained were truncated octahedrons of 10-15 nm in size. TEM analysis showed that the particle surfaces were almost entirely {111}. The octahedral PtNi nanoparticles displayed a specific composition distribution, with the majority of the Pt segregated at the corners and edges.

The catalyst activity of the octahedral PtNi/C was measured using the RDE method. Pt mass activity was 5.3 times that of a market Pt catalyst, while its specific activity was 11.5 times greater. Performance tests of an MEA using the octahedral PtNi/C as a cathode material showed that Pt mass activity at 0.9 V was 3.4 times that of the market Pt catalyst. These results demonstrate that the octahedral PtNi/C is well suited as a catalyst material, displaying a high level of oxygen reduction reaction activity even in an actual fuel cell, and reducing the amount of Pt used in the cathodes by approximately 70%. The octahedral PtNi/C also displays good durability performance, with a rate of decline in mass activity of 19% after 10,000 0.6-0.9 V potential cycles, against 29% for the market Pt catalyst.

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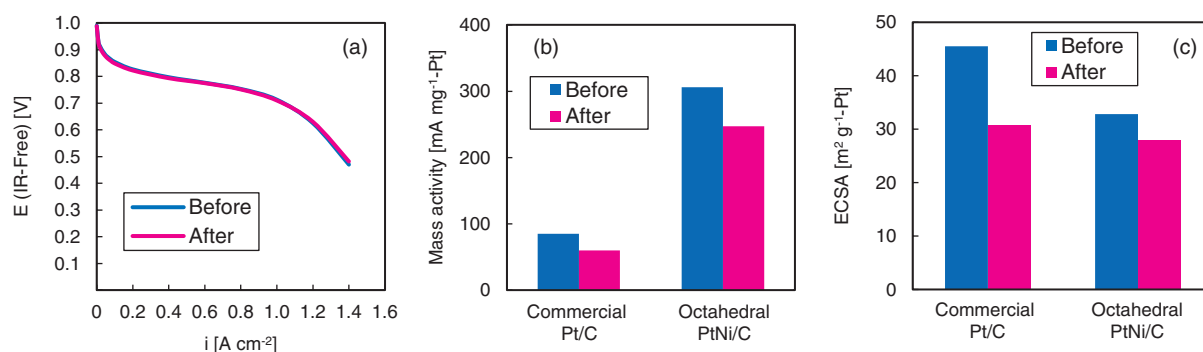


Fig. 6 (a) Polarization curves of PEFC using octahedral PtNi/C before and after 10,000 0.6 - 0.9 V potential cycles. (b) Change in mass activity and (c) ECSA for octahedral PtNi/C and commercial Pt/C as a result of 0.6 - 0.9 V potential cycling.

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Ryogo SAKAMOTO

In-plane Visualization of Oxygen Partial Pressure Distribution on Cathode Side during Fuel Cell Operation

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ABSTRACT

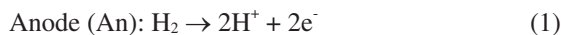
A system capable of visualizing and measuring the distribution of oxygen partial pressure in fuel cells during vehicle operation at a high level of resolution has been developed in order to help enable the creation of a method of control that would ameliorate the decline in fuel cell performance. Changes in the fluorescent intensity of an oxygen-sensitive reagent coating the gas flow paths of an acrylic plate designed for the visualization of generation were used to measure oxygen partial pressure.

The research discussed in this paper made it possible to predict the distribution of increases in the resistance of the materials employed in the fuel cell, which is the main cause of performance declines at high current densities. In addition, the research verified the effectiveness of applying control to reduce the partial pressure of the residual oxygen in the cathode tubes in reducing this increase in resistance, making it possible to develop a method of control that ameliorated the decline in output displayed by fuel cell vehicles.

1. Introduction

The development of clean, high-fuel-efficiency vehicles is an urgent issue in terms of responding to the global environmental impact of pollutants such as CO₂ and NO_x in automotive exhaust gas and the future depletion of fossil fuels. Aiming for the realization of a society based on renewable energy, Honda is advancing the development of fuel cell vehicles, which use hydrogen as a fuel rather than fossil fuels.

Fuel cells are generation devices that produce electricity from the chemical reaction between hydrogen and oxygen. The actual reaction comprises a hydrogen oxidation reaction at the anode (Equation (1)) and an oxygen reduction reaction at the cathode (Equation (2)). Water is produced as a by-product of the reaction at the cathode.



Honda is proceeding with the development of vehicles using lightweight and compact polymer electrolyte fuel cells (PEFC), which are able to be started even at low temperatures⁽¹⁾.

Figure 1 shows a schematic image of a PEFC. PEFC comprise a membrane electrode assembly (MEA), which positions catalyst layers (CAT) and gas diffusion layers

(GDL) on each side of a polymer electrolyte membrane (PEM), and separators that form flow paths for gases and coolant.

The smallest unit formed by these elements is termed a cell. Multiple cells arranged in layers are termed a stack. The PEM promotes the transfer of protons (H⁺) produced in the hydrogen oxidation reaction shown in Eq. (1). The CAT positioned on both sides of the PEM promote the reactions shown as Eqs. (1) and (2). The GDL function to disperse reaction gases to the CAT and to supply power. The separators supply reaction gases to the anode and cathode

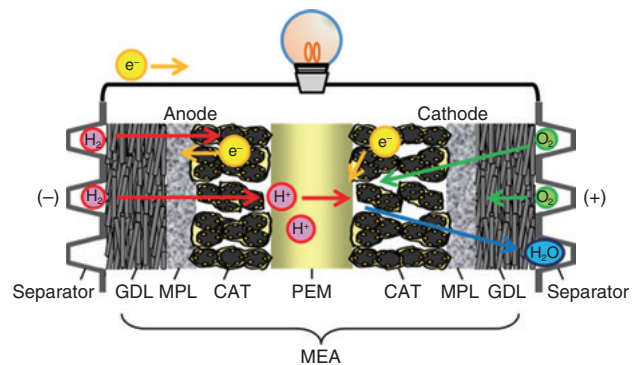


Fig. 1 Schematic image of PEFC

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electrodes, isolate reaction gases from neighboring cells, provide a cooling function through the supply of coolant, and supply power from the CAT.

Technologies for the realization of higher-power and higher-efficiency generation are necessary for the achievement of compactness and light weight in fuel cell systems for fitting in vehicles.

Figure 2 shows the energy loss that occurs during generation in fuel cells due to three forms of polarization loss.

The three forms of polarization are activation polarization originating in activation of the catalyst, ohmic polarization originating in proton and electron transfer, and concentration polarization originating in the transport resistance of the reaction gases. Ohmic polarization and concentration polarization in particular increase significantly under conditions of high current density, making it necessary to reduce these forms of polarization in order to realize high-efficiency operation at high current densities.

The design of cathode electrode materials and oxygen concentration control are necessary for the reduction of concentration polarization. Sensors for the measurement of oxygen at the electrode are necessary in turn for the study of these factors. MEA with inbuilt optic fiber oxygen sensors⁽²⁾ are suitable for this task, meaning that a measurement method is already available. This paper will focus on the remaining issue, the method of reduction of ohmic polarization; it is necessary to control the increase in the resistance of the PEM, which is the major factor in this form of polarization. It is known that when the PEM is exposed to the fuel cell environment, in which both hydrogen and oxygen are present, the sulfone groups that promote proton transfer are eliminated, and resistance increases⁽³⁾. Vehicle lifespan is taken into consideration in the development of fuel cell vehicles, and the development process incorporates system control targeting the increase in the resistance of the PEM. Realizing an accurate understanding of the mixed gas environment in the fuel cell stack is an important factor in the creation of this control.

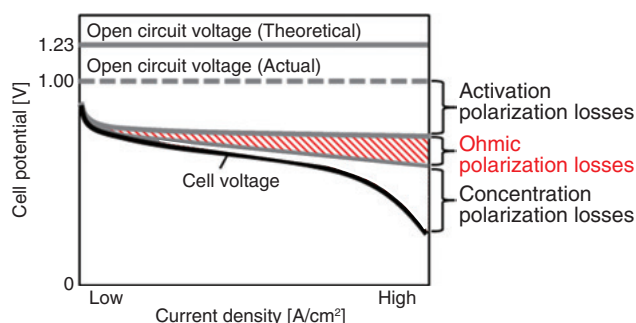


Fig. 2 I-V curve and various polarization losses of operating fuel cell

2. Necessity for Visualization of Oxygen Partial Pressure

2.1. Increase in PEM Resistance due to Hydrogen and Oxygen Combustion Reaction

Figure 3 shows the mechanism of increase in the resistance of the PEM that is generally known. Because the material of the PEM contains water, miniscule amounts of gas are transmitted inside the PEM. When this happens, some hydrogen and oxygen directly combust on the CAT, and OH radicals are produced as a by-product⁽⁴⁾. When these OH radicals make contact with the polymer covalent bonds of the PEM and produce a substitution reaction, molecular structures including the sulfone groups that promote proton transfer are eliminated, and the resistance of the PEM increases⁽⁵⁾.

Determining the quantity of the hydrogen/oxygen combustion reaction and taking the various factors that accelerate the reaction into consideration makes it possible to predict the increase in the resistance of the PEM. In this paper, the quantity of hydrogen consumed in the combustion reaction is defined as the quantity of the combustion reaction. Because the relationship between the quantity of the combustion reaction and the increase in the resistance of the PEM differs with the molecular structure of the polymer materials employed in the PEM, the relationship is determined by experiment. Figure 4 shows the relationship between the quantity of the combustion reaction and the resistance of the PEM obtained from durability tests in which hydrogen and oxygen are supplied and only the chemical degradation of the PEM is evaluated. The resistance of the PEM increases with the quantity of the combustion reaction.

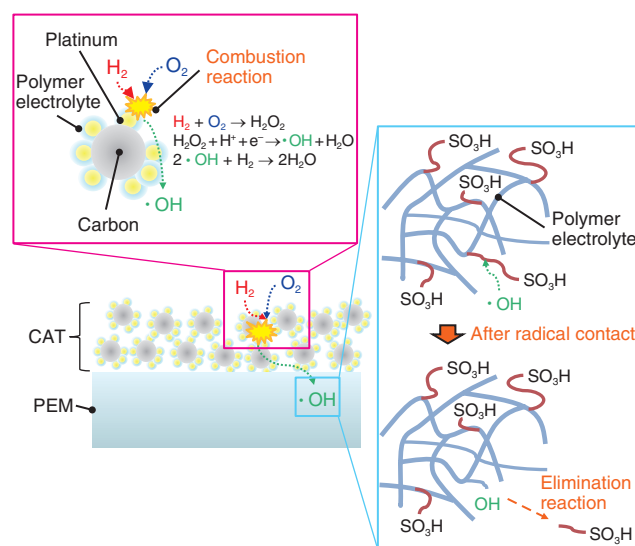


Fig. 3 Mechanism of increase in PEM resistance following combustion reaction of hydrogen and oxygen

The quantity of the combustion reaction is determined by integrating the speed of the reaction at each point in time. The speed of the combustion reaction is chiefly dependent on hydrogen partial pressure, oxygen partial pressure, and temperature, and mapping these parameters makes it possible to understand the quantity of the combustion reaction during operation of the fuel cell vehicle. Data concerning the speed of the combustion reaction is obtained using actual cells. Figure 5 shows an example of actual maps. The theory of the speed of chemical reactions indicates that the combustion reaction will become faster

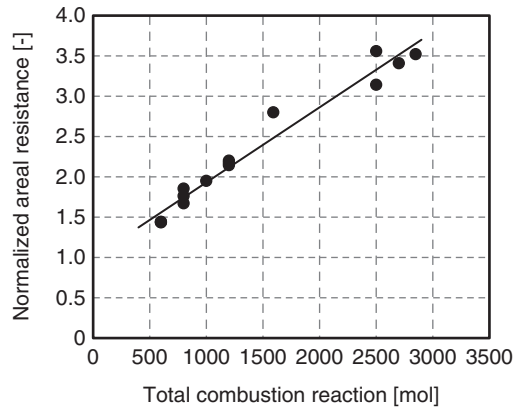


Fig. 4 Relationship between combustion reaction and PEM areal resistance

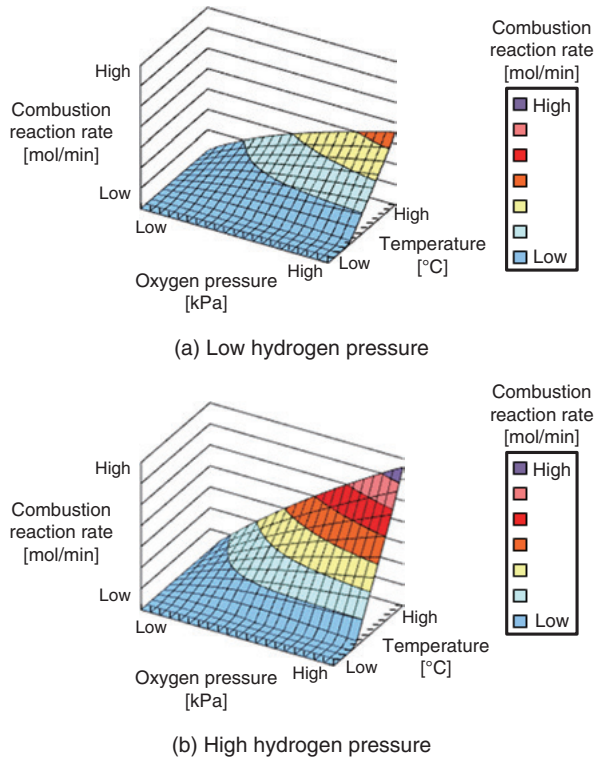


Fig. 5 Examples of combustion reaction rate maps

the higher the partial pressure of the reaction species and the temperature of the reaction system. By determining the hydrogen partial pressure, oxygen partial pressure, and temperature during the operation of a fuel cell vehicle and obtaining the quantity of the combustion reaction from a map of its rate, it is possible to predict the increase in the resistance of the PEM.

2.2. Frequency Durability Tests and Quantity of Combustion Reaction in Fuel Cell Vehicles

During the development of fuel cell vehicles, frequency durability tests modeling the frequency of operation of the vehicle in a normal use environment are conducted in order to help ensure stack performance with consideration of the vehicle's lifespan. These frequency durability tests employ high-accuracy simulations that make it possible to understand the stack environment under various control conditions, such as at start-up and during generation, and incorporate technologies for the determination of the quantity of the combustion reaction. By contrast, when control is suspended (the soak state), which represents the greater part of normal vehicle operation, it is necessary to solve nonlinear simulations incorporating complex reaction diffusion equations in order to understand the stack environment, and the accuracy of determination of the quantity of the combustion reaction is low. In the soak state, because hydrogen, which has a high coefficient of membrane permeability, instantaneously arrives at the cathode generating surface from the anode, while the residual oxygen at the cathode generating surface is simultaneously consumed, the cathode surface is uniformly filled with hydrogen and nitrogen. Following this, the oxygen remaining in the cathode tube gradually arrives at the cathode generating surface. The behavior of the distribution of oxygen partial pressure at this time is complex, affected by the influx and dispersion of the oxygen remaining in the cathode tube and the consumption of the gases on the CAT, and the prediction of the quantity of the combustion reaction represents a challenge. A technology making it possible to measure the oxygen partial pressure at the generating surfaces of the cells is therefore necessary to realizing an accurate grasp of the quantity of the combustion reaction during frequency durability tests.

3. Goals

The research discussed in this paper set two goals in order to reduce performance decline in fuel cell stacks. One of these was to develop a system for the measurement of the distribution of oxygen partial pressure at the generating surfaces in an actual cell, and to determine the distribution of the quantity of the combustion reaction in the soak state based on the actual distribution of oxygen partial pressure. The other was to focus on the distribution of oxygen partial pressure in the soak state in order to create a method of controlling the increase in the resistance of the PEM.

4. Principle of Oxygen Partial Pressure Measurement using LED-Induced Fluorescence

4.1. Selection of Method of Measurement of Oxygen Partial Pressure

Standard methods of measurement of oxygen concentration include zirconia sensors using electromotive force produced by a concentration cell, magnetic methods using the paramagnetism of oxygen, and mass analysis methods using differences in mass numbers. The present research defined the system performance factors necessary to measuring the distribution of oxygen partial pressure at the generating surfaces under actual operating conditions. These factors were that high-resolution image measurement would be possible, that gas would not be consumed by sampling, that measurements would be possible in high-humidity environments, that electrical insulation was possible and the method would not result in explosions, and that it displayed a rapid transient response. A system for the visualization of oxygen partial pressure employing LED Induced Fluorescence (LED-IF), based on the use of oxygen-sensitive reagents, was selected as a method satisfying these performance demands⁽⁶⁾. Photon density was reduced by using an LED light source rather than a laser light source. This made it possible to direct a more uniform light on samples modeling actual cells with high surface areas, and to conduct measurements in a safe environment.

4.2. Oxygen-sensitive Reagent

A Pt-porphyrin complex was used as the oxygen-sensitive reagent. Pt-porphyrin complexes become excited and fluoresce when they absorb light corresponding to their band gaps. When oxygen molecules are present in the vicinity of a Pt-porphyrin complex, part of the fluorescent energy is used as excitation energy for the oxygen molecules. Because of this, the intensity of the fluorescence declines the greater the oxygen partial pressure⁽⁷⁾. Figure 6 shows the relationship between the absorption wavelength region and the fluorescence wavelength region for the

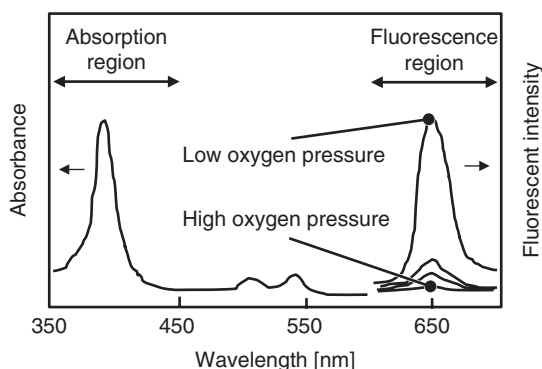


Fig. 6 Luminescence property of oxygen-sensitive reagent

oxygen-sensitive reagent selected for use in the present research. Because the absorption wavelength region and the fluorescence wavelength region are separated, it is possible to remove the effect of reflected and scattered light and selectively focus only on fluorescence originating in the reagent by restricting the measurement wavelength region⁽⁷⁾.

A calibration curve is obtained by shining an excitation light on a surface coated with the oxygen-sensitive reagent and measuring fluorescent intensity under various oxygen partial pressure conditions. Using this curve, it is possible to convert fluorescent intensity into oxygen partial pressure. Figure 7 shows an example of an actual calibration curve.

Because water is produced in the fuel cell generating environment, it is necessary to fix the reagent to help ensure that it will not be washed away by water. The oxygen-sensitive reagent selected for use in the present research contained an organic binder. The application of an annealing treatment to this organic binder strongly fixed the reagent to the coated surface, rendering it suitable for use in the fuel cell generating environment. Under high-humidity operating conditions there were cases in which the surface coated with the reagent became fogged due to condensation and the effect of scattered reflection caused deviations in the measurement results. To help avoid this, the surface coated with the reagent was further coated with a hydrophilic agent.

4.3. Configuration of Measurement Equipment

The developed LED-IF oxygen partial pressure measurement system was employed in a darkroom environment in order to help avoid any effect from external light. Figure 8 shows a schematic image of the system.

An LED light with a wavelength of 405 nm is trained on a sample coated with the oxygen-sensitive reagent. The dimensions of the LED light to be shone on the surface are adjusted using a lens. When excited, the oxygen-sensitive pigment emits fluorescent light of a wavelength

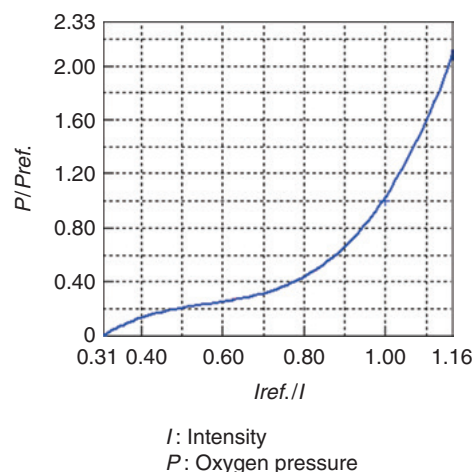


Fig. 7 Example of calibration curve

of 650 nm. At the same time, reflected light and scattered light originating in the LED light are produced around the sample. Because oxygen partial pressure is measured using fluorescent intensity, an optical filter is employed to help ensure that only the fluorescent wavelength region is captured by the camera.

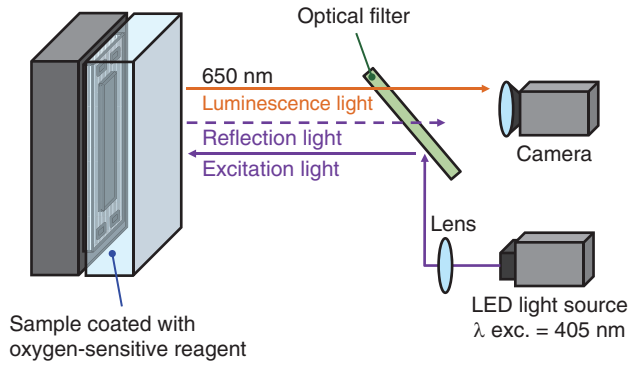


Fig. 8 Oxygen partial pressure distribution measurement system

5. Tests and Results

5.1. Acrylic Plate for Visualization of Generation

The configuration of the evaluation cell was identical to that of the cells employed in the Honda FCX Clarity. Figure 9 shows a schematic image of the cell structure.

In order to visualize oxygen partial pressure in the cathode flow paths using LED-IF, it was necessary to coat the cathode flow paths with the oxygen-sensitive reagent and capture the fluorescence emitted by the reagent using a camera. An acrylic plate for the visualization of generation was created based on the shape of an actual cathode flow path to help enable this. A high-transparency acrylic with no fluorescent agents that would affect the measurements was selected as the material for the plate. Figure 10 shows a schematic image of the plate.

The thickness of the acrylic plate and the structure of its couplings were designed with consideration of heat expansion and mechanical stress in order to make it possible to reproduce the actual high-temperature and high-voltage generating environment.

The use of comb-shaped collectors made it possible to realize uniform generation at the cathode surfaces, as in actual cells. The side of the comb-shaped electrodes for visualization was not part of the target region for measurement of oxygen partial pressure, and in this area scattered reflection affected the intensity of fluorescence when the LED light was shone on the surface. In order to respond to this effect of scattered reflection, parts other than the collecting surfaces were coated in a black pigment.

Spray coating was used to coat the areas of the acrylic plate in the cathode flow paths with the oxygen-sensitive reagent.

5.2. Verification of Operation of LED-IF Oxygen Partial Pressure Visualization System

In order to verify the ability of the LED-IF oxygen partial pressure visualization system and the acrylic plate employed for visualization of generation to determine the distribution of oxygen partial pressure, the stoichiometry-dependence of oxygen partial pressure during generation was studied.

Stoichiometry was given by Eq. (3), and was a relative value against the state in which neither too much nor too little gas was supplied for the reaction in the fuel cell, considered as 1.

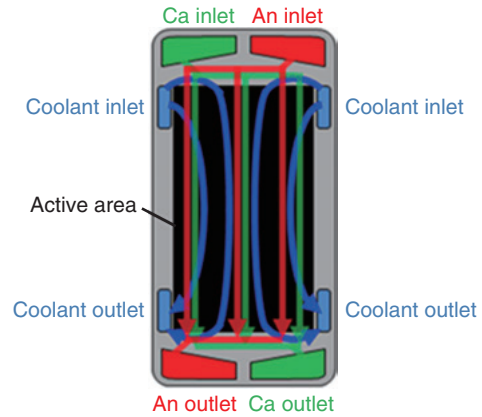


Fig. 9 Schematic image of cell structure

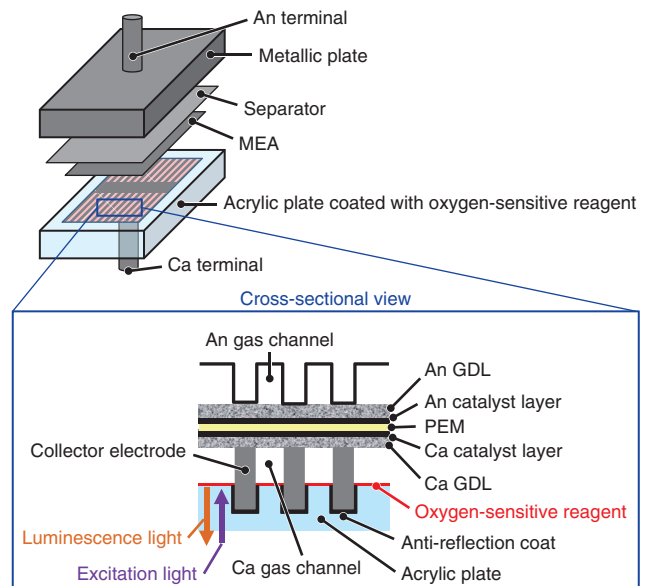


Fig. 10 Transparent acrylic plate for visualization of oxygen pressure

$$\text{Stoichiometry} = \text{Quantity of supplied gas} / \text{Quantity of gas necessary for reaction} \quad (3)$$

When stoichiometry is low, oxygen partial pressure is low due to the fact that there is little residual oxygen downstream in the cathode flow paths. The residual gas is chiefly made up of nitrogen at this time. When stoichiometry is high, oxygen partial pressure is high downstream in the cathode flow paths. Figure 11 shows calculation results.

The results demonstrate that oxygen partial pressure declines from the entrance of the cathode to its outlet. They also indicate that oxygen partial pressure at the cathode outlet increases with stoichiometry.

In order to verify the facts suggested by the calculation results, oxygen partial pressure at the cathode outlet was focused on, and the results of calculations taking oxygen consumption, working pressure, and pressure loss into consideration were compared with measurement results for oxygen partial pressure. Figure 12 shows the results.

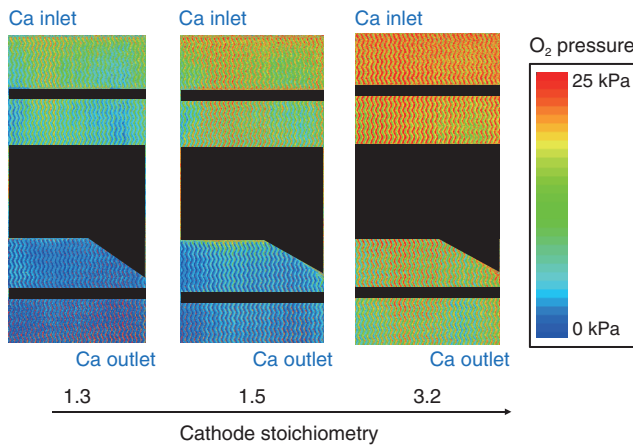


Fig. 11 Change in oxygen pressure distribution with cathode stoichiometry

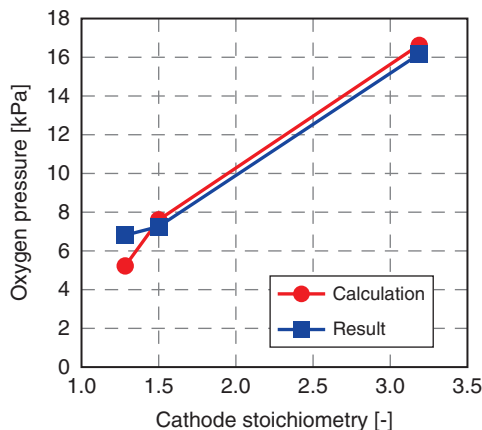


Fig. 12 Comparison of calculation and measurement results for Ca outlet oxygen pressure during generation with cathode stoichiometry

There was a good correlation between the calculation and measurement results, verifying that sufficient accuracy for the purposes of the present research had been achieved. It could also be expected that measurement accuracy would be further increased by modification of the methods of obtaining the calibration curve and of processing noise in the images.

The results discussed here verified that it was possible to measure the distribution of oxygen partial pressure during generation in a fuel cell using the developed LED-IF oxygen partial pressure visualization system.

5.3. Measurement of Oxygen Partial Pressure in Soak State

A vehicle operating environment was reproduced and measurements of oxygen partial pressure were conducted to make it possible to understand the distribution of the quantity of the combustion reaction in a soak state, when the accuracy of calculation of the quantity is low, based on actual measurements. Figure 13 shows the procedure employed in the experiment.

The quantity of water in the MEA was adjusted by means of generation. At this time, the area within the cathode was filled with air [Fig. 13(1)]. The oxygen partial pressure in the cathode tubes was adjusted in order to reproduce the application of control to stop the operation of the fuel cells. At this time, the area within the cathode displayed a uniform, predetermined oxygen partial pressure [Fig. 13(2)]. The supply of gas to the anode and cathode was stopped in order to reproduce a soak state. Because hydrogen has a high

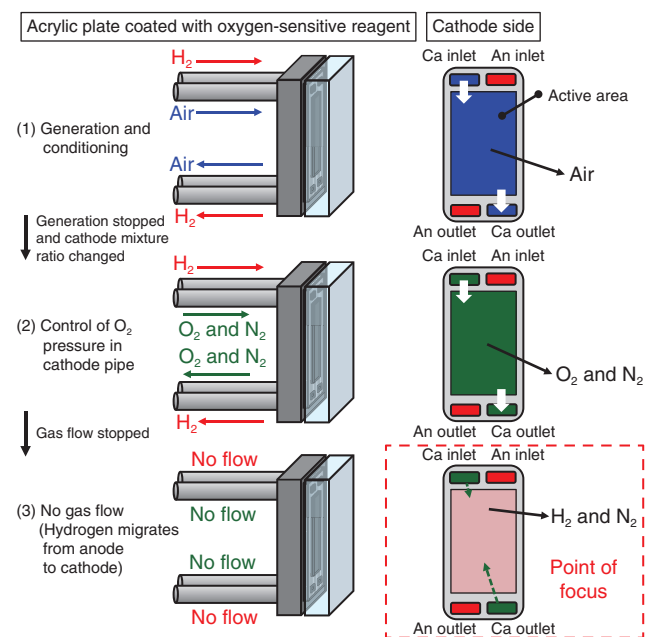


Fig. 13 Experimental procedure for measurement of oxygen pressure distribution after cessation of fuel cell operation

coefficient of membrane permeability, it migrated to the cathode side and immediately began reacting with oxygen following the commencement of the soak. The area within the cathode was therefore filled with a mixed gas composed of hydrogen and nitrogen directly after the commencement of the soak. Following this, due to the effect of buoyancy, oxygen flowed chiefly from the connecting holes at the cathode outlets, producing a mixture of hydrogen and oxygen. The distribution of Oxygen partial pressure was measured in this mixed gas environment [Fig. 13(3)]. Using the method described above, the application of control to stop fuel cell operation was modeled, and the distribution of oxygen partial pressure in the subsequent soak state was examined. Figure 14 shows the results.

It was possible to study the distribution of partial pressure in the oxygen flowing from the connecting holes at the cathode outlet at a high degree of resolution. It was predicted that at this time, hydrogen and oxygen would both be present on the CAT close to the cathode outlet connecting holes, and that the resistance of the PEM would increase simultaneously with the production of radicals by the combustion reaction. It was also predicted that the quantity of the combustion reaction would be greater and that there would be a significant increase in the resistance of the PEM in areas in which oxygen partial pressure was high.

In order to verify these predictions, the quantity of the combustion reaction in each area of the cathode was calculated from a map of the speed of the combustion reaction, using the results of measurements of oxygen partial pressure, hydrogen partial pressure, and temperature. Figure 15 shows the relationship between these results and those for the increase in the resistance of the PEM in each area of the cathode obtained from a durability test modeling a soak state.

These results verify that it is possible to predict the distribution of the increase in the resistance of the PEM using data concerning the distribution of oxygen partial pressure.

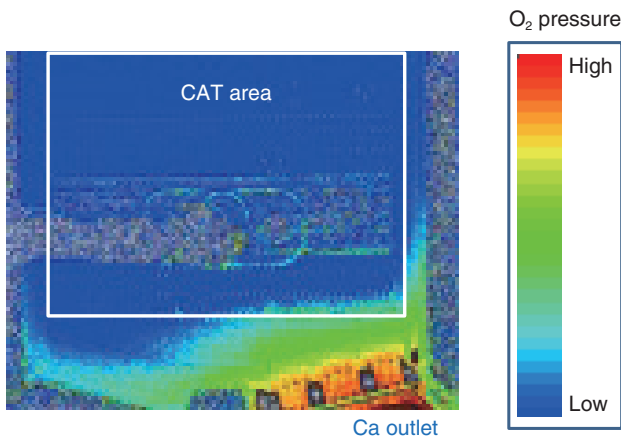


Fig. 14 Oxygen pressure distribution following cessation of fuel cell operation

5.4. Optimization of Control to Stop Fuel Cell Operation and Results of Frequency Durability Tests

Based on the results discussed in Section 5.3, it was conjectured that the main cause of the increase in the resistance of the PEM was the diffusion of oxygen through the connecting holes at the cathode outlets. In order to verify this theory, control was applied to reduce the partial pressure of the residual oxygen in the cathode tubes, and the distribution of oxygen partial pressure in the soak state was measured. Figure 16 shows the results, demonstrating that the partial pressure of the oxygen arriving at the CAT declines as the partial pressure of the residual oxygen in the cathode pipes declines.

Based on these results, it can be predicted that it would be possible to reduce the quantity of the combustion reaction and control the increase in the resistance of the PEM by creating a control that reduced the partial pressure of the residual oxygen in the cathode tubes during frequency durability tests. In order to verify this prediction, frequency durability tests were conducted using conventional control and the newly developed

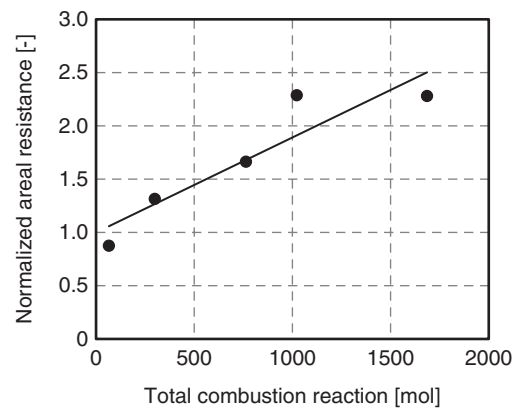


Fig. 15 Relationship between combustion reaction and PEM areal resistance derived from oxygen pressure distribution

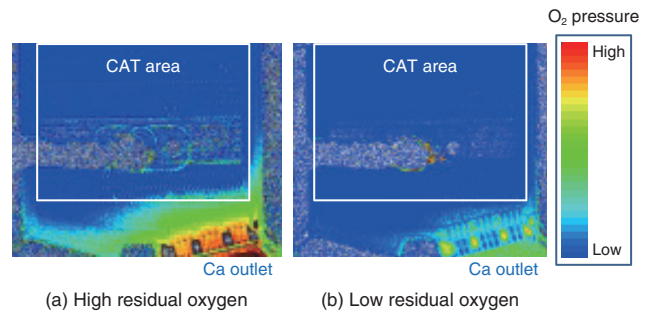


Fig. 16 Comparison of oxygen pressure distribution due to residual oxygen pressure in cathode pipe

control designed to reduce the partial pressure of the residual oxygen in the cathode tubes, and the distribution of the increase in the resistance of the PEM following the tests was compared. Figure 17 shows the results, which correspond well with the prediction that the resistance of the PEM would increase in areas at which oxygen arrives at the CAT, as indicated by the LED-IF oxygen partial pressure measurement system.

These results indicate that by using the developed system it is possible to predict the distribution of increase in the resistance of the PEM in a soak state, and to reduce the increase in PEM resistance by applying control to reduce the partial pressure of residual oxygen in the cathode tubes.

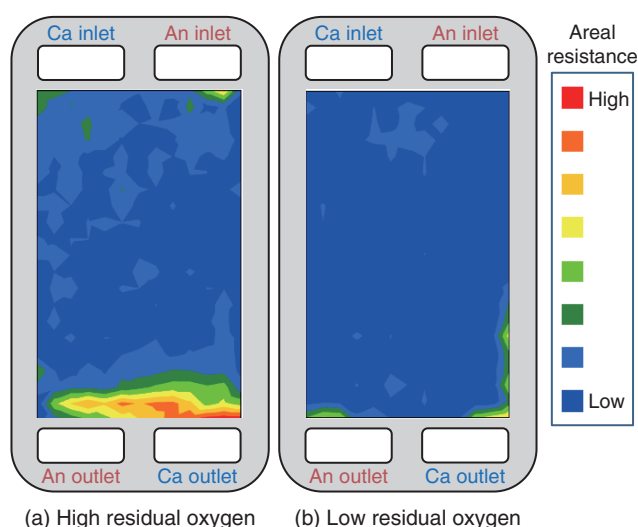


Fig. 17 Comparison of distribution of increase in PEM resistance due to residual oxygen pressure in cathode pipe

6. Conclusion

The LED-IF oxygen partial pressure measurement system developed in the research discussed in this paper was applied in the development of control to stop operation of a fuel cell vehicle, with the following results:

- (1) It was possible to measure the distribution of oxygen partial pressure in the generating environment in a cell of the same size as those used in an actual fuel cell vehicle, increasing the accuracy of determination of the distribution of the quantity of the combustion reaction.
- (2) The application of control to reduce the partial pressure of the residual oxygen in the cathode tubes at the commencement of soak in a fuel cell vehicle made it possible to control the increase in the resistance of the PEM.

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Prediction Method for Vibration Transmission of Hydraulic Engine Mount

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ABSTRACT

A vibration transfer function predictive technique for hydraulic engine mounts was devised in order to reduce medium- and high-frequency band noise (e.g. engine noise, gear noise, motor noise) while the vehicle is in motion. The procedure was to model a hydraulic mount, beginning by predicting the dynamic spring characteristics of highly deformed rubber and then performing coupled analysis of the structure and the fluid sealed therein. Then, the vehicle model was created and a mode synthesis method was used to predict the vibration transfer function from engine to body. As a result, it was possible to predict the transfer function with a precision of less than 4% frequency error and 3 dB response level error at the resonance peak. It also became possible to cut analysis time from the typical 104 hours approximately to only about 35 hours by innovating the modeling technique and calculating conditions. This technique enables advance studies of hydraulic mount characteristics on a simulation model even during the initial stages of engine development, before a prototype vehicle is available.

1. Introduction

It has become imperative in recent years to decide the specifications of vehicles during the initial stages of engine development, before a prototype vehicle is available, in order to cut development costs and time. In the field of noise and vibration, auto manufacturers have to evaluate the vehicle functions and examine the specifications in the initial stage of engine development, without a prototype vehicle.

Noise and vibration while the vehicle is in motion includes engine noise, gear noise, and motor noise in the medium- and high-frequency bands of approximately 200 Hz to 1000 Hz. Reducing this noise is an important issue⁽¹⁾.⁽²⁾ There are two channels by which power train vibration is transferred as noise to the passengers' ears: airborne propagation and solid-borne propagation. The engine mount is often the main channel for solid-borne propagation. For that reason, reducing medium- and high-frequency band noise requires advanced vibration transfer characteristics of the engine mount⁽²⁾.

In this study, a technique was devised to predict the vibration transfer function using a simulation model of vehicles in which the power train and body are coupled

to each other with a hydraulic mount. This paper gives an overview of the technique and gives the results of checking the precision of its predictions.

2. Issues and Aims

Hydraulic engine mounts are often used as main mounts. Currently, however, although there is a vibration transfer function predictive technique for the low-frequency band of up to about 100 Hz⁽³⁾, there have been no reports of the same for the medium- and high-frequency bands. There are three issues involved.

- (1) Engine mount rubber often sustains the power train load and is deformed as a result, so the dynamic spring characteristics in this state have to be predicted
- (2) No fluid and structure coupling technique has been devised for hydraulic mount modeling
- (3) Hydraulic mounts have many components, which means a large number of model elements are needed, so analysis takes a great deal of time

In this paper, the fluid and structure coupling and the long analysis time were taken up as particularly unique issues of hydraulic mounts. The aim of this paper is to devise techniques to resolve the three issues above.

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3. Devising a Hydraulic Mount Dynamic Spring Characteristics Prediction Technique

As Fig. 1 shows, hydraulic mount systems consist of three components, broadly speaking: an engine bracket, a mount, and a holder. This is similar to mount systems with only vibration insulation rubber (referred to below as conventional mounts). Hydraulic mounts are typically used to enhance riding comfort dealing with low-frequency vibration as compared to conventional mount systems. Damping of the viscosity of the fluid inside as it passes through the orifice leads to the damping of vibration in the low-frequency range.

In order to predict the vibration transfer function of a vehicle using a hydraulic mount, it is necessary to predict the dynamic spring characteristics of the hydraulic mount as a unit.

3.1. Predicting Dynamic Spring Characteristics of Vibration Insulation Rubber

As Fig. 1 shows, a hydraulic mount has more components than a conventional mount. Vibratory force input from the engine bracket passes through the vibration insulation rubber and propagates to the holder. Additionally, when the mount is installed on a vehicle, it sustains load from the power train, which causes the vibration insulation rubber to be deformed. In light of these facts, a technique that predicts dynamic spring characteristics of the vibration insulation rubber as a unit was developed, taking account of its deformation under power train load.

3.1.1. Predicting deformation of vibration insulation rubber as a result of power train load

Vibration insulation rubber that sustains power train load often undergoes great deformation, measuring about 5 mm. The stress and strain of rubber that deformed significantly are in a non-linear relationship to each other. In order

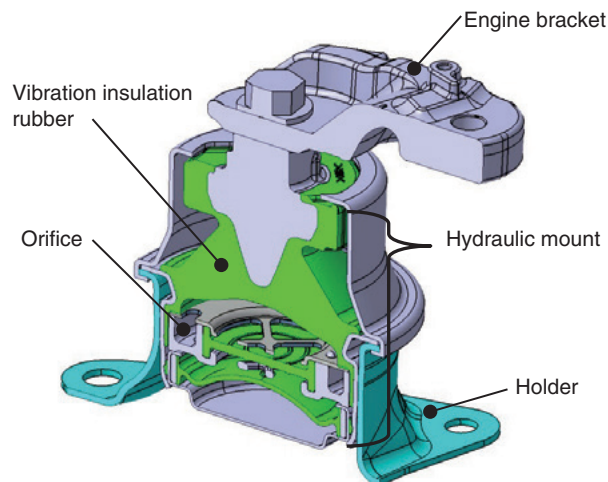


Fig. 1 Hydraulic mount systems

to reproduce this under the Finite Element Method, the Mooney-Rivlin model⁽⁴⁾ of strain energy density function W shown in Eq. (1) was used.

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{11}(I_1 - 3)(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{30}(I_1 - 3)^3 \quad (1)$$

$$I_1 = \lambda_1^2 + \lambda_2^2 + \lambda_3^2$$

$$I_2 = \lambda_1^2 \lambda_2^2 + \lambda_2^2 \lambda_3^2 + \lambda_3^2 \lambda_1^2$$

$$I_3 = \lambda_1^2 \lambda_2^2 \lambda_3^2 = 1$$

$$C_{ij} : \text{deformation tensor} \quad (i=0,1,2,3; j=0,1)$$

$$\lambda_i : \text{stretch ratio} \quad (i=1,2,3)$$

The coefficient C_{ij} in this model is derived from the results of biaxial tensile testing performed for each material and each hardness of the vibration insulation rubber.

Figure 2 shows the state of vibration insulation rubber deformation based on whether there is load, as found by simulation. It also shows results of static spring characteristics analysis of vibration insulation rubber. The analysis model is made of solid elements and yields results after 30 minutes of calculation. Predictive precision was -2.6%. This compares to the regulated target of within $\pm 5\%$ under power train load, depending on the model. This indicates that by databasing the coefficient C_{ij} and using the above model technique, it is possible to predict deformation form and static spring characteristics during the initial stages of engine development.

3.1.2. Predicting dynamic spring characteristics taking account of deformation under power train load

When vibration insulation rubber is subjected to the input of a resonance frequency, the dynamic spring constant rises. This is referred to as surging, and such surging has to be predicted in engine mount vibration transfer.

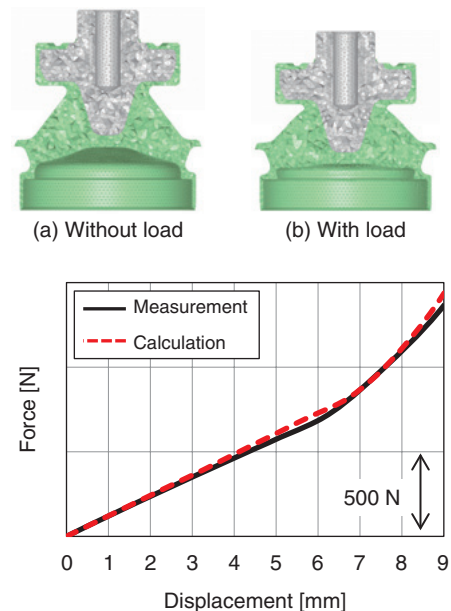


Fig. 2 Static spring analysis accuracy

The vibration insulation rubber's Young's modulus and structural damping coefficient vary according to the material and its hardness. Because the stress and strain of rubber have a non-linear relationship to each other, it is challenging to determine the Young's modulus to apply to it. The Young's modulus must be determined with the amount of strain as based on actual phenomena, or the surging frequency will deviate from actual phenomena. Thus, the following two methods were considered.

- i. Applying a Young's modulus based on strain distribution
- ii. Applying a uniform Young's modulus based on rubber form, hardness, and material

Vibration insulation rubber that is deformed as a result of sustaining power train load shows the distribution of strain, as illustrated in Fig. 3.

In Method i, a Young's modulus is applied based on the strain distribution derived in Section 3.1.1. In Method ii, a Young's modulus and structural damping coefficient are applied uniformly to the vibration insulation rubber model. Points A and B in Fig. 3 are the points where the greatest and least respective amounts of strain as derived in Section 3.1.1. were found. Figure 4 shows the relationship between stress and strain. The slope is the Young's modulus. The difference in slope of the same rubber hardness at Points A and B is small for the engine mount, which is the subject of this paper, and the relationship between stress and strain shown in Fig. 4 could be deemed as linear.

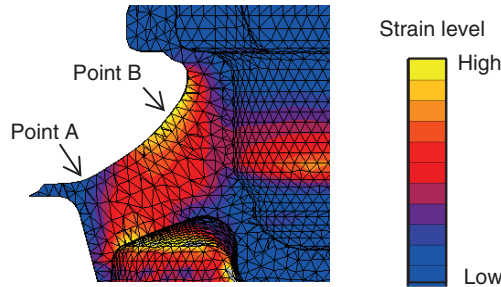


Fig. 3 Distribution of strain

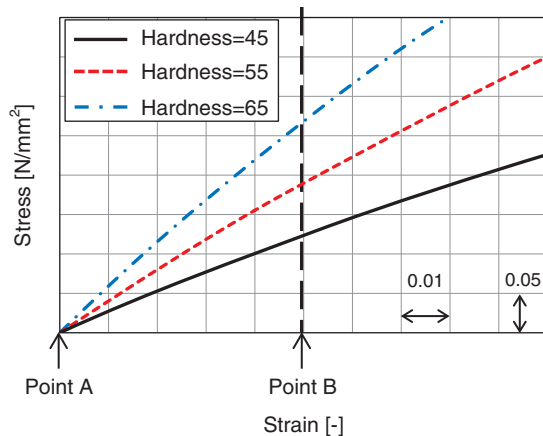


Fig. 4 Stress-strain characteristics

On the other hand, the difference in slope at hardness levels 45 and 55 was 54.5% at Point A and 55.7% at Point B, which is not negligible.

Therefore, it was assumed that equivalent calculation accuracy was obtained by creating a database for each hardness level and applying the same Young's modulus to all elements. A database was made not just for each rubber hardness but also for each rubber form and material, and structural damping coefficients were also included in a database. This method (Method ii) requires creating new databases, but it has an advantage in that it makes calculation time only about 10 minutes, even as it provides equivalent calculating precision to Method i (the precision difference between these two methods is within 2.8%). Based on the above consideration, it was decided to use Method ii.

Following are details on the method for databasing the Young's modulus and structural damping coefficient of Method ii. The method of measuring dynamic spring characteristics is as shown in Fig. 5. The vibration insulation rubber is affixed to a shaker and given the same initial strain that occurs in a vehicle when a power train is installed. After that, forced vibration is applied to the engine bracket at a fixed acceleration and the frequency is increased at fixed intervals. In the simulation model, rigid elements were used to reproduce a similar affixing as when the vibration insulation rubber was measured and a similar input as when the measurement was applied from the engine

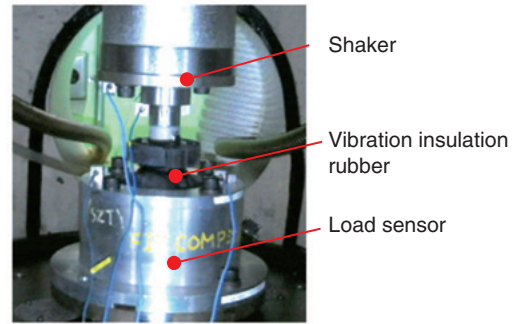


Fig. 5 Test setting

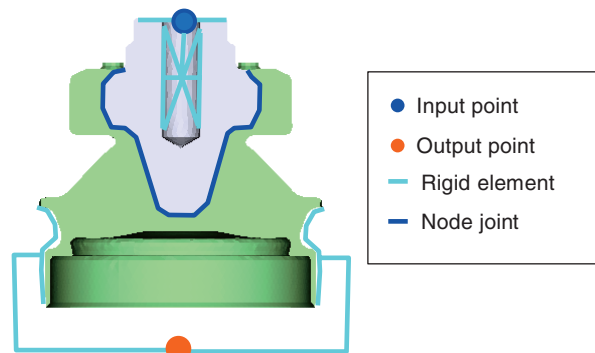


Fig. 6 FE model

bracket (Fig. 6). Proceeding in the above manner, it was possible to find a Young's modulus and structural damping coefficient satisfying the target precision during surging, namely within $\pm 3\%$ for frequency and $\pm 10\%$ for dynamic spring level, as shown in Fig. 7.

Figures 8 and 9 give examples from the materials databases created for this research, illustrating databases for a heat-tolerant super-low-motion amplifier for the conical mount shown in Fig. 6. Figure 10 shows results of general usefulness testing by making several models using the values established from these databases. In all cases, the results satisfied the target precision of within $\pm 3\%$ for frequency and $\pm 10\%$ for dynamic spring level. Therefore,

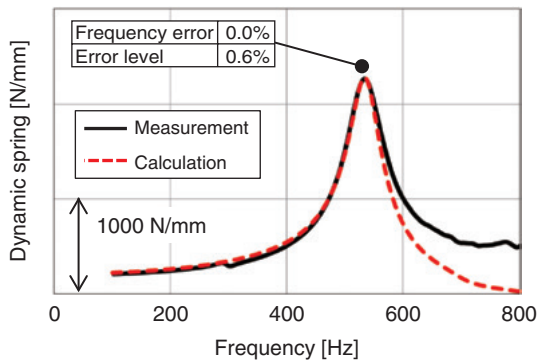


Fig. 7 Accuracy of dynamic spring analysis

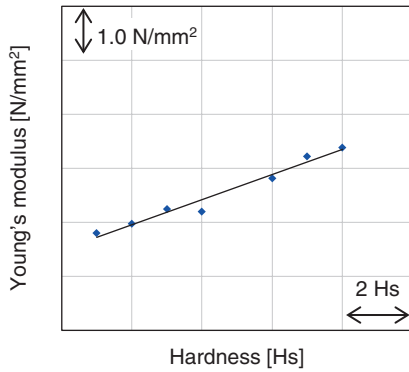


Fig. 8 Material database of Young's modulus

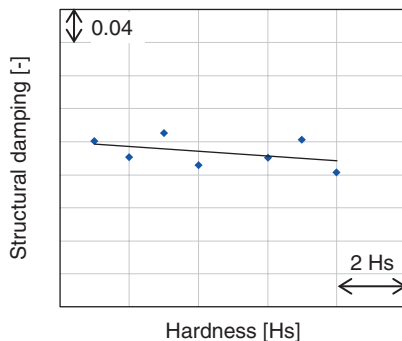


Fig. 9 Material database of structural damping

once the form, hardness, and material of vibration insulation rubber have been determined, it is now possible to estimate the Young's modulus and structural damping coefficient at the initial stages of engine development. Using the above technique, one can now predict the dynamic spring characteristics of the vibration insulation rubber as a unit, taking account of its deformation under power train load, during the initial stages of engine development.

3.2. Predicting Dynamic Spring Characteristics of Hydraulic Mount Components

Hydraulic mounts have an incompressible fluid sealed inside the mount, as illustrated in Fig. 1. To simulate this precisely, it is necessary to do a coupled analysis of fluid and structure. In the medium- and high-frequency bands, the mount input is of very slight amplitude, so the fluid flow was considered nonexistent. Taking Eq. (2) as a precondition, Eq. (3) expresses the coupled analysis as based on the fluid and structure pressure.

$$\rho \ddot{u} = -\nabla p \quad (2)$$

ρ : density
 $\ddot{u}$: acceleration
 p : pressure

$$\begin{bmatrix} M_s & 0 \\ -A^T & M_f \end{bmatrix} \begin{Bmatrix} \ddot{u}_s \\ \ddot{p} \end{Bmatrix} + \begin{bmatrix} B_s & 0 \\ 0 & B_f \end{bmatrix} \begin{Bmatrix} \dot{u}_s \\ \dot{p} \end{Bmatrix} + \begin{bmatrix} K_s & A \\ 0 & K_f \end{bmatrix} \begin{Bmatrix} u_s \\ p \end{Bmatrix} = \begin{Bmatrix} p_s \\ p_f \end{Bmatrix} \quad (3)$$

M : mass, B : damp, K : stiffness, u : displacement
 s : structure, f : fluid, A : boundary matrix, P : load

The fluid's volume elasticity modulus K_f is defined in Eq. (4).

$$K_f = C^2 \rho \quad (4)$$

C : speed of sound

The first thing to do was to judge whether coupled analysis of the fluid and structure is possible. In order to start from a simple structure, an analysis model and hydraulic engine mount trial equipment from which the membrane had been removed was prepared. The membrane

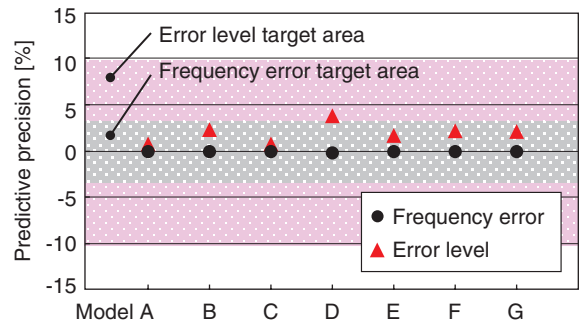


Fig. 10 General-purpose inspection of predictive technique

was made of rubber and separated the fluid chamber inside the mount into two parts, above and below, as shown in Fig. 11.

The measuring technique was similar to the measurement of dynamic spring of the vibration insulating rubber as a unit in Section 3.1.2.: trial equipment was put into the dynamic spring tester, forced vibration was applied at a fixed acceleration, and the frequency was increased at fixed intervals. In the analysis model, the same internal structure with the membrane removed as in the trial equipment was also prepared in the analysis model. In the model, similar affixing and input as in the actual experiment were given. The vibration insulation rubber material values used were values showing correlation between analysis and experiment as in Figs. 8 and 9. Additionally, the fluid model was defined with solid elements. In order to perform more precise coupling, the boundary nodes of the fluid model elements and solid model elements were set to have the same coordinates (Fig. 12). The material values of fluid elements were defined as density ρ , damping B_f , and speed of sound C .

Results of analysis as compared to measurement are shown in Fig. 13, along with dynamic spring characteristics of vibration insulation rubber as a unit, as measured in Section 3.1.2. The results showed that the technique was able to simulate the hole resonance close to 200 Hz as well as the dissipation of the surge close to 500 Hz. Hole resonance is a phenomenon such that the vibration insulation rubber is dynamically vibrated, and the enclosed fluid, which is under pressure from the vibration insulation rubber, resonates as a result of open holes in Device A shown in Fig. 11. The results showed that this hole

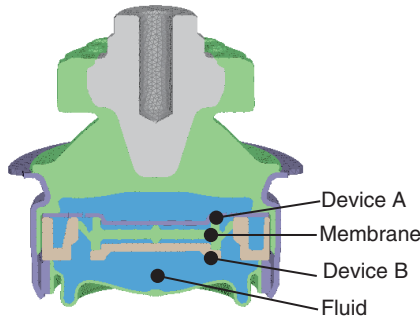


Fig. 11 Hydraulic mount

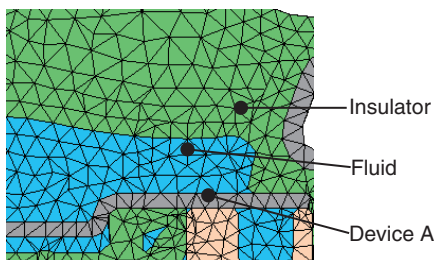


Fig. 12 Boundary condition of liquid model

resonance satisfies the target precision (frequency error within $\pm 10\%$, dynamic spring level error within $\pm 20\%$), so it may be concluded that it is possible to use pressure to perform coupled analysis of fluid and structure.

Next, the predictive precision with actual products containing membranes was tested. First, to confirm the impact of the membrane on hydraulic mount dynamic spring characteristics, three products were prepared with different membrane hardnesses. Then dynamic spring characteristics were measured in the same manner as for the vibration insulation rubber as a unit and for trial equipment with the membrane removed, as described above. Measurement results are given in Fig. 14. With the previously mentioned specimens with the membrane removed, after the hole resonance at 200 Hz, the dynamic

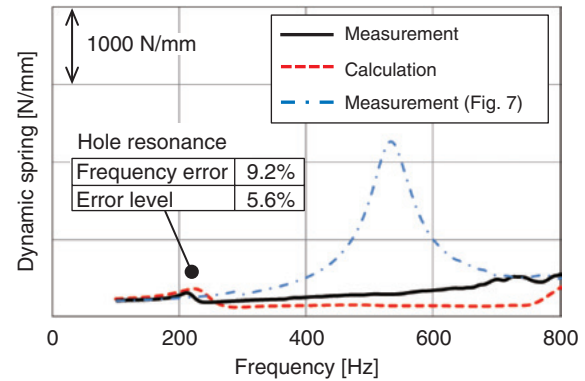


Fig. 13 Hydraulic mount without membrane model

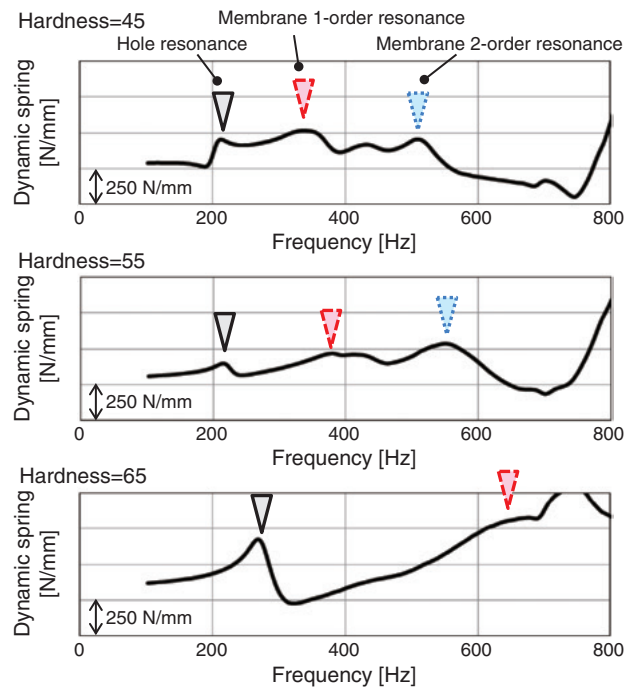


Fig. 14 Dynamic spring of hydraulic mount affected membrane hardness

spring was flat until almost 800 Hz. However, this graph shows that having a membrane causes resonance to occur between 300 Hz and 500 Hz, and as the hardness increases, so does the resonance frequency. The above indicates that the membrane affects hydraulic mount dynamic spring characteristics, so it is necessary for the analysis model to be able to reproduce membrane resonance as well.

As for the boundary conditions of the membrane and surrounding structures, these are not rigidly joined to each other in actual products, but rather are held together with a crimped structure. Therefore, the technique of joining them with a spring element was considered. For the spring constant, a value identified from results of several types of model was used.

Figure 16 and Table 1 show results of modeling with a spring element. In only about two hours of calculation time, the model was able to satisfy measuring target precision for both hole and membrane resonance (frequency error within $\pm 10\%$, dynamic spring level error within $\pm 20\%$). Based on the above, one can now predict the dynamic spring characteristics of hydraulic mount components, taking account of deformation under power train load, starting from the initial stages of engine development.

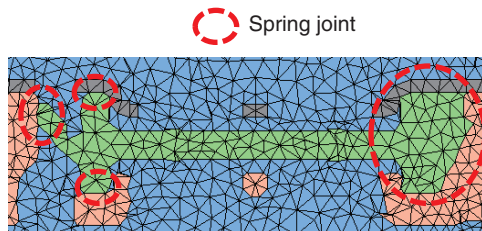


Fig. 15 Membrane mesh model

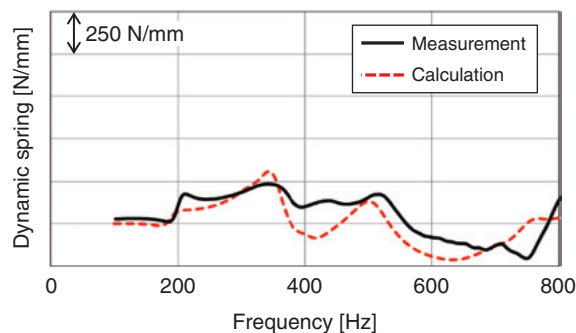


Fig. 16 Dynamic spring analysis result of hydraulic mount systems

Table 1 Accuracy of dynamic spring analysis

	Hole	Membrane 1-order	Membrane 2-order
Frequency error	-5.0%	0.9%	-3.1%
Error level	-19.7%	15.2%	-9.8%

4. Results of Application to Vibration Transfer Function for Vehicle

The mount vibration transfer function was predicted with the mount on a vehicle, as shown in Fig. 17. The new technique joined the existing technique⁽²⁾ — a computational model for metal fixtures like the bracket and holder — with power train and body models. Also, the vibration insulation rubber sustained the load of the power train and thus underwent great deformation. In attempting to reduce the technique's calculating costs, the power train model and body model were simplified to cover only those components affecting the engine mount transfer function. Also, modal reduction was performed at the mount bolting point and a vehicle model was developed by joining the components by component mode synthesis⁽⁵⁾.

The transfer function from the bolting point between the power train and engine mount to the bolting point between the body and engine mount, as found by component mode synthesis, is shown in Fig. 18. The results (peak frequency precision within 4% and peak level precision within 3 dB

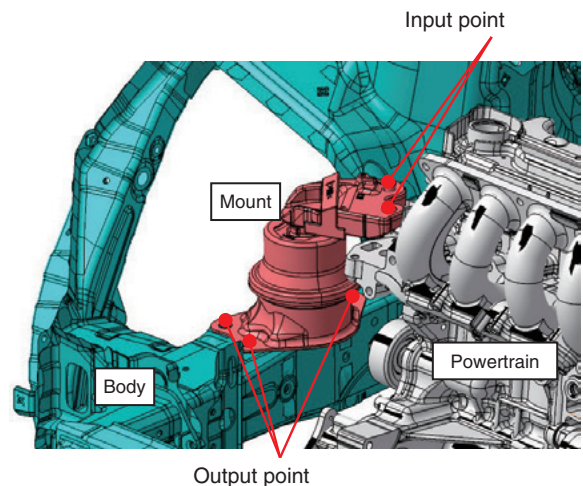


Fig. 17 Layout of mounting systems

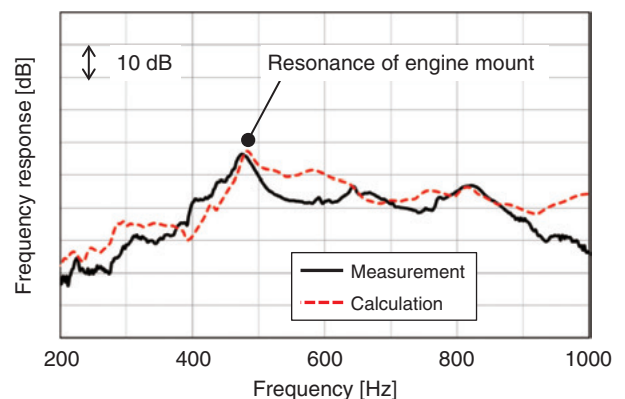


Fig. 18 Comparison between calculation and measurement for frequency response

of measured results on a vehicle) were precise enough to satisfy the targets (peak frequency precision within $\pm 5\%$ and peak level precision within ± 3 dB). Therefore, the model was able to predict the hydraulic mount vibration transfer function for engine, gear, and motor noise, etc. in the medium- and high-frequency bands of approximately 200 Hz to 1000 Hz with adequate precision.

In addition, by innovating the modeling and calculating conditions, etc., it was possible to perform analysis in just 35 hours: 24 hours to build the model and 11 hours to run the calculations. It conventionally took 56 hours to build the initial model and 48 hours to run the calculations, making a total of 104 hours. This was because of the time needed to mesh complex structures and the lengthy calculation time resulting from the increase in, for example, the coupling elements used at interfaces.

5. Conclusion

The following results were obtained in relation to a prediction technique for vibration transfer functions of hydraulic engine mounts in the medium- and high-frequency bands.

- (1) Through databasing the relationship of Young's modulus and structural damping coefficient in respect to rubber hardness, a technique was developed that predicts the dynamic spring characteristics of vibration insulation rubber while accounting for great deformation.
- (2) In addition to the technique described in (1), the dynamic spring characteristics of hydraulic engine mounts is able to be predicted by using coupled analysis of fluid sealed inside and structure.
- (3) By innovating the calculation techniques, using modal reduction of a large model, simplifying boundary conditions, and so on, the technique reduced calculating costs by about 66%.

The above made it possible to develop a technique to predict vibration transfer functions on an actual vehicle with sufficient precision for hydraulic engine mounts, which highly contributes to gear, motor, and other engine noise vibration transfer functions. This prediction technique can be applied in vehicle development, even in the initial stages of engine development, before a prototype vehicle is available.

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A Fundamental Study of Tool Embodiment for Human Dynamic Analysis Relating to Handling and Stability of Driving

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ABSTRACT

In the course of formulating methods for evaluating the handling and stability of driving an automobile, attention was focused on embodiments of the size of the automobile and its movements, which the operator absorbs into his or her own sensorimotor system. An experiment was devised to clarify the relationship between embodiment and sensorimotor activity. The experiment involved cutting paper with scissors in a virtual reality environment, where that action would be considered equivalent to steering an automobile from the perspective of processing sensorimotor system information.

In a virtual reality environment, the sensory quantity that accompanies activity is provided to the operator as feedback information. When this information was changed in various ways, the corresponding changes that occurred in the cerebral blood flow clarified the relationship between the feeling of actual operation generated during operation and the activity of the central nervous system. It was also found that the feeling of actual operation requires an appropriate sensory quantity to be presented, and that time delay in presenting the sensory quantity alters the feeling of actual operation. This experimentation during the manipulation of tools produced results that led to new ideas regarding evaluation of the handling and stability of driving of automobiles from the perspective of embodiment. In other words, it led to the proposal that it is necessary to evaluate the sensory information generated during driving.

1. Introduction

Automobiles and motorcycles have the basic capabilities to go, turn, and stop. Drivers operate these vehicles with the basic operations of providing driving power, steering, and braking. Or, for motorcycle riders, the basic operations would be providing driving power, distributing weight, and braking. Performance of the automobile or motorcycle in terms of movement according to the will of the operator is termed handling and stability of driving.

At present, quantitative evaluation of such performance in automobiles is carried out by the open-loop testing method, which looks only at the automobile, and closed-loop testing, which includes a simulated driver. In open-loop testing, movement is imparted to the automobile by means of the drive wheels, the steering system, and so on. For example, there are numerous reports of research on tire grip characteristics and simulations of vehicle movement⁽¹⁾. In closed-loop testing, on the other hand, research and development⁽²⁾ are underway on simulation technology for a driver model that is a simplified representation of a function model equipped with an input-output system that includes

a feedback loop for steering and other such operations. In closed-loop testing, robustness and other such positive and negative aspects of handling and stability of driving are evaluated from the cause-and-effect relationship between vehicle behavior and operation quantities.

Both these test methods involve the driver acting on the vehicle using prescribed methods of operation. The vehicle behavior that is generated is then quantized to be subjected to evaluation. Meanwhile, experimental systems to make quantitative observations of the driver have been designed in order to carry out the vehicle evaluation from the driver's viewpoint, and that is where handling and stability of driving have been verified using sensory evaluation, steering performance, and other such means⁽³⁾. However, the reason that the driver is able to judge the positive and negative aspects of vehicle behavior remains unexplained. In order to determine an explanation, the present research has focused on the driver's brain. Since the brain is an information processing organ, it would appear that the driver acquires some kind of vehicle information in conjunction with operation of the vehicle, and that the driver processes this information in the brain

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in order to arrive at some kind of evaluation. However, the characteristics of that information processing have not been examined. For the present research, therefore, a summary was made from presentations given to date regarding the relationship between sensorimotor information and sensory evaluation as explained by functional brain imaging and psychology experiments. This led to the concept that the perspective of sensory information provided to the driver is important in evaluating handling and stability of driving, and that concept will be described in the following.

2. Functional Brain Imaging of Sensory Information Quantities

The question here is what kind of information processing is performed by the driver's brain while driving? Driving an automobile is in effect like treating the automobile as a part of one's own body. In other words, when a driver has formed an embodiment with respect to the automobile, then the driver himself or herself is the bodily representation of the behavior in the traffic environment resulting from the movement of the driver's own hands and feet. Therefore the information processing is complex both conceptually and somatically. The conceptual aspect has to do with driving actions that can be verbalized, such as what route to take to what location at what time, what to do at the signal in the intersection, what kind of vehicle interval to maintain while driving, and so on. The somatic aspect has to do with driving actions, such as steering while feeling the lateral acceleration of the vehicle, stepping on the accelerator pedal while feeling the frictional force of the road surface, and so on. Even while driving, the control of vehicle behavior is this kind of somatic information processing⁽⁴⁾.

It is not easy, however, to make quantitative observations of some specific activity in the brain of a driver who is engaged in driving and, out of this complexity of information processing, to isolate only that information processing that is related to the sensorimotor system. Moreover, information processing in the brain has not been examined by anyone, so that the relationship, for example, between the magnitude of the lateral acceleration of a vehicle and driver operation or sensory evaluation remains unexplained. Controlling the disarrangement of driving posture caused by lateral acceleration while driving through a turn also constitutes information processing in the brain that involves the sensorimotor system. Even if the focus is placed on operation of the steering wheel in such a situation, there is a chance that other components of brain function will also end up being included in the measurement. Thus, it is not easy to separate out the multiplicity of brain function tasks that arise simultaneously in the same signal.

What requires attention in making quantitative observations of brain function, therefore, is how the tasks are framed. The aim of the present research is to begin by first laying a cornerstone. Attention was therefore focused on sensorimotor information processing during the activity

of tool operation that is qualitatively equal to the operation of an automobile. The experimental system described below was built and used to make quantitative observations of brain functions. An overview of that research will be given⁽⁵⁾.

2.1. Configuring an Experiment Qualitatively Equal to the Operation of an automobile

Functional brain imaging in a sensorimotor system requires comparative experiments in which research participants are presented with multiple types of sensory information. At the same time, when planning the experiment, as noted above, it is necessary to simplify the experiment in order to extract only sensorimotor system data from the complex information processing environment. It was decided, therefore, to use virtual reality (VR) technology to make the sensory information quantities variable. In order to reproduce qualitative equality with the operation of an automobile from the perspective of sensorimotor information processing even in a simplified experiment, an experiment using scissors to cut paper was planned.

The question of why operating an automobile and using scissors are qualitatively equal was addressed. In operating an automobile, the driver predictively establishes a line on which to drive over the route to the destination. In order to convert the power generated in the vehicle to movement, the driver turns the steering wheel, for example. The changes in physical quantities that constitute vehicle behavior are sensed by means of receptors, and movement proceeds while the driver makes adjustments in the amount of steering applied. Similarly in operating a pair of scissors, the user predictively establishes a course that the scissors will follow in order to cut out the envisioned shape. While sensing changes in resistance from place to place due to differences in paper thickness as well as differences in the fiber direction, the user engages in the work of connecting the cutting points along a line while adjusting the speed in opening and closing the scissors and the point of cutting action. Proceeding from this perspective, an experimental evaluation of sensorimotor information processing was performed with a focus on the qualitative equality of driving an automobile and operating scissors in terms of the following six items:

- (1) The tools are familiar;
- (2) The feedback is not instantaneous, as with the blows of a hammer, but is continuous during the operation;
- (3) The operation occurs through comparison of prediction and results;
- (4) The results along the way make up the course to the final objective;
- (5) The operation is carried out with care because errors could lead to injury; and
- (6) There is a double interaction: between the person and the object of operation, and between the object of operation and the outside world.

The work tasks were configured at four levels, with variations occurring only in sensory information relating to the cutting work. In other words, as shown in Table 1, there were these four tasks: the task of using real scissors to cut real paper (referred to below as the real scissors task); the task of opening and closing the right hand while wearing a sensor glove so as to use scissors drawn using computer graphics (CG) to cut CG paper in virtual reality (referred to below as the VR scissors task); the same task with the addition of the sound of cutting and a tactile vibration signal (referred to below as the VR scissors task with added auditory-tactile stimulus); and the task of observing VTR playback of recorded imagery showing another person performing the work of cutting in a real environment (referred to below as the VTR observation task).

The research participants were five right-handed adult males of the Mongoloid type. In their left hands, they held real paper and virtual paper that they drew toward themselves as if reeling it in. Tactile vibration signals were provided by vibrators placed at multiple locations on a glove, as shown in Fig. 1. The vibrators consisted of motors that rotated eccentrically placed weights to produce vibration. The research participants wore these gloves and made motions as though they were using a pair of scissors. As shown in Fig. 2, imagery of these hand movements was generated on-screen by CG.

2.2. Cerebral Blood Flow Imaging by NIRS and Experimental Protocol

Functional brain imaging was performed by observing changes in cerebral blood flow. When neuron clusters in the brain are active, arterial blood to the activated area increases in order to supply it with oxygen and sugar. Near Infrared Spectroscopy (NIRS) is able to observe the cerebral hemodynamics of oxyhemoglobin and deoxyhemoglobin, which have different light-absorbance properties, by directing near infrared light from the outside of the scalp and detecting the scattered light that returns from the brain. Hemoglobin is contained in the blood, so changes in hemoglobin concentration indicate changes in blood flow. When hemoglobin increases, its absorbance increases so that there is a decrease in the amount of scattered light detected. Although the simultaneous equations and other detailed information on this method will not be provided here, different amounts of scattered light are detected from oxyhemoglobin and deoxyhemoglobin at the multiple wavelengths of light to which they are exposed, and based on those values, relative changes in hemoglobin concentration can be calculated⁽⁶⁾. Sensors are placed from the forehead to the top of the head, distributed in a left-right symmetrical grid that has 24 sensors at 3 cm intervals. The experimental protocol calls for participants to perform 10 experimental blocks. For each block, they rest quietly with eyes closed for 20 seconds, then perform their tasks continuously for 20 seconds, immediately following which they again rest quietly with eyes closed for 20 seconds. The

Table 1 Experimental tasks for measurement of brain

	Real task	VR tasks		VTR observation task
Experimental scenarios				
	Real paper with real scissors	VR paper with VR scissors generated using sensor glove on right hand	Auditory and tactile sensory information added to task at left	Observing video recording of real task performed by someone else

blocks are separated by intervals of two to three minutes. Other tasks are presented to participants on different days at the same time of day, taking the influence of their circadian rhythm into consideration. The order in which tasks were presented was randomized and differed for each research participant.

In quantizing the changes in oxyhemoglobin concentration (ΔCoxy), the average of hemoglobin concentration changes in the period of 0-20 s was defined as the change in concentration for the period at rest. The average of hemoglobin concentration changes in the period of 20-40 s was defined as the change in concentration for the work period. Since each task is performed for 10 iterations, 10 sets of rest values and work values are



Fig. 1 Vibrators on right-hand glove. Five small motors are placed at circled locations on the tops of the fingers and one on the palm.

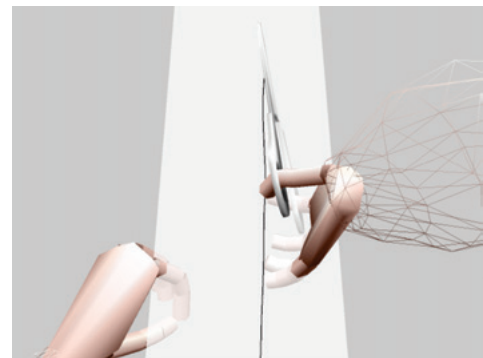


Fig. 2 VR environment with right and left hands, a pair of scissors, and a sheet of paper displayed by CG

calculated for each experimental level. These values were used to judge whether changes in hemoglobin concentration during work on tasks was significantly different from concentrations when at rest by conducting paired, two-tailed t-tests. Quantization of data on changes in hemoglobin concentration in the period of 40-60 s was used to eliminate drift components caused by imaging equipment.

2.3. Results from Analysis of Functional Brain Imaging

The area that showed conspicuous activation to a significant degree in all research participants during the real scissors task was the prefrontal area of the left hemisphere. Since the research participants were using the scissors with their right hands, the resulting activation in the left hemisphere was in agreement with findings to date that sensory input and motor output involve opposite hemispheres of the brain. The observation of activation in the prefrontal area during work is also in line with the findings of neuroscience, since the prefrontal area is said to govern the integration of movement and sensory information, and activation of this area would be expected with work that involves both motor output for opening and closing the scissors and sensory input of feedback information from receptors. On the other hand, no activation was observed around the prefrontal area of the left hemisphere in any research participants during the VTR observation task, and no common areas of activation were observed in imaging areas among the research participants. Neither were any common areas of activation observed in any of the research participants in either of the VR scissors tasks. In order to make a comparison across all tasks, therefore, the focus was placed on hemodynamics in the vicinity of the left prefrontal area where activation was observed during the real scissors task. The arithmetic mean of the change in oxyhemoglobin concentration in the vicinity of the left prefrontal area during this work was calculated for all the experimental subjects. According to ANOVA, the difference in magnitude between the two is $F(3,12)=6.712$ and $p<0.01$, suggesting that the difference is due to the difference in task. The results are shown in Fig. 3. The fact that the VR scissors task showed a greater change in blood flow by comparison with the VTR observation task in the vicinity of the left prefrontal area, where activation occurred with real scissors, suggested that the VR scissors task results in greater cerebral activity. The VR scissors task with auditory-tactile stimulus showed even greater change in blood flow and so suggested greater cerebral activity than the VR scissors task, which involved only the visual sense.

Before this imaging was carried out, the research participants were given opportunities to make trial runs of each task in order to become accustomed to it. At that time, the participants were asked to rank the tasks in order of the extent to which they felt real. All the research participants ranked the tasks in ascending order of feeling of reality from VTR observation task (lowest), to VR scissors task, VR scissors task with added auditory-tactile stimulus, and

real scissors task (highest).

Listing the tasks in order from smaller blood flow change to larger, they go from VTR observation task (smallest), to VR scissors task, VR scissors task with added auditory-tactile stimulus, and the real scissors task (largest), which is the same order of tasks in terms of the feeling of reality related above. The magnitude of blood flow indicates the degree of activation of the brain, which expresses the degree of information processing activity in the brain. This experiment allows for variation of the sensory information quantities, and it is also apparent that the feedback information in the sensorimotor system during the performance of the tasks increases in order of sensory information quantity, from the VTR observation task (lowest), to VR scissors task, VR scissors task with added auditory-tactile stimulus, and the real scissors task (highest). The results of this experiment, therefore, yielded the suggestion that information processing in the brain that integrates the abundance of work feedback information and physical activity is required in order to obtain the feeling of actual operation of a tool, or in other words, to obtain a response. The above are the experimental results relating to the presence or absence of sensory information quantities accompanying activity and to their magnitude.

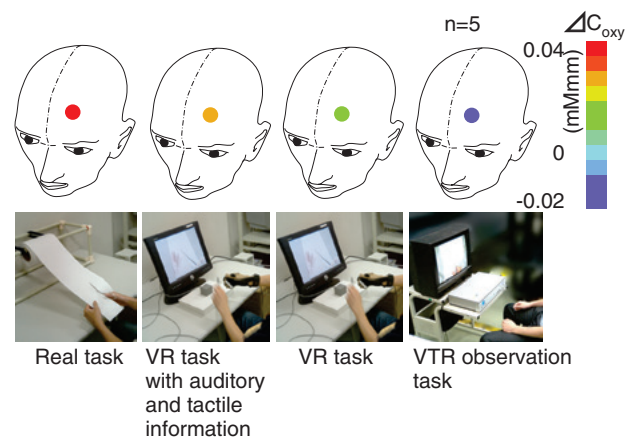


Fig. 3 Experimental result for measurement of brain activation

3. Evaluation of Time Delay in Manifestation of Sensory Information

Evaluation tests were conducted to determine what kind of operating impression the operators had regarding the time characteristics of sensory information, and those research results⁽⁷⁾ will be outlined next. The eight research participants were right-handed. At this point the VR scissors task with added auditory-tactile stimulus described in Chapter 2 was used as the basis for preparing a test environment in which the timing for presenting sensory information feedback to the research participants

was deliberately delayed. Even when the system is not specially configured for a delay in presentation, this VR experimentation system includes a delay of 50 ms that accompanies the sensor input, which occurs approximately 20 times per second, together with the various types of computation process and the drawing updates. There were four presentation test conditions of no delay (including the 50 ms), 200 ms, 500 ms, and 1000 ms. The VR system used for functional brain imaging described above was used with the no delay condition.

The experimental protocol has the research participants using VR scissors to cut the equivalent of 50 cm of VR paper under two of the four types of delay conditions. After the cutting work, they provide a comparison in terms of sensory evaluation. Using all combinations, there are six combinations of test conditions for paired comparison. Their order is randomized so that the order will vary with each research participant. Participants respond to the sensory evaluation using the following five levels regarding each combination of cutting work: (1) the operational feeling is better with the former delay environment; (2) the former is somewhat better; (3) there is no discernible difference; (4) the latter is somewhat better; and (5) the latter is better.

Since each delay was randomized, as described above, it was supposed that there was no order effect and the analysis was carried out using Scheffe's method of paired comparison with Nakaya's modification, in which the order is not shuffled. The results of analysis are shown in Table 2.

As shown in Table 2, no significant difference was found between the evaluation by research participants and the evaluation by combinations of delay conditions. However, a significant difference was found in the evaluations of delay conditions, with a significance level of 1%. The magnitude relations of those delay conditions, based on their statistical scores, are as follows. In terms of operational feeling, the no delay condition was best, followed by the 200 ms delay condition. Both these conditions yielded positive impressions. In terms of negative operational feeling, however, the 500 ms and 1000 ms delay conditions were cited, and the 1000 ms delay condition produced even more negative impressions.

In interviews conducted after the experiments, all the research participants indicated a similar tendency in their impression of operation with the 200 ms delay, using such expressions as, "It was sluggish," "It felt like I was cutting through something thick," "The scissors were stiff and their movement was slow," and so on. For this reason, half of the research participants responded that work under no delay conditions was "somewhat better." Under 500 ms and 1000 ms delay conditions, they related their impressions with such statements as "It wasn't possible to perform cutting operation in a normal manner, and that was very stressful," "It was difficult to cut in a straight line," "It felt as though I had become an old person," and so on. This showed that providing sensory information feedback generally simultaneously through a sensory organ elicits a positive

Table 2 Results of Scheffe's method of paired comparison with Nakaya's modification

Source	Sum of squares	Degree of freedom	Unbiased variance	F
Total	100	48		
Main effects	85.187	3	28.395	241.54
Main effects × personal	9.3125	21	0.4434	3.7721
Combination effects	0.5625	3	0.1875	1.5949
Error	4.9375	42	0.1175	

Here, $F(3,7,0.01)=8.451252 < 241.54$, $F(21,7,0.01)=6.132382 > 3.7721$, $F(3,42,0.01)=4.285255 > 1.5949$

operational feeling, and, on the other hand, that a longer time interval from when the operation is completed to when sensory information is obtained makes the operation itself difficult to perform or gives the impression that the tool being operated, or the object of operation, or even the operator has somehow deteriorated or changed into something different.

4. Evaluation of Sensory Information

In the research introduced in Chapter 2, the research participants simultaneously experienced both tactile and auditory sensory information. The question then is how the different kinds of sensory information affected the operating impression. The following will provide an overview of research on the relationship between sensorimotor information and the operating impression⁽⁸⁾.

4.1. Relationship between Tactile Stimulus and Operating Impression

The experiment introduced here involved cutting in the VR system, described above, carried out under the no delay condition, which includes a 50 ms delay, and without any cutting sound, meaning without any auditory signal. The tactile vibration signal provided during VR scissors operation was in three levels of intensity. Five sets of tactile vibration signals of different intensities were prepared according to the fingers or palm area where the vibration sensation was to be provided. Given the earlier examination results obtained prior to this experiment, the tactile vibration feeling was assigned three levels of intensity: (1) imperceptible unless the operator is paying attention; (2) perceptible; and (3) no vibration. The stimulus provided to the fingers was to the thumb, index finger, and middle finger, and to one location in the palm. The following five combination patterns were prepared:

- (a) Fingers: Vibration (2) + Palm: Vibration (2)
- (b) Fingers: Vibration (2) + Palm: Vibration (1)
- (c) Fingers: Vibration (2) + Palm: Vibration (3)
- (d) Fingers: Vibration (1) + Palm: Vibration (2)
- (e) Fingers: Vibration (3) + Palm: Vibration (2)

Six research participants cooperated with the

experiment, each performing every pattern three times in random order for a total of 15 iterations. The participants were asked to describe whether the operating impression obtained in the various VR scissors environments was close to an actual operational feeling, rating the presence or absence of realistic sensation in seven levels.

As a result, the average values for operating impression placed the patterns in descending order as follows: (b)>(c)>(a)>(d)>(e). It was found from this that a lower intensity of tactile vibration feeling in the palm was preferred, and that having some tactile vibration feeling in the fingers that is not too strong was effective in producing an operating impression with a realistic sensation.

4.2. Relationship between Auditory Stimulus and Operating Impression

The next example to present here is the experiment to determine how cutting sounds, which are an auditory stimulus, affect the scissors operating impression. This experiment involved cutting in the VR system, described above, carried out under the no delay condition, which includes a 50 ms delay, and without any tactile vibration signal. The cutting sounds were not electronically synthesized sounds, but rather recordings of actual cutting sounds made using ordinary printer paper. The sounds were replayed to match the operation using VR scissors to cut VR paper. Seven types of recorded sounds that were envisioned with the use of everyday tools were prepared:

- (A) Blade length 45 mm, stainless steel, office use
- (B) Blade length 60 mm, stainless steel, office use
- (C) Blade length 75 mm, stainless steel, office use
- (D) Blade length 105 mm, stainless steel, office use
- (E) Blade length 140 mm, stainless steel, office use
- (F) Blade length 40 mm, stainless steel, zigzag scissors, office use
- (G) Blade length 100 mm, steel, sewing scissors, cloth use

Cutting sound (C) was used for the functional brain imaging described above as well as for sensory information delay tasks.

Six research participants were presented with three iterations of the experiment conditions in random order, for a total of 21 iterations. The participants were asked to evaluate their impressions of the sounds using seven levels to indicate the extent to which the sounds were close to actual operation sounds.

Results from comparison of the averaged impression evaluation scores showed that there was a descending order as follows: (A)(best)>(D)>(E)>(C)>(G)>(B)>(F) (worst). In addition, for example, comments from several of the research participants indicated that the cutting sound from (G) was a higher sound so that it felt lightweight in operation and did not feel real. Every cutting sound used in this experiment had its unique characteristics. From this existence of the evaluation order for the operating impression, it was found that there is an effective frequency band of cutting sounds for operating scissors, and that not

only the presence or absence of cutting sound but also the sound characteristics can change the operating impression. According to sensory evaluation for fatigue, the results showed that participants grew less tired in environments with a cutting sound⁽⁹⁾.

4.3. Relationship between Auditory-Tactile Stimulus and Operating Impression

From the sequence of research described above, the last experimental results⁽⁸⁾ to be introduced here will clarify how these auditory stimuli and tactile stimuli affect the operating impression. The experiment carried out with six research participants took place as follows. The VR experimental system was configured with condition (b) from Section 4.1 and condition (D) from Section 4.2 for the cutting sound conditions. The following four conditions were used in the comparative experiment.

- (1) CG only
- (2) CG with tactile stimulus
- (3) CG with auditory stimulus
- (4) CG with tactile stimulus and auditory stimulus

The research participants were asked to evaluate their impressions, responding with seven levels to indicate the extent to which the stimuli were close to actual operation stimuli. One point would be given when there was no realistic sensation, and seven points given when there was realistic sensation. Results from comparison of the averaged impression evaluation scores were (1) 2.3 points, (2) 3.8 points, (3) 5.3 points, and (4) 6.0 points. It was found from these results that the tactile stimulus raises the evaluation score in the VR paper cutting task using VR scissors, but that the effect is not as great as that achieved by auditory stimulus.

5. Handling and Stability of Driving as Viewed from Human factors

The paper to this point has described how sensory information and operating impression are related in connection with movement or activity. These findings will be summarized and examined in terms of the relationship between tools and human beings.

An abundance of sensorimotor system information accompanying operation is required, as explained in Chapter 2, in order to obtain the actual feeling of using a tool. Neural activity has a hierarchical structure. At the lower level that sends signals directly to the muscles, it is thought that before a muscle becomes active, it simulates the results of an activity program, or, in other words, it predicts its activity⁽¹⁰⁾. The activity simulation also simulates the sensory signals that are probably generated by activity. These simulations in the sensorimotor system compare the predictions with actual results of activity; that is, they compare to see whether the predictions match up with the physical world. Therefore, a sensory system has a predictive anticipation of input from the physical world for the kind of

sensorimotor activity that is going to be generated. In other words, the brain creates an information processing loop with respect to the control objective in order to ascertain the difference between the input and the prediction.

Meanwhile, activity programs, cognitive processes and other such activities of consciousness that have a cohesive unity are known to be retained for about three seconds at most, so that phenomena occurring within a period of three seconds are treated as a single psychological unit by the nervous system⁽¹¹⁾. There is also Pavlov's classical conditioning, and learning related to the stimulus is known to be reinforced by delayed conditioning as well as by simultaneous conditioning⁽¹²⁾. In other words, the central nervous system has a predisposition to automatically reinforce learning by the relationship between information input and motor output. Therefore, the operator's central nervous system works automatically to look for and form associations between work and information generated during work, and it learns the sensorimotor information processing loop.

Although termed learning, this is not some special cognitive activity. Any activity of the central nervous system simultaneously involves not only performance that achieves the work objective, but also learning that acquires knowledge and skills for the purpose of performing work tasks⁽¹³⁾. As described in Sections 4.1 and 4.2, simulated vibration and cutting sounds are presented as sensory feedback during VR scissors operation. That auditory-tactile VR information is presented at approximately the same time as the work task, and even though it is presented through the backs of the fingers and the palm of the hand, and from speakers, which makes it differ from the actual operation of scissors, this information is taken into the sensorimotor information processing loop and ends up being treated as real. This indicates how powerful learning is. Evaluation of the cerebral blood flow showed that the extent to which these sensations appear real was correlated with the abundance of sensory information input that is integrated with motor output. Therefore, the tool that is being operated becomes an extension of the operator's body, and in order to enhance that embodiment, or to maintain the embodiment, it is necessary to have sensory information of a quantity and quality appropriate to the work.

However, sensory information that is appropriate to the work does not simply mean sensory quantity. Chapter 3 led to the conclusion that time information must also be taken into account. When a time delay occurred in the presentation of sensory information, it was found to affect the magnitude of the operational load. A similar kind of phenomenon can occur during the operation of a personal computer when dragging an icon, but the response is delayed. This kind of phenomenon is described by the term "heavy" in Japanese (meaning sluggish), and it is referred to as pseudo haptic⁽¹⁴⁾. This suggests that when a driver evaluates a steering wheel as being "heavy," it is possible that the driver is not actually evaluating the steering

torque, but is rather experiencing what could be termed a kinesthetic illusion. When a driver operates an automobile, a time component is also incorporated into the sensorimotor system, so it is likely that the evaluation by a human being of handling and stability of driving must take time constant evaluation into account.

As noted earlier, sensory information appropriate to the work means information from the physical world relating to the control objective. Work in which the volume of information processing diminishes was found to have reduced cerebral blood flow in the area of activation. On the other hand, the absence of a cutting sound, meaning that there is no input of sensory information, invited a feeling of fatigue. These results mean that the information processing load in the brain and the feeling of fatigue or the sensation of load are not in a one-to-one correspondence. One of the brain's functions is to govern information processing, and it appears likely that when it is easier for the brain to create a sensorimotor loop that integrates action and sensory information so they are consistent, then that will contribute to the amelioration of fatigue.

The ultimate control objective in the operation of scissors is determined by whether the operator has been able to cut as desired. In the case of scissors, this is confirmed by the visual sense. It was found through the present experiments in a VR environment that the presentation of tactile and auditory information in addition to visual information, as described in Section 4.3, affects the feeling of engaging in actual operation. Information processing by the brain has a hierarchical structure, with conceptual levels placed higher and sensorimotor levels placed lower. The various hierarchical levels have their own separate control objectives for execution of the ultimate control objective of the highest order at those levels⁽⁴⁾. In other words, the system is structured so that execution of the information processing loop at each hierarchical level supports execution of the information processing loop of the highest order for the ultimate control objective. In the case of scissors, the ultimate control objective is to confirm the cutting trajectory. This is done by visual information, but additional auditory-tactile information is also important and affected evaluation of the feeling of having executed the ultimate control objective. The feeling of actual operation obtained by execution of the control objective at a lower level elicits more positive evaluation of the operation feeling of having executed the ultimate comprehensive control objective. It has also been reported, however, that in the case of a musical instrument, for example, a sensorimotor information processing loop for playing the instrument is also constructed⁽¹⁵⁾, but the control objective is the sound, which is auditory information. As this shows, the sensory information required for the operator to create a sensorimotor information processing loop differs with the tool. It is necessary, therefore, to clearly identify what sensory information is associated with physical information for evaluation of the handling and stability of driving in

the case of an automobile, and it is necessary to evaluate the extent to which information processing loops are constructed between the driver's operation oriented toward the control objective and the sensory information from that control objective.

The sensory information that is provided as feedback to receptors will be integrated as a rule when it has been generated in the same area as the motor output. However, although automobiles are operated using the hands and feet, the automobile behavior also constitutes sensory input to the driver's body in the form of acceleration or turning. For example, the feeling of accelerator pedal operation forms a sensorimotor information processing loop with the muscle activity in the foot and leg that pressed the pedal. When the operation simultaneously imparts movement to the automobile, movement by the automobile in five degrees of freedom also generates stimuli to the semicircular canals that are acceleration sensors in the driver's body, to the visual sense that detects optical flow, to the tactile sense and the pressure and pain sense in the driver's back when pressed against the seatback, to the somatic sense that grasps changes in the driver's body posture, and so on. Since this sensory information is generated simultaneously with movement, the nervous system by its nature will automatically create a sensorimotor information processing loop. In that sensorimotor information processing loop, sensory input that is created from changes in vehicle yaw, for example, may be felt with the driver's buttocks or hips, or sensed through the eyes, apparently depending on the individual. This input may also contain sensory illusions. The result in respect of formation of a loop to the ultimate control objective, however, is the same. What is important is that an information processing loop for sensory information that leads to an ultimate control objective is created at the same time that action is taken. Out of this variety of sensory information, only the information that can be associated with the action is selected and an information processing loop is created. It is due to the flexibility of the nervous system capable of doing this that people can switch from sedans to sports cars to trucks, and so on, all with different steering torque, steering wheel mounting angle, pedal force, and so on, and yet are still able to drive.

The above has demonstrated how important the perspective of sensorimotor information is in arriving at an evaluation of handling and stability of driving. When these factors are taken into consideration in thinking further about what we want automobiles to be, we find we must take care that measures against vibration and improvement of soundproofing performance not go too far. The driver's brain is always seeking the sensory information needed for movement and activity. That is to say, out of the variety of environmental information, it handles that information that is consistent with action as signal S, and it handles that information that cannot create an information processing loop as noise N. N cannot be generally defined as signals in the frequency band of so many kilohertz, and S as signals

in another. Suppose, for example, that a driver considers the 10 kHz band to be N in terms of evaluating drive comfort. The engineers pursue measures to block several decibels in the 10 kHz band. They take certain measures and then check the 10 kHz band for change. As this process repeats, the 10 kHz band represents the target for control by the engineers. The 10 kHz band is no longer N for these engineers but rather S, and even if it is buried inside another frequency band, that 10 kHz band is still an S representing soundproofing results. Information can be divided in this way into S and N according to the various information processing loops of different people, so vibration evaluation requires a perspective that takes into account what kind of information processing loop the driver will create when driving. A higher S/N ratio as well as the magnitude of S itself and time information are necessary to the operational feeling, but if S is vibration-proofed and sound-insulated to an excessive degree together with N, then the feeling of steering will become attenuated and the end result will be that the relationship between physical vehicle behavior and the driver becomes fragmented. This kind of vibration and sound are necessary as sensory information to generate an actual feeling that the driver is driving. Furthermore, these elements of sensory information change according to the physical environment while driving. Given considerations like these, it is conceivable that the handling and stability of driving is not simply about the capability of a vehicle, for example, to make a 0.2 G turn, but also involves an evaluation of time information processing of how physical information was acquired in conjunction with vehicle operation and how that process resulted in a 0.2 G turn.

6. Conclusion

The question of how making changes to the sensory information of a sensorimotor system in an experimental environment using VR technology affects the impression of using a tool was discussed in the course of introducing the results of preceding research on the subject. Given those various experimental results, the question of what it means to operate an automobile was examined in terms of neuroscience and psychology, and in doing so, an approach to establishing a method for evaluating the handling and stability of driving was found.

The aim for the future will be to clarify what physical phenomenon is the ultimate control objective for the driver in the vehicle movement that is achieved through steering, and what accompanying physical information is associated with that ultimate control objective. These can then contribute to the development of vehicles that enable more drivers to feel the vehicle behavior for themselves and operate the vehicle in ways that make it physically stable. A further aim is to examine the fun of driving as an emotion resulting from information processing, and to pursue its clarification. It is to be hoped that this paper will give impetus to the shift from evaluation of handling and

stability of driving in terms of tangible, hardware-related elements to evaluation in terms of intangible, software-related elements. Since this research has just begun, any opinions and suggestions will be welcome.

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— Editorial Afterword —

The Honda R&D Technical Review serves as a chronicle of the way of life of the engineers who work at our Research Centers, and its publication has been thanks to the efforts of a multitude of people. Lately, a great shift seems to be occurring in society, with the value of craftsmanship being undermined at its very roots.

For engineers to survive in this day and age, it is important for them to not only do what they are told, but also motivate themselves and have the courage to aim high. Personal growth is something that is achieved by acting on one's own initiative.

Many have sensed the shift in society, yet remain unsure of how to proceed. Nonetheless, in the midst of continuous change, there is unlikely to be a universal solution, and what is instead essential is the readiness to constantly be seeking solutions that fit the occasion.

Some may merely perform their everyday assigned tasks in a routine manner and consider that sufficient. But by thinking outside the box, even tasks that seem routine at first glance can yield creative results.

It is essential for engineers to not just do passive work, but also act on their own initiative in order to aim for even greater heights. Writing a technical paper is one such approach.

With a technical paper, authors take responsibility for content that they wish to assert and proactively send it out into the world. I encourage engineers to take on the challenge of writing a technical paper as a chance to both leave their mark on this ever-changing society and further their own growth.

— Kimitoshi TANAKA/Akira KANEKO —

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