

Honda R&D

Technical Review



April 2021

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Comment on the Cover

For this cover image, we created a motif of the heat pipe structure inside a piston that is taken from “Heat Pipe with High Heat Transfer Rate by Reciprocating Motion.”

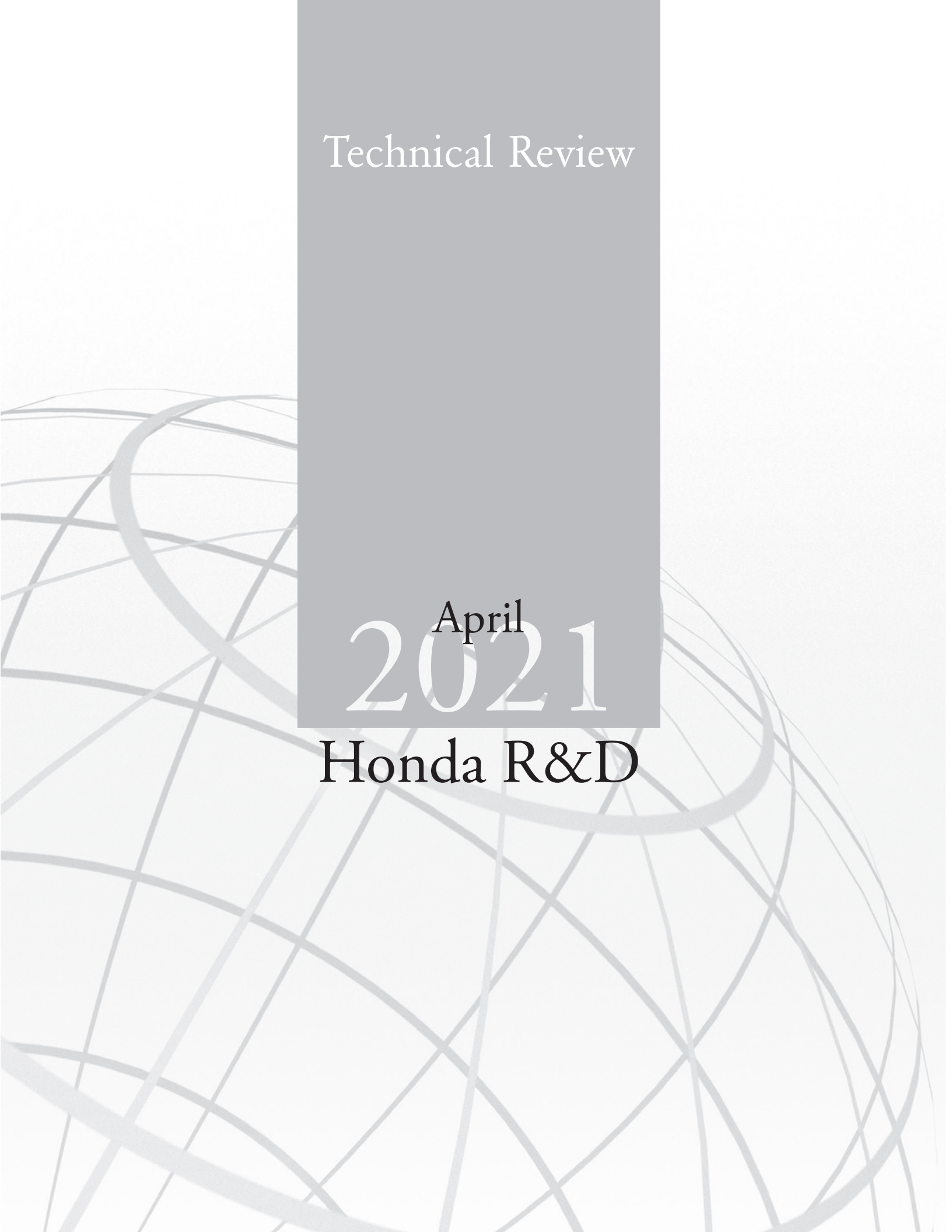
Among all the varieties of mobility, I think that the motorcycle in particular has a form that vividly expresses the concept of “necessity born from function.”

The heat pipes on the inside of the piston being used for this cover are structures that we would never ordinarily be able to see.

The technique used to show them here provides an interesting visible form that captures their image in the same way as the skeletal system of a living organism, or as objects emerging by necessity from their function.



Design Center
Ryohei OYAMA

The background features a light gray wireframe sphere on the left side. A solid gray vertical bar is positioned in the center of the page, serving as a backdrop for the main text.

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Development and Styling Design of Airport Guide Robot System

Yoko SAITO¹ Takeshi KOSHIISHI²

ABSTRACT

In an effort to create “a robot that coexists and cooperates with people and performs useful functions in society,” the concept of a “Compass to Accompany” was formulated during the development of a robot system to provide a guide service inside an airport facility as one public space in which individuals are coming and going. A questionnaire was administered to airport staff and to families of Honda employees, and a design was brought to fruition that entails identifying a potential request while listening to a live voice. Thorough consideration was given to enhancements to driving mechanisms and to the feasibility of various types of sensors associated with advancements in development; mockups and prototypes were obtained; and reception and guide robots were realized as easy to talk to, functional designs.

Development efforts yielded an interface that guests can use without confusion and a feature capable of performing guided movement in the same manner as a human, even in an environment crowded with pedestrians, confirming the potential of offering a service consistent with this concept in an actual airport setting.

1. Background

1.1. Development Background of Honda Robotics

Honda has set forth its 2030 Vision to “serve people worldwide with the ‘joy of expanding their life’s potential,’” and as one such initiative has continued to make progress in the development of robots as typified by ASIMO⁽¹⁾. Moreover, in seeking to realize a robotics society that will further highlight the inherent greatness of human beings, Honda has looked at how robots can actually coexist with people and provide useful functions instead of merely serving as demonstrations.

Demand for robots capable of coexisting with people is growing due to interest in higher living standards and social environment changes, such as lifestyle shifts like telecommuting and teleconferencing that assume remote environments, and demand for services that do not rely on human facilitators. Robots are also expected to help fill the gap where labor shortages occur in fields such as delivery, cleaning, and guide services. In guide services in particular, multilingual capability is a key issue for

responding to people from diverse countries and regions, but it is a challenge in Japan to secure human resources capable of providing information in multiple languages. Personal information terminals such as smartphones have become widespread and the provision of information via multilingual map apps is progressing; however, a certain degree of media literacy is needed, and there are limits to services received on a personal device for addressing challenges involving movement such as exploration inside a facility.

The authors set out to realize a system that enables even users not familiar with a facility to navigate it without confusion, by linking existing services offered by the facility with a robot system.

1.2. Background and Overview of Airport Guide Robot Development

This development was done as a joint research effort with Narita International Airport Corporation concerning the use of robots in airports, with Narita International Airport (hereafter, Narita Airport) as the verification facility.

¹ Life Creation Center

² Design Center

Narita Airport is a public space facility that is planning and implementing the introduction of robots to revolutionize productivity by promoting innovation⁽²⁾. Images of robot utilization such as depicted in Fig. 1 were examined while searching for an advanced application that would address concerns of airport personnel, pedestrians, and facility management. As a result, guide service was selected as a challenging theme presenting many technical issues, as a case of utilizing autonomous navigation technology whereby a robot smoothly navigates an environment with many people. The reason for this selection is that compared with delivery and cleaning, guide service calls for the robot to navigate a crowded environment at the same speed as people and to smoothly avoid oncoming people and obstacles without stopping when detected. Through a process of discussing matters of this sort, the two research partners commenced development of an airport guide robot system.

Figure 2 shows the guide robot system standing by to receive pedestrians. The system comprises a robot home that serves to promote the presence of the robot guide service inside an expansive facility and is also the place where the robots reside, a reception robot inside that is responsible for interacting with guests and providing reception service, and one or more guide robots that

actually guide guests to the desired destinations while navigating the airport starting from the robot home. A cloud-based system called the management system⁽³⁾ coordinates and operates the robot home, reception robot, and guide robots.

Figure 3 shows the utilization flow of the robots by pedestrians. The reception robot displays a map to the destination and other information such as recommended shops on a touch-screen display, and provides detailed guidance in a cordial manner while interacting with the guest. Meanwhile, the guide robot refines and reduces the information to display to enhance maneuverability and efficiently guide the guest through spaces where people come and go. Although duties are divided between the reception robot and the guide robot, they are seamlessly linked in providing guide service to the guest.

The realization of these features will allow for offering guests a new form of guide service in Narita Airport, and the new experience of being guided to their destination by a robot. It will also create a new service in which robots continue to work in an environment where they coexist with people and supplement workforce shortages.

This paper introduces the concept and styling design of the guide robot system, and also discusses newly developed functionality and verification at Narita Airport.



Fig. 1 Image of robot utilization at airport

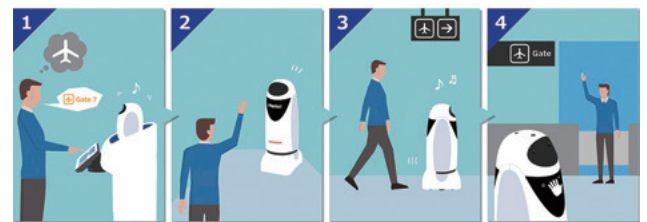


Fig. 3 Utilization flow of guide robot service

2. Concept

Studies were done to determine the appearance and gestures suitable for a robot that smoothly navigates a public space traversed by many people and provides guide service without provoking anxiety in people, and the desired feelings of guests receiving guide service was also examined. This resulted in the concept of a “Compass to Accompany” (Fig. 4).

“Accompany” indicates attention to maintaining a comfortable distance and being a reassuring presence, and “Compass” indicates a tool of unmatched accuracy showing the direction and route to a destination. The goal was to become a memorable presence that guests would want to meet again after encountering and receiving this guide service at the airport.

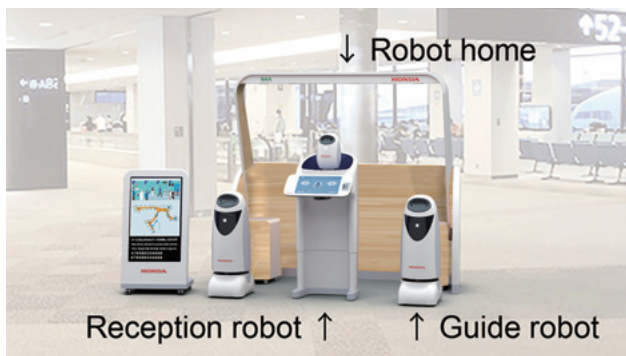


Fig. 2 Robot home, reception robot, and guide robot



Fig. 4 Development and styling design concept

3. Guide Robot Design

3.1. Design Process

Figure 5 shows the transition in the robot appearance design.

The initial design was an extremely simple one based on an omni-directional movement mechanism developed with the UNI-CUB⁽⁴⁾, and prioritized functionality [Fig. 5(a)].

Next, pseudo-models made of panels were brought into Narita Airport during a time when there were few people and compared with items such as luggage carts and baby strollers used in the airport, as shown in Fig. 6. It was determined that the optimal robot size, which would neither be lost among such items nor overpower them, was a total height of about 1100 mm. The drive mechanism changed to a ball drive that can respond evenly to input from various directions conceivable when operating among people, and which enabled minimization of the robot's floor projection footprint^{(5), (6)}. The design progressed to a body shape with a hexagonal cross section that would help stop continued rolling in the event that the robot tips over [Fig. 5(b)].

Refinement continued while performing operations testing with the prototype, and the robot was exhibited in April 2018 at the International Airport Expo, which was presented as a future form of airport services. The graphics were also changed and a dynamic exhibition under the name

P.A.T.H. Bot was performed at the Consumer Electronics Show (CES) held in Las Vegas in January 2019 [Fig. 5(c)]. While design did not elicit a negative response, it also did not leave a lasting impression. This was attributed to the fact that the robot had purposely been given an inorganic appearance to allay concerns that people might approach the guide robot owing to its novelty and thus interfere with guide operations. From the point of view of how a guest would feel when actually being guided by a robot at an airport, it was thought that a more lifelike design with the sense of an animating spirit within was desirable. Therefore, the design was modified to reflect an image common to both the design survey results described in Section 3.2. and the ASIMO design described in Section 3.3., elevating it to the Compass to Accompany concept.

Additional testing was conducted at the airport, and the fisheye cameras positioned on both sides of the body were changed to wide-angle cameras in a five-eye layout (two front, two upper, one rear) to enhance recognition accuracy. Also, the drive mechanism was changed from a ball drive to a differential two-wheel drive to enhance stability during travel. Although this drive system was unable to move directly to the side, which limited some expression during interactions, it made for easier handling and greater stability of behavior, and also increased the visual sense of reassurance [Fig. 5(d)].

3.2. Design Survey

A roundish design that focused on "a feeling of being accompanied (approachability)," a linear design that focused on "a compass (functionality)," and an intermediate design incorporating features of both were studied and full-scale mockups were created as appearance designs to convey the concept of a Compass to Accompany. In addition, a digital signage video to be displayed by the robot during guide service was created and steps were taken to enable checking on a PC screen.

Airport personnel and family members of Honda employees reviewed these designs and video, after which interviews and questionnaire surveys were conducted to ascertain whether the concept had been communicated as

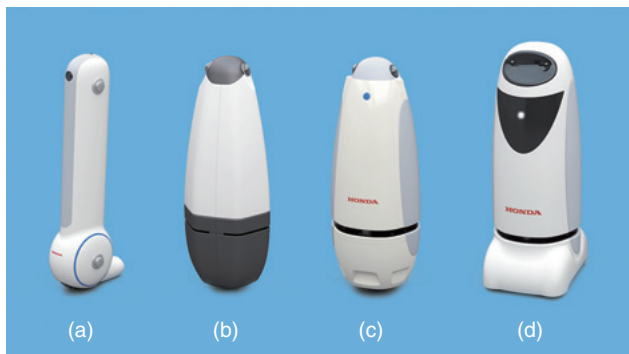


Fig. 5 Design process

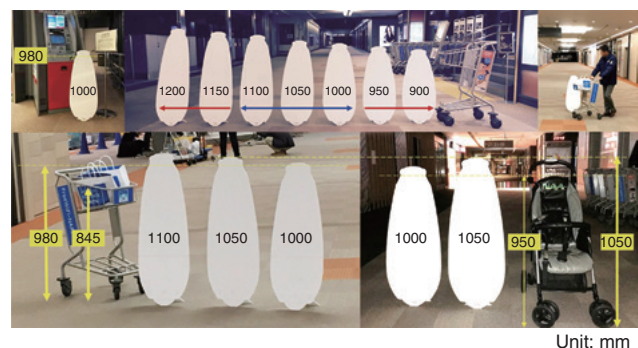


Fig. 6 Study of robot heights in Narita Airport

intended. The results showed that, as initially predicted, the design that focused on approachability was highly rated, but it gave the impression that the vital objective of providing accurate guidance to the destination could be a challenge. Responses indicated that the other designs did not have what people wished for in a guide robot, and it was found that none of the designs had achieved the concept.

It should also be noted that no difference was seen between responses given by children and those given by adults. It had been predicted that the more approachable design would score highly with children but this was not the case.

3.3. Shared Design Image with ASIMO

It is believed that the reason ASIMO has been able to maintain steady popularity over a 20-year period stems not from a playful design that has the goal of conveying approachability, but rather from its functionally straightforward and simple design⁽⁷⁾ in line with the concept of “harmony between being advanced and being people-friendly” (Fig. 7). The airport guide robot also has a simple and functional form like ASIMO. At the same time, the shape of its face, the slightly rounded body, the side pads suggesting arms, and the digital signage area were designed with the goal of conveying a sense of being not cold and unfeeling but alive. The exterior paint colors also use the same white and gray tones seen on ASIMO (Fig. 8). The

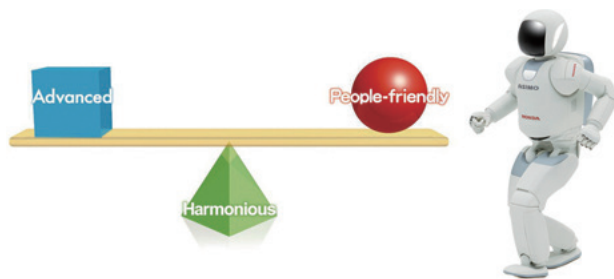


Fig. 7 ASIMO design concept



Fig. 8 Final design

result successfully embodies the concept of a Compass to Accompany with an approachable and functional design that is considered ideal for providing guide service at an airport.

3.4. Digital Signage Design

A study was done to investigate the optimal signage displays while providing guide service to guests in an airport. At a time when no pedestrians were present in the airport, a simulated experience was conducted in which a Honda employee assuming the role of a guest followed an existing remote-control robot equipped with a small monitor that displayed digital signage information, as shown in Fig. 9. The results revealed the following.

- When there are many displayed contents, the guest focuses on the screen and does not monitor their surroundings, which can be dangerous.
- When much information is displayed, the guest slows down in order to understand it.
- Displays are needed not only for the guest being guided but also for others around the robot.

This led to a digital signage policy of conveying only the information needed at a given point in time, in a simple display. The information was organized in line with the following three perspectives, and digital signage display areas were provided on the front and rear sides of the robot body, as shown in Fig. 10. The front side displays information for the guest being guided and others around the robot, while the rear side displays information for the guest walking behind the robot.

- At the start of guidance: Displays the destination using graphics based on pictograms in use at the airport.
- En route to destination: Turning directions, cautions, stopping
- Acknowledging other parties: Greetings and attentiveness

In addition to the above, when the design survey described in Section 3.2. was conducted, universal design



Fig. 9 Simulated experience of temporary guide robot

proponents at Narita Airport shared important insights, pointing out that for individuals with impaired color vision, displays such as blue text on a white background have lower contrast, making them a challenge to distinguish, and white or yellow on a black background is best for achieving the highest contrast. The displays were changed to luminescent white on a black screen to enhance distinguishability for both older individuals with deteriorating eyesight and persons with impaired color vision, and digital signage was created to express information such as the standby state, greetings, guidance in progress, and arrival at the destination.



Fig. 10 Guide robot signage displays

4. Reception Robot Design

Consideration was given to what approach would best enable people to use the airport guide service naturally and without confusion. It is usually considered ideal for people to receive help from people, but there are also cases where, due to human nature, people may hesitate to avail themselves of services due to worries about language differences or because there is a crowd at the guide service counter and it looks busy. On the other hand, while it may seem reasonable to completely automate reception, lack of familiarity may give rise to anxiety about usage, and there are scenarios in which this approach may fall short as a guide service. The method shown in Fig. 11 where the guest is provided with not only a screen interface but also the physical presence of a robot seemed to be an effective way to attract people and impart a greater sense of reassurance.

As a presence that invites guests into the extraordinary and enjoyable world of air travel, the reception robot's appearance was designed to achieve commonality with the guide robot, and referenced the proportions of familiar and long-favored symbols of welcome and good fortune. These objects include Daruma dolls (traditional round dolls depicting the Bodhidharma), maneki-neko ("beckoning cat") figures, and Fukusuke dolls (male figure bowing from a kneeling position). The robot responds to guests with motions such as bowing (a), tilting (b), and looking back over its shoulder (c). In addition, a large 19.5-inch touch-screen display is used as a visual aid to increase the guest's comprehension by displaying details about the destination. The robot and touch-screen part use an electric lift device⁽⁶⁾ to enable comfortable access by various people, including very tall individuals and those using a wheelchair.

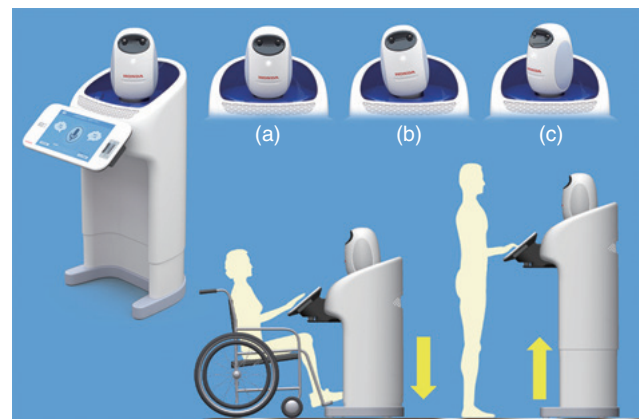


Fig. 11 Reception robot design

5. Interaction Design

5.1. Flute Sound and Body Movements

As a non-humanoid robot using human language in a strange manner when providing reception service may engender a sense of unnaturalness, it was assumed that it might be effective to attract guests by means of non-linguistic sounds and physical movements. Airports are typically loud, with public announcements and miscellaneous bustling noise, and thus in an attempt to cut through that noise and reach people's ears, the sound produced by the robot was created as that of a ryuteki "dragon flute" of traditional Japanese court music as a motif.

The melody is performed while the reception robot is in operation and as guide robots provide guide service, and simple body movements like shaking or rotating are used to stir the imagination of observers. Every effort is taken to help ensure that the guest remains the focus.

5.2. Ways of Making an Impression

In an attempt to casually convey a sense of Japan to foreign visitors at the airport, a traditional Japanese pattern called Asanoha, in use since the ancient Heian Period, was applied over the ventilation area on the rear side of the guide robot and on the speaker portion of the reception robot, as shown in Fig. 12.



Fig. 12 Japanese traditional pattern, Asanoha

6. System Configuration and Features

6.1. Overall System Configuration

The guide robot system comprises a robot home, a reception robot, one or more guide robots, a management system, and information provided in real time by the airport (Fig. 13).

The robot home is positioned as a place for the reception robot and guide robots to reside. To make the robot home stand out amid the busyness of the airport, a tall structure is put in place as a landmark to attract the attention of pedestrians who, having taken notice, see a digital signboard explaining the functions of the robots. After a guide robot finishes guiding a guest, it returns to the robot home, charges its battery with a dedicated charger, and prepares for the next guide operation. The guide robot details are presented in Section 6.2.

The management system⁽³⁾ is responsible for operation management to execute efficient guide service with multiple robots of various types cooperating with one another. As the goal is to not be bound by the limitations of the robots' movement range or infrastructure construction, a server-free configuration that uses Cloud services and the Internet of Things (IoT) to communicate was employed.

Real-time information provided by the airport is used while searching for the destination. As a result, the information provided uses the same maps and names as those provided by other guide services in the airport, such as face-to-face guidance at Information Centers and digital information boards. This also enables guests to check the latest flight information, including when changes occur in flight schedules or boarding gate numbers, which spares them rush and confusion.

The reception robot has the functions of searching for a destination and displaying a map and route according to

the needs of the guest, and uploading to the management system the information needed to guide the guest to the destination. This robot is the first point of contact for guests using the guide service, and the goal was to create an interface that can be used without confusion. The details are described in "Development of Reception Robot for Airport Guidance"⁽⁸⁾.

6.2. Guide Robot Features and Functions

The role of the guide robot is to perform the function of leading a guest to a destination and then to return to its original position after doing so. As the goal is to navigate smoothly even in crowded conditions, a feature of the robot is that when it detects someone passing by or an obstruction ahead, it selects a smooth path and proceeds without stopping, in a manner similar to that of a person.

Figure 14 shows the hardware configuration, and Table 1 lists the main specifications. The environmental conditions in the airport and other considerations that formed the basis for this configuration and the specification settings are described below.

- (1) As described in Section 3.1., the total height of the robot is set to a value that enables easy recognition by people in the area, even in an environment crowded with people and carts, but also so as not to be intimidating in size.
- (2) The footprint of the robot is set to a size that does not interfere with the progress of people in the area and enables smooth path planning. The wheel layout uses two driving wheels with motors and four driven wheels (double-row omni-wheel).
- (3) A low center of gravity is used so that the robot will not lose balance and tip over even if it comes in contact with an obstacle or structure. For this reason, components whose placement is not restricted for functional reasons

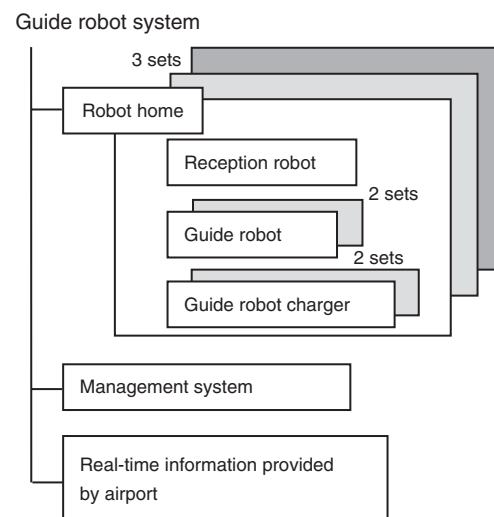


Fig. 13 Guide robot system architecture

Table 1 Guide robot specifications

Height [mm]	1080
Footprint [mm]	410 (Width) x 510 (Depth)
Height of center of gravity [mm]	300
Weight [kg]	33
Speed [m/s]	Max. 1.11 (4 km/h)
Acceleration [m/s ²]	Max. 1.67 (6 km/h/s)
Slewing angle speed [deg/s]	Max. 90
Braking distance [mm]	350 or less
Allowable difference in height [mm]	Max. 5

are situated in the lower portion of the robot.

- (4) Navigation speed, acceleration, slewing angle speed, and braking distance are set so as to enable movements similar to those made by people.
- (5) The difference in flooring levels that the robot should be able to negotiate is set so as to leave some margin from the greatest level difference it can actually negotiate. The robot is equipped with suspension to buffer the electronic components from impact while the robot negotiates differences in flooring levels. The greatest level difference in the airport is 3 mm in places where there is a change in the type of floor surface (e.g., short pile carpet, linoleum, decorative tile). The robot is

configured not to proceed when there is a large level difference such as a staircase.

- (6) As described in Section 3.1., a five-eye camera layout is used. The front cameras detect people and objects, the upper cameras enable the robot to recognize its location by extracting characteristics of the ceiling above, and the rear camera is used to recognize the guest (follower) being guided.
- (7) In order to fulfill the requirements outlined in Section 3.4., two short focus projectors are mounted on the robot for front display and rear display.
- (8) The robot uses a laser rangefinder (LRF) to detect people and objects ahead and to recognize its own position. The LRF is positioned at a height that enables detection of people and structures inside the airport.

A feature of the guide robot's autonomous navigation is its ability to navigate while providing guidance under crowded conditions like a person would. In order to quantify this feature, a target level was established to indicate the degree of crowdedness that the guide robot can navigate. Using definitions of service levels⁽⁹⁾ as an index of crowded conditions, "a state in which pedestrians have limited freedom to choose their own travel speeds or overtake others" was set as the target level. The reason for selecting this level is that it presented the greatest challenge of all likely service levels for the autonomous navigation of a guide robot in the crowded environment of an airport. Below this level there are fewer people in the airport and the robot could navigate easily, and at higher levels of congestion the robot would lose all freedom of path planning, and thus the challenge of path planning would decrease.

Examples of issues that a crowded environment raises for the guide robot functions of follower recognition, localization, and obstacle (people) avoidance, and measures for addressing those issues are as follows:

- (1) For follower recognition, the guide robot continues to perform recognition even when follower occlusion occurs due to other pedestrians intervening between the follower and the guide robot under crowded conditions, and maintains a distance that is comfortable for the follower. The details of this function are covered in "Research of Robust Follower Recognition Function for Airport Guide Robot"⁽¹⁰⁾.
- (2) For localization, even when the guide robot cannot obtain information about structures in the area through one sensor under crowded conditions, the guide robot combines information obtained from various sensors (LRF, cameras, inertial sensors) to avoid losing track of its position⁽¹¹⁾.
- (3) For obstacle (people) avoidance, the guide robot is equipped with learning capability that uses the avoidance actions of people as training data, so that the robot does not make clumsy maneuvers when people do not behave as expected under crowded conditions, and chooses a smooth evasion path just as a person would⁽¹²⁾.

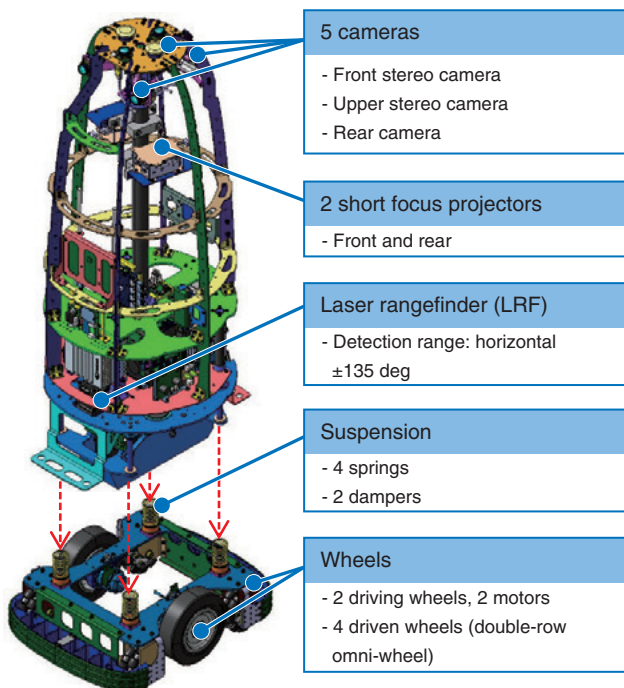


Fig. 14 Hardware configuration of guide robot

7. Verification of Feasibility

It was envisioned that the service verification would be performed over a period of three consecutive months (excluding holidays), with an operating time of eight hours between 9:00 a.m. and 5:00 p.m., using the entire area of one floor that could be traveled without the use of stairs or elevators. In addition, to increase opportunities to provide service to guests, it was decided to install robot homes in three locations on the floor. Given these factors, it was anticipated that the number of guests who would experience the guide service during the verification period would be 4500 or more parties for route guidance by the reception robots and 1000 or more parties that would be led to their destinations by a guide robot. Furthermore, some 20000 pedestrians visiting the airport each day might observe the reception and guide robots working in coexistence with people.

To investigate whether service verification would be feasible under the anticipated conditions described above, a guide robot system consisting of a reception robot, a guide robot, and a management system that linked the two was operated in Narita Airport with pedestrians coming and going, and a mock trial was conducted of the robot utilization flow shown in Fig. 3. Figure 15 depicts a developer playing the role of a guest during verification of the service.

Meanwhile, on the assumption that this configuration would be insufficient to provide service to guests in general, a trained, dedicated staff member was deployed to provide a thorough operation. In other words, it was decided to handle the following items with people during verification of the service, and these items were identified as issues for complete automation in the future.

- Shore up functionality of the reception interface at the robot home.

Automate responses to questions from guests who do not understand the digital signboard, display of service wait time during busy periods, and explanation of how to use the touch screen.



Fig. 15 On-site simulation at Narita Airport

- Simplify the work of dedicated staff.
Automate or digitize daily routine work such as charging guide robot batteries, understanding when to check and maintain the consumables of both robot types, record keeping, etc.
- Expand functionality of guide robot body surface.
Add an interaction interface so that the guide robot can respond to inquiries from the guest being guided as well as other pedestrians in the area while navigating.

8. Conclusion

Development of a new robot system is useful not only to Honda but also to its joint research partner Narita Airport, and a new form of robot service that can fulfill an active role at airports was designed while recognizing the need to create satisfaction for pedestrians. The concept of a Compass to Accompany was established, and on that basis a reception robot and guide robot with approachable and functional designs were created.

An airport guide robot system was constructed with a management system that links these two types of robots, and the system feasibility was verified in Narita Airport amidst pedestrian traffic.

As a result, knowledge necessary to have advanced robots that fulfill a role at an airport offer continuing service was gained.

9. Afterword

Public facilities such as airports and service facilities such as restaurants are striving on a daily basis to technically address issues related to workforce reduction and enhancement of efficiency across a wide range of operations. Under these circumstances, robotics technology has become all the more important due to changes in our living situations, and a landscape in which robots perform work and have a natural role to fulfill is fast becoming a reality.

There are many challenges to realize autonomous navigation robots actually working while coexisting with people. However, what is needed to achieve this is not repeated demonstrations, but rather to identify issues arising from actual use of robots in the field and the achievement of social acknowledgment by repeatedly verifying measures to address those issues.

Going forward, the knowledge gained from this development effort will be utilized in continuing initiatives to achieve the Honda goal of realizing a robotics society that will further highlight the inherent greatness of human beings.

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Development of Reception Robot for Airport Guidance

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ABSTRACT

We proposed a novel guide robot system that uses robots to provide guidance at Narita International Airport. The system implements the guidance through collaboration between robots having two different service roles: a reception role and a guide role. The reception robot greets guests, shows the route to a destination identified by a guest through voice and touch-screen input, and, by means of the Guide Robot Management System, communicates the destination to the guide robot. As this reception robot was developed, the concept of “Compass to Accompany” in the guide robot system was implemented through the functions of universal design (multilingual support and height adjustment), impasse-free dialogue (voice recognition and dialogue engine), and natural responses from the robot (motion, sound, and display). In user evaluations, 80% of survey participants indicated that they would like to try using the system if it becomes available at an airport.

1. Background

In its 2030 Vision, Honda announced a commitment to “serve people worldwide with the ‘joy of expanding their life’s potential’.” Honda has continued the development of robots such as ASIMO as one part of that endeavor⁽¹⁾.

Among fields interested in employing robots are the delivery, sanitation, and travel businesses. In recent years, having a multilingual response capability for responding to people from diverse countries and regions has become an important issue due to labor shortages in the service and distribution industries, and especially in the travel industry, with an increasing number of international guests coming to Japan. However, it is not easy in Japan to enlist personnel capable of providing information in multiple languages. With the spread of individual information terminals such as smartphones, progress continues with environmental enhancements that provide information in multiple languages; but as these require a certain degree of media literacy, a demand exists for robots capable of communicating in multiple languages.

The objective of the airport guide robot system⁽²⁾ is to show the potential of a new guide system by offering guests at Narita International Airport (hereafter, Narita Airport) the new experience of being guided to their destinations by a robot, while the aim is also to reshape the public image of robots as not merely performing demonstrations but as

coexisting and cooperating with people, performing useful functions in society.

As shown in Fig. 1, the guide robot system performs the guide service while coordinating the two types of robot, reception and guide robots. The reception robot in Fig. 1(b) shakes its body to attract the attention of a guest, and shifts its body toward the guest when approached. When the guest selects a language using a touch-screen terminal, the reception robot faces to the front where the touch screen is located.

As shown in scenario 1 of Fig. 1(a), when the guest mentions a destination the reception robot performs a nodding motion and displays a selection list on the touch-screen display. When the guest touches one of the destinations in the list, detailed information showing how to proceed to the destination is displayed. If, as shown in scenarios 2, 3, and 4 of Fig. 1(a), the guest selects the option to go with a robot, then through the management system⁽³⁾ the guide robot, shown in Fig. 1(c), receives the destination and face-identifying information⁽⁴⁾ for the guest from the reception robot, and accompanies the guest, leading the way to the destination. Although responsibilities are divided between the reception robot and the guide robot, the guide service is provided to the guest quite seamlessly.

This paper discusses the reception robot in the Narita Airport robot system.

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Fig. 1 Guide service overview

2. Reception Robot Concept and System Configuration

The guide robot service incorporates the concept of a Compass to Accompany. “Accompany” expresses taking care to remain at a comfortable distance and proving to be a reliable presence while “Compass” indicates a tool of unmatched accuracy showing the direction and route to a destination.

During development of the reception robot the foundational concept of a Compass to Accompany was further broken down into concepts (1) through (3) below. Five functions developed to implement these three concepts are multilingual support, height adjustment, voice recognition, a dialogue engine, and motion-sound-display. Figure 2 shows how these concepts and functions correspond to one another.

- (1) Universal design (multilingual support, height adjustment)
- (2) Impasse-free dialogue (voice recognition, dialogue engine)
- (3) Natural robot response (motion, sound, display)

Universal design is configured so as to be responsive not only to foreign guests but also, since it is used in a public

space, to users of wheelchairs, and is implemented with the features of multilingual support as well as height adjustment to accommodate an individual sitting in a wheelchair. Impasse-free dialogue is implemented with voice recognition and a dialogue engine to enable information to be obtained regardless of media literacy skill levels. To provide the guest with the experience of a robot engaging in communication, responses to actions by the guest are implemented through motion, sound, and display, which enables natural responses by the robot.

Figure 3 shows the system configuration that implements these functions in the reception robot. The system is configured with a camera and a microphone, an input system based on a Laser Range Finder (LRF), a recognition system for recognizing inputted images, voice, and point group data, a motion generation system, and a search system.

When the LRF detects that a guest has approached or when there is vocal input to the microphone, motion and sound are generated in the robot, achieving the concept of natural robot response. Vocal input from the microphone is applied to a destination search in the multilingual support function and potential destinations are displayed. During

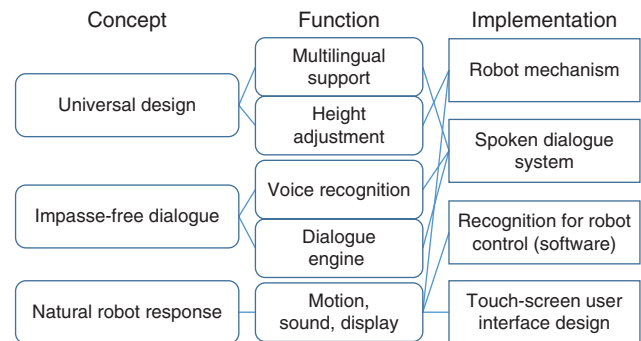


Fig. 2 Table of correspondences among concepts, functions, and implementations

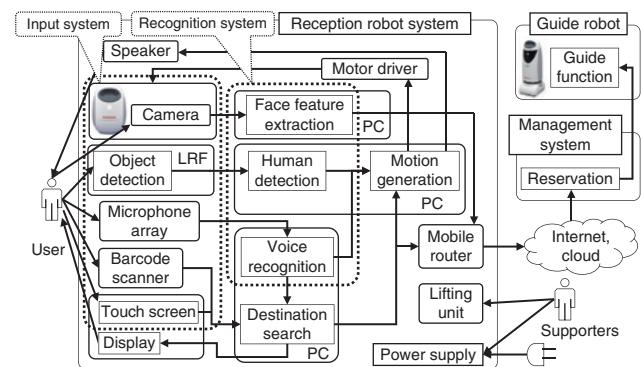


Fig. 3 System diagram

response to a person in a wheelchair the microphone is set by staff to a height convenient for use.

The reception robot communicates with the management system and the guide robot for coordination purposes, communicating the guest's destination to the guide robot to deliver seamless guidance.

The five functions mentioned above are achieved through a combination of the system configuration shown in Fig. 3 and the four features of a robot mechanism, a spoken dialogue system, recognition for robot control, and a touch-screen user interface. These four features are shown in the third column in Fig. 2 together with their relationships to the five functions, and are explained in Chapters 3 through 6. Chapter 7 describes the results of an impressions evaluation conducted to understand what aspects of these five functions called for enhancement.

3. Robot Mechanism

3.1. Robot Motion Mechanism

When a guest approaches the reception robot and operates the touch screen to begin a search for a destination, the reception robot executes motion suited to that scenario. Figure 4 illustrates an overview of actual motions.

A mechanism to accomplish motions of this sort is shown in Fig. 5. To make the robot bow or tilt there is a structure capable of rotating around each of three axes, X, Y, and Z, which are centered at the bottom of the robot and are orthogonal to one another. In addition, by configuring the drive mechanism to use links it is possible to minimize the curvature of a wire harness, which makes it possible for the robot to be used at the airport over a long period of time. In the section where the three axes intersect a universal joint is employed, which connects through the links to a bearing that slides vertically, and communicates forward-and-back and side-to-side motions while enabling rotation. These

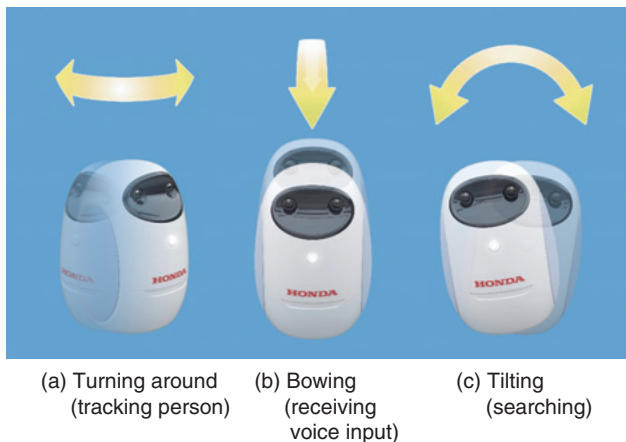


Fig. 4 Robot motion examples

portions of the mechanism were developed in a joint effort with ARRK Corporation.

By the use of this type of motion mechanism the concept of natural robot response was implemented.

3.2. Height Adjustment

To provide universal design, a height adjustment feature was provided to make it easy for people of various heights and for wheelchair users to see the touch screen and to enhance sound collection capabilities. This height adjustment feature is shown in Fig. 6.

In order to accommodate heights ranging from wheelchair users to tall foreign visitors, the touch screen was specified to be adjustable in height between 927 and 1310 mm. A commercially available height-adjusting unit intended for desk use was employed.

Use of this height-adjustment mechanism enabled realization of the universal design concept.

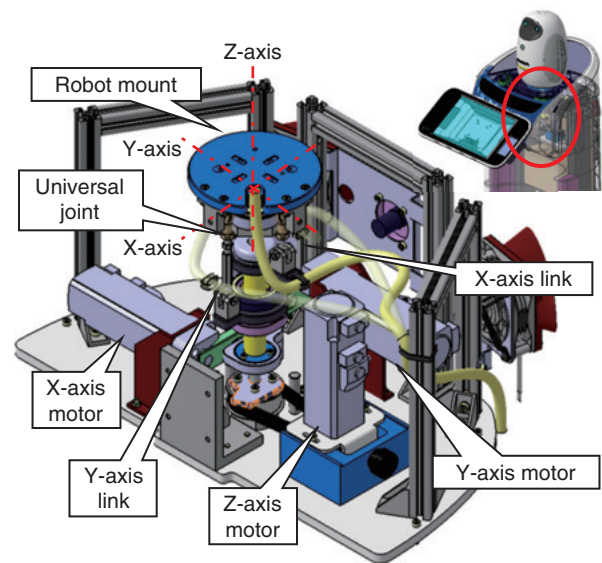


Fig. 5 Robot drive mechanism

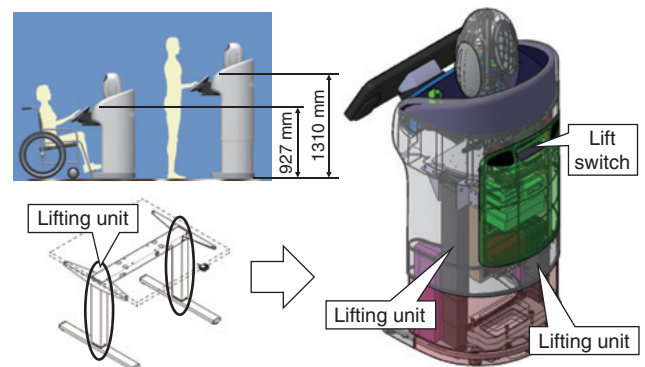


Fig. 6 Lifting mechanism

4. Spoken Dialogue System (Microphone, Dialogue Engine)

Figure 7 shows the sequence of the voice dialogue search system. When the guest speaks, the microphone converts the sound into a voice signal, and only the signal for the human voiced segment is extracted by Voice Activity Detection (VAD). After being processed, the voice is transmitted to the dialogue engine Houndify, and once the destination has been recognized and understood, search results are returned and displayed on the touch screen. When the guest makes a selection from the resulting list, information is obtained from the Narita Airport official app (NariNAVI), and relevant details (including a map) can be displayed.

4.1. Microphone

The microphone used for voice recognition needs to perform recognition accurately in the noisy environment of the airport. A design requirement of the voice recognition and dialogue engine is that the Character Error Rate (CER) for voice recognition results in a noise environment mimicking the inside of an airport be set to 10% or less, and the task incompleteness rate, which is the voice recognition result when sentence meaning has been taken into account, be set to 15% or less. These settings are based on the experience of Fairy Devices Inc., a company that develops voice recognition and voice dialogue technology, with

respect to voice response services in public facilities.

For the microphone array, a bar-shaped 16-ch. multi-microphone system produced by Fairy Devices was used. Using a microphone array makes it possible to approximate the direction of a sound source even in the midst of interfering noise, and to select only sound that comes from sources in a specific direction. Parameters are adjusted to isolate sound coming from the presumed position of the guest from noise in the environment and extract only the guest's speaking voice, achieving a CER of about 2 to 4% and a task incompleteness rate of about 11%, which is considered wholly sufficient to perform voice recognition smoothly. Voices in the vicinity of the microphones were assumed to have an input sound pressure between 65 and 75 dB.

4.2. Dialogue Engine

In order to respond to diverse guests, the dialogue engine used a modified version of the voice AI platform Houndify, which was provided by SoundHound Inc. on request. This dialogue engine performs at a level of anticipated dialogue so as to be able to recognize expressions and vocabulary close to everyday speech in the four languages of Japanese, English, Chinese, and Korean. It performs at a level that users indicated they would like to be able to converse at with a robot, and is able to recognize about 70% both within that standard and outside of that standard. One setting requirement for voice recognition and the dialogue engine, established after the results of user evaluations described in Chapter 7 were obtained, was that the response time between voice input and the display of results be within three seconds. Conventionally, data has been taken from a voice file, temporarily converted into text, and then applied to a dialogue engine, but Houndify, the dialogue engine that was used, generates a response directly from the voice file, so response time was shortened and results were displayed within three seconds of voice input.

5. Recognition for Robot Control (Software)

In order to achieve a function whereby the robot turns its face to a guest for the purpose of drawing the guest near, simple configurations were implemented for the detection of people in the environment, user selections, and robot posture.

LRF has been proposed⁽⁵⁾⁻⁽⁷⁾ as a method of detecting people in the environment using leg or torso detection. One can imagine that in an environment where a reception robot would be installed there would be multiple people moving or standing about in the vicinity of the robot; and it was thus decided to detect torsos using LRF, which was set within a height range that allowed individuals' torsos to be line-scanned. The robot had a height-adjustment function but the head of the robot would remain at a standard height until a guest stood in a position to operate the touch screen. It was confirmed that at the standard height LRF detection

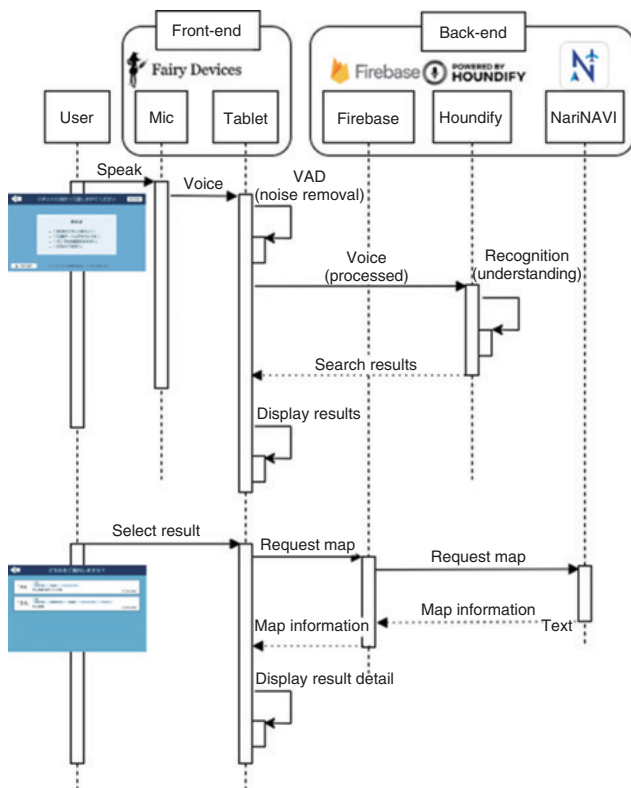


Fig. 7 Sequence diagram for dialogue search engine

was possible from the level of a user in a wheelchair to the height of a tall individual. An overview of the sensing area and installation position is shown in Fig. 8 from a perspective above the head of the robot.

Figure 9 is a schematic drawing relating to the detection of people. Among those point groups sensed by the LRF, a set of points was regarded as a cluster if the points differed from those nearby within a threshold value. It was assumed that points associated with a human torso would form a roughly elliptical shape, which was judged to be human based on the width and orientation of the cluster. Specifically, the distance between edge points in a cluster $\|v_w\|$ shown in Eq. (1) is within the width of a human chest.

$$l_{\min} < \|v_w\| < l_{\max} \quad (1)$$

Here, $l_{\max}$ and $l_{\min}$ are the highest and lowest values, respectively, for chest width. Both were empirically adjusted based on human chest width measurements.

One can expect that someone interested in the reception robot will orient their body toward the robot. With respect to the direction a person is facing, a cluster believed to be

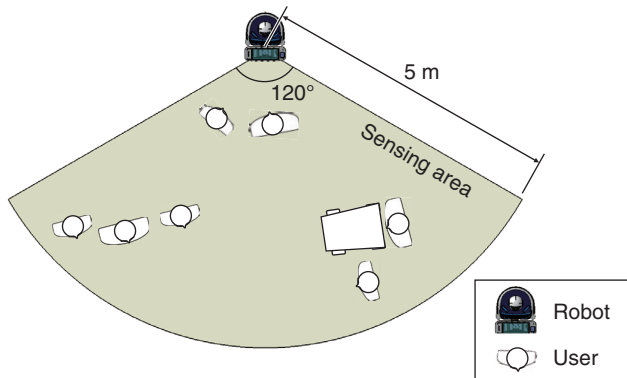


Fig. 8 LRF sensing area

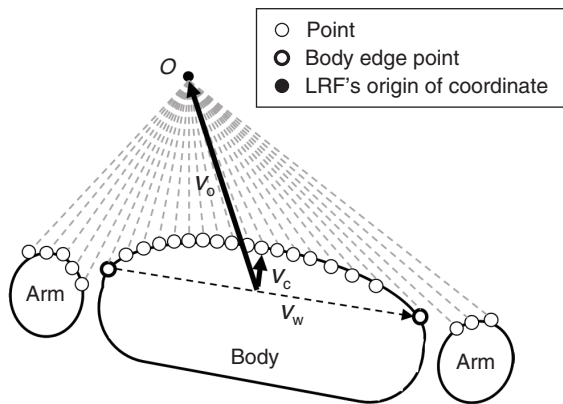


Fig. 9 Definition of vectors for detecting people from point cloud data

associated with a human is treated as a person facing the direction of the robot when the degree of cosign similarity between two vectors, shown in Fig. 9 as a vector v_c in the direction of the center of the cluster and a vector v_o in the direction of the LRF point of origin O , both vectors emanating from the midpoint between the two edge points of the cluster judged to be a person, is as expressed in Eq. (2).

$$\cos(v_o, v_c) > 0 \quad (2)$$

Among individuals facing the robot, the person who is the shortest distance v_o away from the robot is the person selected as the target user. Attitude control for the robot is performed by an attitude angle control system that takes as input the attitude angle that the robot should adopt as determined by the positional relationship between the target user and the robot. When the target user operates the touch screen, the operations described in Section 3.1. are performed.

6. Touch-screen User Interface Design

6.1. Design Considerations

In order to achieve impasse-free dialogue with all guests, the front of the robot is equipped with a touch screen. The guest uses the touch screen to select a language for interacting with the guide service and can choose to proceed with searching for a destination through dialogue with the robot or by using a list displayed on the touch screen. This ability to respond to the needs of various guests is one feature of the system.

6.2. User Interface Flow

The configuration of the touch screen and the user interface flow are based on results from a survey of user evaluations, described in Chapter 7. When a guest faces the touch screen, selects a language from the tutorial screen shown in Fig. 10, scenario 1, and acknowledges the consent form that is presented concerning personal data protection and cautions relating to the robot, a voice chat screen is displayed, as shown in Fig. 10, scenario 2. Because one objective of the reception service is to make conversing with a robot a fun experience, performing a search by way of vocal dialogue is given precedence over searching by means of a list. Thereafter, a list of search results is displayed as in Fig. 10, scenario 3. The search term is displayed at the top of the list so that the guest can check that voice recognition was performed correctly. When the guest selects a destination from the list and taps on the display, the display transitions to a results screen that provides detailed information about the destination, as in Fig. 10, scenario 4. The search proceeds from beginning to end with as few as three taps, a great step forward in useability. The results screen uses NariNAVI to display a map of the route from the guest's current position to the destination. Landmarks appear on the map, making it easier for the guest to follow the route. Finally, the guest

chooses to be accompanied to the destination by a robot or to proceed without escort, and a reception service closing screen is displayed.

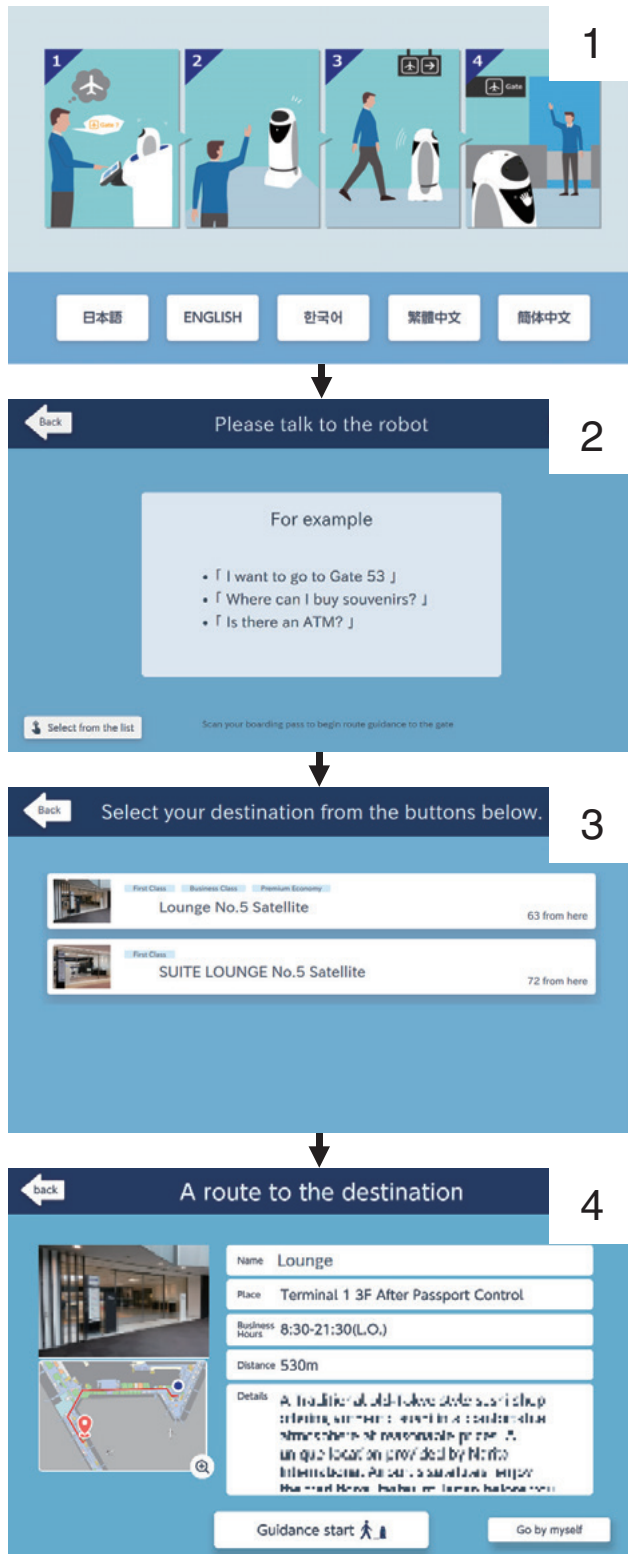


Fig. 10 User interface flow

7. User Evaluation Survey

7.1. Objective

In order to understand what enhancements the functions described in Chapter 2 needed, this survey asked about impressions received, with a focus on the following points:

1. Touch screen usability
2. Impressions of the robots
3. Willingness to use the reception service in the future

7.2. Survey Method

Survey participants included five Japanese (two men, three women) and five foreign nationals (three men, two women). The Japanese were Japanese citizens whose native language was Japanese, and the non-Japanese were native English speakers with foreign citizenship. Efforts were made to achieve as much diversity as possible with respect to age and frequency of experience interacting with a voice recognition terminal or robots.

The survey was conducted between January and February of 2020 in the Wako Building at Honda R&D Co., Ltd. An environment very closely resembling the one in which the guide service would be offered was created in a conference room inside the building. The survey involved a usability test and interview. Survey participants attempted to execute six tasks using the reception service. One such example was to request to be accompanied by a robot after communicating a desire to go to a lounge. At the beginning of the survey, administrators explained the nature of the survey to the participants and obtained their informed consent.

Prior research⁽⁹⁾ was consulted for the evaluation of touch screen usability, and a questionnaire suited to evaluation of the reception service in this instance was used. After the participants had completed all of the tasks, they were asked to evaluate their experience using a rating scale of 1 (disagree) to 5 (agree) on the questionnaire. The reasons for their ratings were noted in an interview following the evaluation.

In evaluations of the impression made by the robot, GODSPEED⁽¹⁰⁾, a standardized evaluation index in the field of Human-Robot Interaction (HRI), was used. This is a questionnaire encompassing five concepts (anthropomorphism, animacy, likeability, perceived intelligence, and perceived safety) important in the field of HRI. For example, the words “fake – natural” are paired together, and participants rate anthropomorphism on a scale of 1 to 5, choosing 1 if the robot seemed fake and 5 if the robot seemed natural. In addition, the four additional items of “apathetic – sympathetic,” “fear – secure,” “unpleasant – pleasant,” and “inaccurate – accurate” were used. These were chosen as items to evaluate the Compass to Accompany, the guide service concept in this instance. Survey participants filled out the evaluation questionnaires after completing all tasks. Their reasons for giving the ratings they did were noted in the interviews that followed.

An evaluation index called Affect Grid⁽⁸⁾ was used to evaluate users’ feelings about the reception service and their

willingness to use it. The Affect Grid represents the feelings experienced at that moment on two orthogonal axes, namely, pleasure – displeasure, and arousal - sleepiness. If a user said, “It was somewhat pleasant and fairly stimulating,” the extent of those impressions was evaluated on each of the two axes using 10 levels, and a mark was inscribed on points corresponding to a plane consisting of the two axes. Survey participants evaluated their feelings before performing the tasks and after completion of each task. This served the purpose of investigating time-series variation in the user’s feelings before and after experiencing the reception service as well as during. In the post-evaluation interview, the user’s

impression of the entire reception service and willingness to use it if encountered at an airport were noted.

This survey was conducted with approval from the Bioethics Committee of research and development at Honda R&D Co., Ltd.

7.3. Survey Results and Conclusions

Survey results for all participants relating to touch screen usability are shown in Fig. 11. The blue line shows average ratings by Japanese and the red line shows average ratings by non-Japanese. The average response rating was 3.57 for Japanese as a group, and 4.06 for non-Japanese.

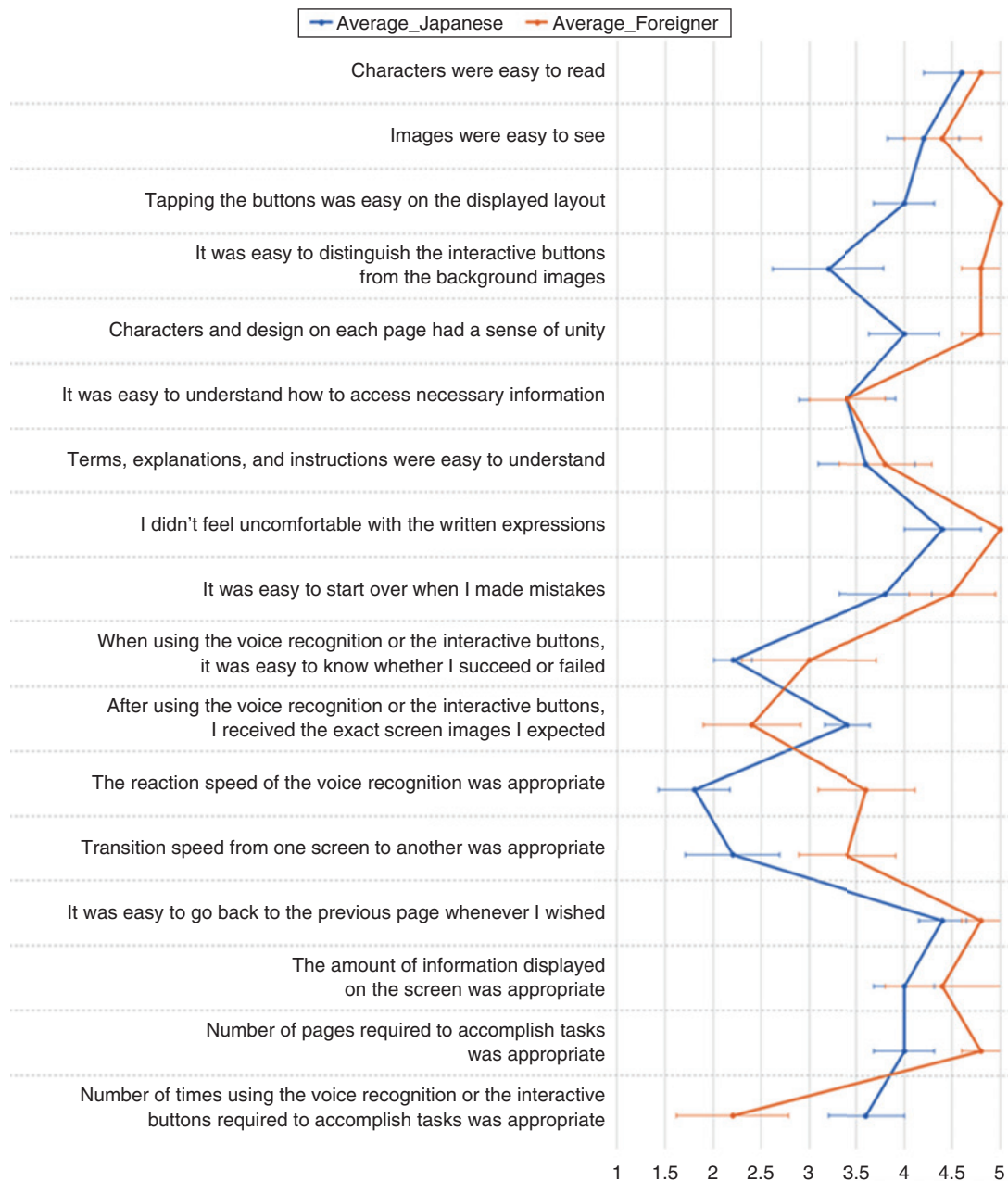


Fig. 11 Evaluation results for touch screen usability

The survey results, including the interviews, suggested five areas needing enhancement. These are: response at the time of vocal input (delay in acknowledgement, uncertainty as to whether input was understood, handling of recognition flaws); the microphone button (operation, understanding where to direct speech); list display (no coherence in items, inconvenience of behavior); map screen (smallness of map, understanding expansion button); and keyboard input (text entry). Based on these results, an allowance of up to three seconds for a response time was set for the voice recognition system described in Chapter 4. In addition, the touch-screen configuration and user interface flow laid out in Chapter 6 were configured on the basis of these results.

Survey results for all of the participants' impressions of the robots are shown in Fig. 12, using the GODSPEED index. The blue line is the average rating by Japanese and the red line is the average rating by non-Japanese. Non-Japanese tended to have a more positive response on average with respect to anthropomorphism than Japanese. Non-Japanese were apt to have a more positive response on average for animacy than Japanese. Likability tended to be rated highly by both Japanese and non-Japanese. Both Japanese and non-Japanese tended to give high ratings for sense of intelligence. Japanese and non-Japanese tended to assign similar ratings, on average, for sense of safety. On the four items that were added, both Japanese and non-Japanese gave high ratings, but on average, ratings by non-Japanese were higher.

The interviews suggested the following findings. Feedback relating to anthropomorphism and animacy ratings concerned the robot's appearance, movements, and sound, which generally had a positive impact. Ratings for likability, sense of intelligence, and the additional items "sympathetic" and "accurate" indicated that negative

impressions of the touch screen carried over into negative impressions of the robot. It became clear that negative impressions of the touch screen, which is a separate system, caused a negative assessment of the robot, and thus changes were made to address areas that required enhancement according to touch screen usability evaluations. Also, rating results for the four additional items selected for evaluation of the Compass to Accompany concept suggested that survey participants experienced the robot much in the manner that had been intended.

When the Affect Grid index was used to analyze all participants' reactions to the reception service, it was evident that changes in the impression made during the course of the reception service were strongly influenced by how smoothly tasks were executed. Participants had a sense of curiosity and anticipation prior to executing tasks, but were left feeling frustrated if they could not easily complete the tasks by means of the touch screen. Regarding willingness to use the reception service, 8 out of 10 individuals replied that they would be willing to use it if they actually encountered it at an airport, assuming that the issues with the touch screen had been addressed. When asked the reasons for this in interviews, Japanese and non-Japanese indicated differing tendencies. Japanese expressed negative opinions about their willingness to use the service, citing concerns about their companions or others present in the area. On the other hand, non-Japanese expressed largely positive responses to the idea of using the service. Thus, it was clear that willingness to use the service was strongly related to individual characteristics, and in particular that it might be influenced by experience in conversing with a robot or concerns about feeling self-conscious. Enhancements suggested by the survey results were incorporated into the design.

8. Conclusion

A guide robot system was developed to perform a guide service at Narita Airport, and as part of that service a reception robot was introduced. During development of the reception robot the concept of a Compass to Accompany in a guide robot service was broken down into the following elements: universal design, impasse-free dialogue, and natural responses, as well as functions corresponding to each of these requirements, i.e., multilingual support/height adjustment, voice recognition/dialogue engine, and movement-sound-display, were provided. User evaluations conveyed that survey participants experienced the robot much as envisioned in the Compass to Accompany concept, indicating success in the development of a robot aligned with that concept. The interviews revealed that negative impressions of the touch screen negatively impacted impressions of the robot, and that negative opinions of the touch screen, which was a separate system, negatively impacted impressions of the robot itself. Still, the fact that 80% of survey participants responded that they would like

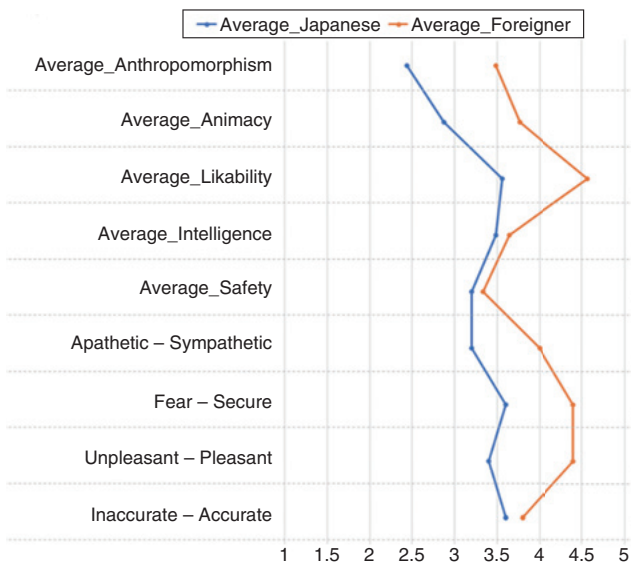


Fig. 12 Evaluation results for impressions of robot

to try the system if it were actually installed in an airport, with the proviso that the touch screen issues be resolved, indicates that this would be a useful service.

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Research of Robust Follower Recognition Function for Airport Guide Robot

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ABSTRACT

Hospitality is a key factor for the success of guide robot service. This paper defines a new recognition function called follower recognition, and proposes a hybrid approach to realize the follower recognition function. This approach creates a fusion of facial recognition, human body tracking, and person re-identification algorithms and takes advantage of the respective technological characteristics to realize robust follower recognition against issues such as recognition distance change, illumination change, and occlusion from the robot's perspective. The proving test result at Narita International Airport showed that the proposed approach is practical in guide robot service.

1. Introduction

With the shrinking of the working population due to a chronically low birthrate and rapidly aging population, an increase in single-person elderly households, and heightened interest in enhancement of living standards as lifestyles have become more diverse and efficient, demand is increasing for service robots that can coexist and cooperate with people. One example of this is social implementation of guide robots that are capable of autonomous movement in environments where people come and go⁽¹⁾. The authors had the goal of realizing a robot that performs useful functions in society while coexisting and cooperating with people, and developed and conducted a proving test of an airport guide robot system equipped with follower recognition functionality that enables a robot to lead a follower to the destination within Narita International Airport (hereafter, Narita Airport). This system provides people with the new experience of being guided to their destination by a robot, and has the goal of showing the potential of new guide services, creating robots that are not demonstrations but rather coexist with people and perform useful functions in the real world⁽²⁾.

The proposed guide service is described in detail in references^{(2), (3)}, and Fig. 1 shows an outline of the utilization flow. As shown in Step 1, the follower performs guide reception such as setting the destination through interaction with a guide service reception robot (reception robot) installed in the airport. At this time, a registration image for follower face identification is acquired by the

reception robot, and the facial feature values are transferred to the management system. Next, the guide robot acquires the destination and the facial feature values from the management system and commences guide operations (Step 2). During guide operations, the guide robot recognizes the follower's position using a camera mounted on the back of its head, as shown in Fig. 2, automatically adjusts its speed to match the movement speed of the follower, and leads the follower while maintaining an appropriate distance, as shown in Step 3. When the destination is reached, the guide service ends and the robot returns to the reception area (Step 4).

In order to provide the follower with the experience of "being guided by a robot," it is thought that simply following a robot that moves monotonically toward the destination is not sufficient, and that the follower needs to feel that the robot is operating according to the follower. In other words, the follower feels "guided" when the robot proceeds with a comfortable sense of distance according



Fig. 1 Utilization flow of guide robot service

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to the follower's movement pace, as shown in Fig. 2. It is thought that robot operation according to the follower's pace in this manner will lead to enhanced guide service hospitality and increase overall satisfaction with guide service. A key factor for achieving this is that the robot continues to recognize the follower's position in a stable manner so that robot operation does not become unnatural or awkward. This paper proposes an approach for realizing a robust follower recognition function that can be implemented in a guide robot that moves autonomously in the complex indoor environment of an airport, and demonstrates robust recognition through evaluation using image data acquired in an airport. Hereafter, Chapter 2 describes the relationship between conventional approaches and follower recognition, and Chapter 3 describes follower recognition using the proposed approach. Chapter 4 describes the evaluation data, and Chapter 5 examines the evaluation results and the usefulness of the proposed approach.

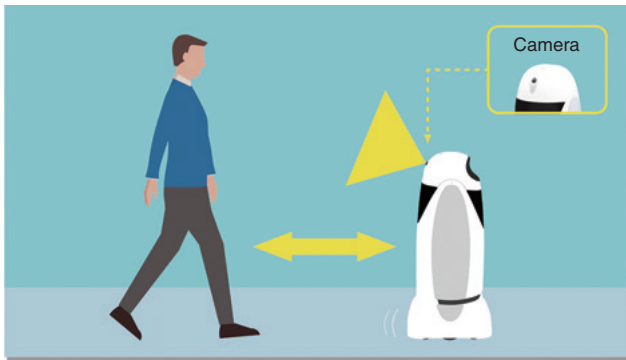


Fig. 2 Adjustment of distance from follower

2. Conventional Approaches

The follower recognition function continues to stably recognize the relative position of the person who is the follower from the perspective of the leading guide robot in a dynamic environment of movement. No precedents could be found at the time of writing this paper of technology for a guide robot to maintain an appropriate relative distance by using a camera to recognize the relative position of the follower and adjust its movement speed accordingly.

Although there are few cases of R&D for follower recognition, the person-following⁽⁴⁾ function whereby a robot follows a person, as shown in Fig. 3, has been mentioned and active R&D has been carried out since the 1990s as a technique for recognizing the dynamic relative position with a person from the robot's perspective in the same manner as follower recognition⁽⁵⁾⁻⁽⁷⁾. The biggest difference from follower recognition is that the person leads in front of the robot. However, there are many common issues with follower recognition in terms of recognizing

people in dynamic and complex environments, and R&D is underway on corresponding measures using a wide variety of sensors and algorithms. Pierre⁽⁸⁾ performed person recognition and tracking from a computer vision approach using a monocular camera. Chen et al.⁽⁹⁾ and Wang et al.⁽¹⁰⁾ realized person following by combining a computer vision approach using a stereo camera and RGBD images with depth information. Leigh et al.⁽¹¹⁾, Peng et al.⁽¹²⁾, and Germa et al.⁽¹³⁾ realized tracking by various means such as a laser range finder (LRF), ultrasonic sensor, and radio frequency identifier (RFID).

Person re-identification (Person re-id)⁽¹⁴⁾ algorithms identify persons from whole-body and half-body images between cameras and frames, as shown in Fig. 4, and have continued to evolve. A Person re-id algorithm mainly uses a whole-body color image of a person as the input, extracts appearance features such as the shape and color of the person using a deep learning model, and compares



Fig. 3 Person following



Fig. 4 Person re-id

them with the same features acquired from the registered image to check if it is the same person. The authors previously worked to adapt a Person re-id algorithm to robot perspective images⁽¹⁵⁾. Person re-id algorithms have lower personal authentication accuracy compared with face identification, but high robustness against posture and distance changes, and thus they are also thought to be adaptable to person following and follower recognition. However, there is the precondition that advance registration of the whole-body or half-body image of the recognition subject is needed.

It is thought that these conventional approaches related to person following can serve as references for realizing a follower recognition function. However, there are also characteristics that differ from those of person following, such as being able to see the follower's face and the challenge of predicting the follower's behavior (looking away, detour, sudden stop, U-turn, etc.), and thus an approach similar to person following is not necessarily suitable.

A method based on conventional approaches that continually recognize the follower by facial recognition (including face detection, face identification, and face tracking), human body tracking, and the use of special devices (RFID, etc.) and marks (QR code, etc.) can be considered as a way of realizing follower recognition. However, these conventional approaches have various issues, such as those described below.

When using facial recognition, robustness is extremely low with respect to issues specific to robots arising from a low viewpoint and dynamic changes in the surrounding environment due to movement^{(16), (17)}. These issues include recognition distance and illumination changes, image blur, cutoff from the camera angle of view, and occlusion by objects or people. For example, the follower's face may be lost suddenly due to face cutoff, such as when the follower turns sideways or as a result of sudden illumination changes associated with indoor movement. In addition, multiple variations of face images can be acquired and registered in advance to increase robustness even slightly, but it is not preferable from the viewpoint of usability to take multiple photos with different postures when acquiring images for face identification with the reception robot.

Human body tracking performs tracking between frames in a time series by comparing relatively monotonous feature values of the person (for example, local features such as color and edges, and relative positions of bounding boxes in the person detection results), in the area around the tracking target. When using this human body tracking, it is necessary to recognize by some means at the start of guide operations that the person in the camera image is the follower. In addition, it is expected that there will be frequent cases during tracking where tracking is unsuccessful due to occlusion or other factors in the same manner as with facial recognition described above. Furthermore, individuals cannot be identified by human body tracking alone, which

makes recovery from unsuccessful tracking a challenge⁽¹⁸⁾.

The use of a special device or mark places the extra burden on the follower of carrying or wearing the device or mark during guidance, which leads to reduced hospitality and usability. Furthermore, RFID is able to grasp that the target is nearby, but not the relative position of the target.

In this manner, with regard to a follower recognition function that uses separate algorithms based on conventional approaches, issues remain for realizing a guide robot with high hospitality.

3. Proposed Approach

This paper proposes a follower recognition approach that creates a fusion of Face/Body tracking and Person re-id algorithms in order to address the issues with conventional approaches described in Chapter 2 and realize a highly robust follower recognition function. The proposed approach took the two-step method of creating a base function by combining facial recognition and human body tracking for RGB monocular camera images, and then combining Person re-id with that base function. Use of only a monocular camera instead of combining various sensors was decided on with a view toward guide robot safety (impact reduction in the event of collision or tip-over) as well as payload and cost aspects, etc.

3.1. Follower Recognition by Fusion of Face/Body Tracking

This section proposes an approach for fusing the features of facial recognition and human body tracking. Figure 5 shows an outline of the Face/Body tracking processing. Face/Body tracking detects the face and body

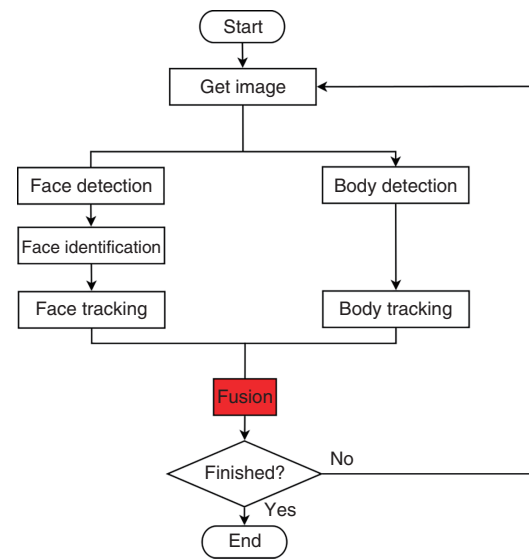


Fig. 5 Flow chart of Face/Body tracking based follower recognition

from the image acquired by the camera, and assigns a face-tracking ID to the detected face area and a body-tracking ID to the body. For the face area, the degree of difference from the registered facial features of the follower is calculated and an ID score is obtained. When the ID score exceeds the threshold, the face is determined to be that of the registered follower (face identification successful) and the face-tracking ID corresponding to the follower is updated. Tracking is performed separately for the face and the person, and the same tracking ID is retained for each when tracking is successful.

The fusion processing shown in Fig. 5 creates a fusion of the facial recognition and human body tracking results. Figure 6 shows the specific fusion method. The face-tracking ID (face_id) and body-tracking ID (body_id) for the same person are linked using the relative positional relationship between the bounding boxes of the detected/tracked face and person, and the face- and body-tracking IDs corresponding to the follower are updated. Figure 7 shows an example of linking judgment by the relative positions of the face and body bounding boxes corresponding to the red part in Fig. 6. By bundling and retaining the face- and body-tracking IDs corresponding to the follower in this manner, follower recognition can be expected to continue through mutual complementation even if one of the recognition approaches is unsuccessful. That is

to say, even if facial recognition is unsuccessful, follower recognition can continue as long as tracking of the linked body-tracking ID is successful. Conversely, even if the body cannot be detected/tracked, follower recognition can be performed as long as the face can be detected and facial recognition is successful.

In a complex environment such as an airport, however, facial recognition and human body tracking may be unsuccessful at the same time, and further enhancement of robustness is necessary to achieve stable follower recognition.

3.2. Follower Recognition by Fusion of Face/Body Tracking and Person re-id

The proposed approach uses Person re-id to supplement the abovementioned Face/Body tracking fusion approach and further enhance the robustness of follower recognition. Compared with face identification, Person re-id can identify a person from a whole-body or half-body image even when occlusion occurs or in a long-distance (low-resolution) image, and has a high likelihood of being able to recognize the follower even in scenes where recognition by the Face/Body tracking fusion approach is a challenge. However, the identification performance is not as good as that of facial recognition under conditions ideal for recognition, such as illumination and face orientation. In addition, as there are many feature values to handle and the processing load is high, Person re-id is slower than facial recognition. Furthermore, a registered whole-body or half-body image of the follower is needed, but the camera of the reception robot mainly takes a photo of the follower's face during guide service reception. For these reasons, the proposed approach mainly uses the results of successful recognition by high-speed Face/Body tracking based on highly reliable face identification, and uses Person re-id in a supplementary manner.

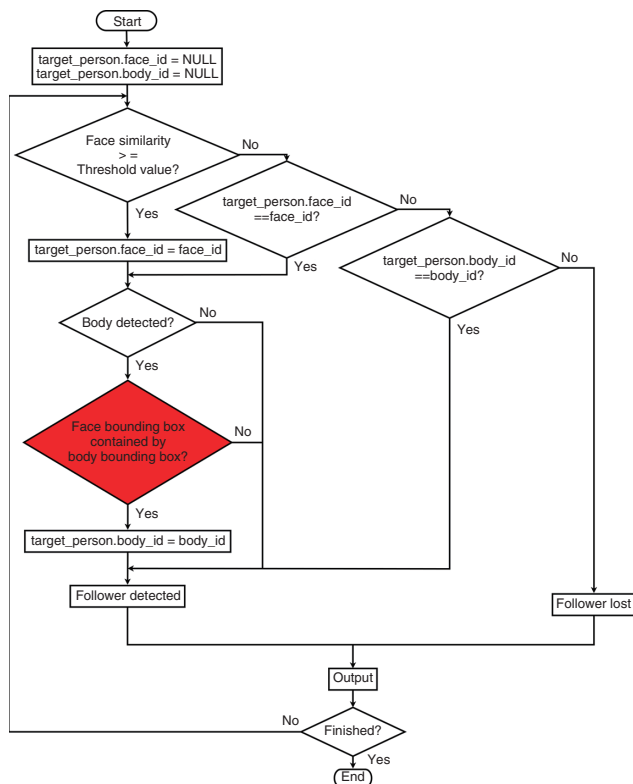


Fig. 6 Flow chart of Face/Body tracking fusion

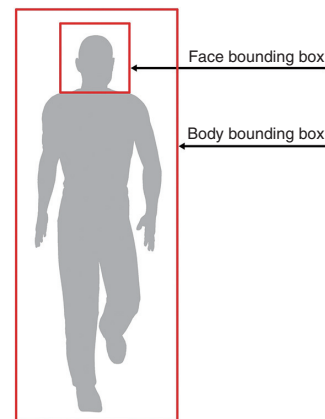


Fig. 7 Link of Face/Body bounding boxes

Figure 8 shows an outline of the processing. The part enclosed by the red frame in the figure corresponds to the Face/Body tracking approach shown in Fig. 5. The Face/Body tracking and Person re-id processing proceed separately. The system first confirms the follower recognition results of the Face/Body tracking approach. While follower recognition by Face/Body tracking is successful, a whole-body registration image for Person re-id is acquired at regular intervals and added to update the

database. This enables retention of the most recent follower whole-body image, which serves to increase the robustness of recognition even with respect to changes in the illumination environment or changes in appearance, such as taking off a jacket or changing the way a bag is held. When follower recognition using the Face/Body tracking approach is unsuccessful, the Person re-id processing results are used as the final follower recognition results. This fusion of the Face/Body tracking and Person re-id approaches can be expected to realize an effective follower recognition function that compensates for the disadvantages of each approach.

4. Evaluation Data

The follower recognition function was verified by actually operating a guide robot in the departures area of Narita Airport Terminal 1, as shown in Fig. 9⁽¹⁹⁾. In order to quantitatively and comprehensively evaluate the performance of the approach proposed in Chapter 3 in various scenes, images covering sufficient distance as a guide route and including various environmental changes along the way were used as evaluation data.

Specifically, a camera was installed at a height of 1 m and an elevation angle of 25° on a cart simulating an actual guide robot. The image data used for evaluation consisted of approximately 9 minutes (5541 frames) acquired at a resolution of 2056 × 1542 and a shooting speed of 10 fps while moving from the Central Building to the edge of the No. 4 Satellite of Terminal 1 in a manner simulating actual guide operations. The guide robot did not adjust its speed by follower recognition while acquiring the test data. In addition, the test subject follower followed the robot while maintaining a distance simulating the condition of being guided by the robot, but performed various actions along the way, such as stopping in front of shops in the airport

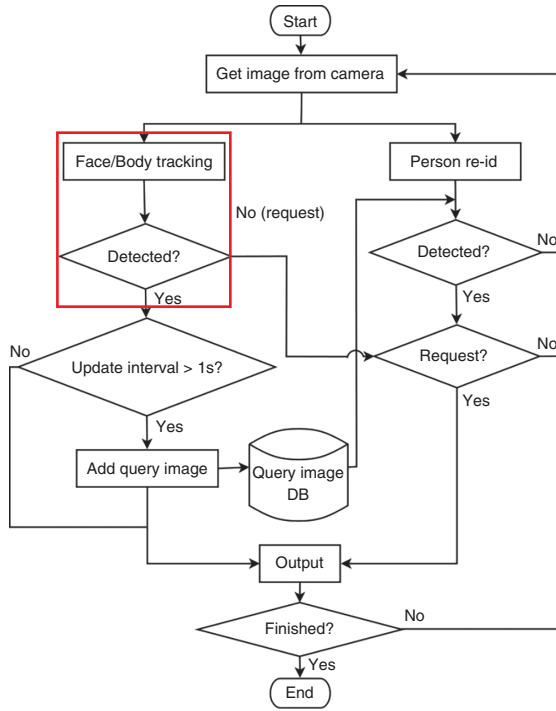


Fig. 8 Fusion of Face/Body tracking and Person re-id



Fig. 9 Evaluation test path on 3rd floor of Narita Airport Terminal 1

and looking to the left and right. Figure 10 shows examples of the test data, and the corresponding shooting locations are indicated in Fig. 9. Various situations were recorded in which robust recognition functions are needed due to dynamic changes in the environment, such as illumination changes due to factors such as backlight and lighting changes, image blur due to guide robot movement, face orientation and distance changes and cutoff due to changes in follower behavior, taking off and putting on a mask, and occlusion due to intersection with people and objects, etc. The red mark in the figures indicates the test subject follower.

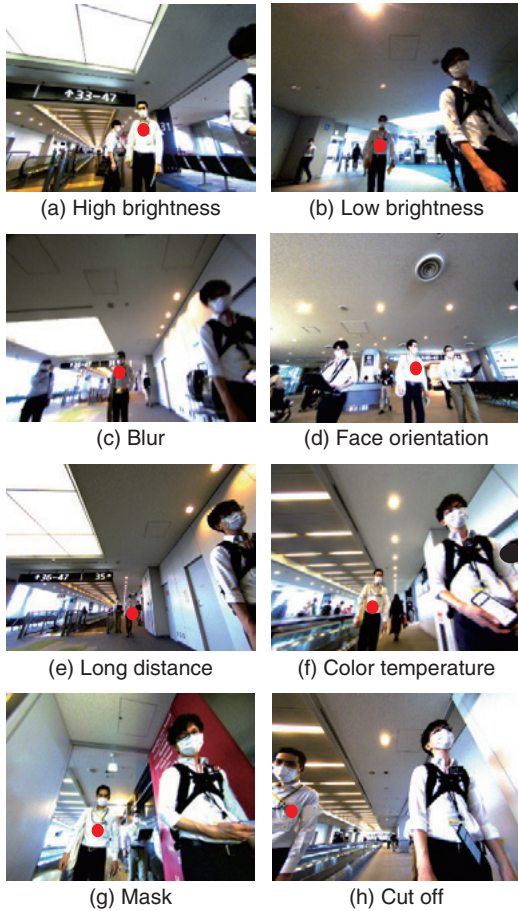


Fig. 10 Scenes that call for robust recognition

5. Evaluation Results and Examination

Figure 11 shows result images of the follower recognition processing, and the corresponding shooting locations are indicated in Fig. 9. Figure 11(a) shows the case when the Face/Body tracking approach succeeded in both facial recognition and human body tracking, and the respective bounding boxes (orange frames in this

Table 1 Results

	Total (Frame)	True Positive (Frame)	False Positive (Frame)	False Negative (Frame)	Success (%)
Face/Body (1)	5541	4540	0	1001	81.9
Person re-id (2)	1001	835	32	134	83.4
(1) + (2)	5541	5375	32	134	97.0

case) could be linked. Figure 11(b) shows the case when facial recognition was unsuccessful due to the impact of a mask, but the linked human body tracking was successful. Figure 11(c) shows the case when both facial recognition and human body tracking were unsuccessful, but the follower could be recognized by Person re-id. Figure 11(d) shows the case when all approaches were unsuccessful, resulting in unsuccessful follower recognition.

Table 1 shows the results of evaluating the proposed approach using the data described in Chapter 4. Evaluation was carried out by visually confirming whether the bounding box in the processing results surrounded the follower as shown in Fig. 11. True Positive (TP) in Table 1 is the number of frames where the system was judged to have correctly recognized the follower. False Positive (FP) is the number of frames where a person other than the follower was recognized as the follower. False Negative (FN) is the number of frames where the follower was present but could not be recognized. Success is the follower recognition success rate. In other words, out of a

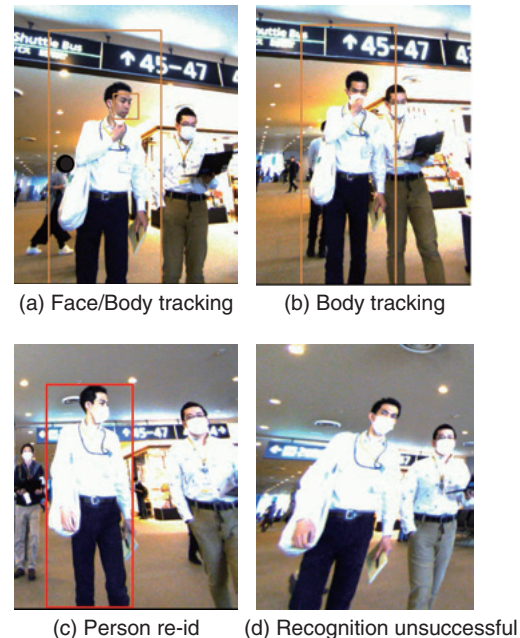


Fig. 11 Result images of proposed follower recognition

total 5541 frames of test data images, recognition by only the Face/Body tracking fusion approach was successful in 4540 frames, with 0 FP frames and 1001 FN frames, for a recognition success rate of 81.9%. Of the 1001 frames where Face/Body tracking was unsuccessful, the Person re-id approach was able to correctly recognize the follower in 835 frames, with 32 FP frames and 134 FN frames, for a Person re-id approach recognition success rate of 83.4%. Based on the above, the final recognition success rate of the proposed approach that created a fusion of Face/Body tracking and Person re-id was 97.0%.

Figure 12 plots the time series data of the distance from the robot to the follower estimated based on the follower recognition results for the test data used for evaluation. This graph shows the results of the Face/Body tracking approach alone in orange and the results of Person re-id alone in blue. The distance to the follower was estimated by the size of the bounding box that detected the follower. Frames with the estimated distance plotted as lost are scenes in which follower recognition was unsuccessful. Of these, locations where lost is plotted in orange but the estimated distance is plotted in blue for the same frame are scenes where the Face/Body tracking approach was unsuccessful but the follower could be correctly recognized by Person re-id. The red frame in Fig. 12 is an example of this, and shows that recognition by the Face/Body tracking approach was unsuccessful because the distance to the follower increased, but recognition by Person re-id was successful. In this manner, stable follower recognition can be realized by creating a fusion of the Face/Body tracking and Person re-id approaches. Recognition by the Face/Body tracking approach was unsuccessful in each of the scenes that call for robustness shown in Fig. 10, but use of Person re-id led to recognition success, which shows that the desired effect was achieved.

According to the results in Table 1, however, there were 166 frames or approximately 3% of the total scenes where recognition was not achieved even by Person re-id, with the result that follower recognition was unsuccessful. Events that may occur when follower recognition is unsuccessful are (1) the FP case where the follower is not present but is recognized as present, and the robot continues to guide a person other than the follower,

and (2) the FN case where the follower is present but is recognized as not present, resulting in a lost judgment even though the follower is present. In both cases, the longer the unsuccessful condition continues, the greater the impact on guide service. In this evaluation, the longest period during which Case (1) continued was 1.5 s. The top speed of the guide robot in this guide system is 1.11 m/s, and thus in this case the robot runs freely for around 1.7 m, but this is not far from the previous recognition successful position, and is thought to be a distance that enables adequate adjustment after re-recognition. The longest period during which Case (2) continued was 3 s. This is a scene where the follower was walking nearly side by side with the robot and was nearly cut off from the angle of view, such as shown in Fig. 10(h). It is explained to the follower beforehand at the start of this guide service that the follower should, in principle, follow, i.e. be behind, the robot. However, this kind of side-by-side positioning and large deviation from the angle of view are also assumed, and the guide robot enters deceleration mode when a lost judgment is made. Deceleration makes it easier for the follower to notice the unusual behavior of the robot and provide more opportunities to return to being behind the robot, which can be expected to increase the likelihood of re-recognition. The robot returns to normal speed after re-recognition, and thus FN of a few seconds is not considered to pose a hindrance. From the above, it can be said that the effective follower recognition approach proposed in this paper, which creates a fusion of Face/Body tracking and Person re-id to take advantage of the strengths of each to complement their respective disadvantages, achieves sufficient recognition performance for guidance in airports with a drastically changing environment. As such, it is considered that prospects have been achieved for practical use.

The factors resulting in unsuccessful follower recognition are analyzed below. The biggest factor for lack of success was confirmed to be an unsuccessful person detection process in the stage before Person re-id processing. This occurred in 96 frames out of the 166 recognition unsuccessful frames, and accounted for nearly 60% of unsuccessful follower recognition. The remaining 40% of unsuccessful recognition cases was

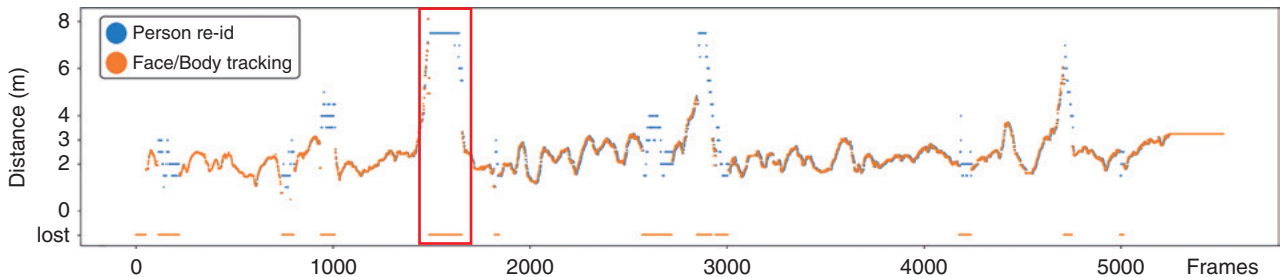


Fig. 12 Estimated distance

misrecognition by Person re-id. Figure 13 shows an example of misrecognition (FP), but the misrecognized person and the follower have similar appearances that even a human may mistake at first glance. Looking ahead to practical use, further enhancement of accuracy is thought to be an issue for recognizing these types of scenes where follower recognition was unsuccessful. Potential means for addressing this include selection of algorithms for each recognition processing (facial recognition, person detection, human body tracking, Person re-id) in this approach that are better suited to specific environments, careful examination and expansion of the amount of learning data, and addition of enhancements such as mutual complementation using various sensors, etc.



Fig. 13 Person re-id False Positive

6. Conclusion

This paper proposed a robust follower recognition approach that uses a monocular RGB camera mounted on a guide robot in an airport guide robot system. In the proposed approach, the existing recognition algorithms of the Face/Body tracking and Person re-id approaches were effectively fused to enhance robustness against various issues arising frequently in a dynamic airport environment and that reduce the follower recognition rate, such as occlusion due to crowds of people, changes in illumination due to movement, and changes in recognition distance and face orientation due to follower movement. It was confirmed that high robustness was achieved, with recognition successful for 97% of the evaluation data acquired in an airport.

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Coloring Design for 2020 CRF1100L Africa Twin

Midori KATSURAGAWA¹

ABSTRACT

In 2016, Honda revived the iconic Africa Twin with three color schemes: Tricolor (red/blue/white), CRF Rally (red/black/white), and monotone (black, silver). Instead of being simple color variations, they create distinctive moods for the respective models with differing primary usage. The 2020 model has two versions: the Africa Twin with enhanced off-road riding experience, and the Africa Twin Adventure Sports with enhanced comfort for touring. In considering the color schemes, we sought to express a deeper worldview of the iconic model by linking each color scheme to its own characteristics and the model's heritage.

1. Introduction

The first-generation Africa Twin, which debuted in 1988, was an adventure model developed with feedback from the technology of the NXR750, which had won the Paris-Dakar Rally for four consecutive years since 1986. Its high off-road capability and unique styling with a full fairing won it the support of many customers in Europe and elsewhere. After going through multiple updates and model changes, including increasing the displacement, the model was discontinued in 2003.

In 2016, in response to customer requests for a revival of the Africa Twin, the CRF1000L Africa Twin was launched with the basic concept of "Go anywhere: a full-fledged adventure model that can be used from everyday commuting to riding in the vast land of dreams." As the successor to the Africa Twin, the CRF1000L Africa Twin follows the tradition of the Africa Twin, but has been updated to incorporate environmental performance and technologies suitable for next-generation models⁽¹⁾, expanding the range of enjoyment from daily commuting to weekend adventures (Fig. 1).



Fig. 1 The 2016 CRF1000L Africa Twin

In 2018, the Africa Twin Adventure Sports (AS) model was added to the basic Africa Twin (STD) model with an increased gasoline tank capacity for longer distance touring, expanding the range of enjoyment as an adventure model (Fig. 2).

In 2020, the Africa Twin underwent a full model change, and its specifications were revamped to give sharp differences in the character between the two types⁽²⁾: the STD type (Fig. 3) with a slimmer and lighter body for agile off-road riding, and the AS type (Fig. 4) with a larger fuel tank and larger fairing to fully enjoy touring.

In considering the livery for the 2020 CRF1100L Africa Twin, we examined each of the three color schemes on the previous models to see how they have been received by users and what images they received.

In this paper, we describe the results of the above discussion and the method of embodiment in the 2020 model based on these results.



Fig. 2 The 2018 CRF1000L Africa Twin AS

¹ Design Center



Fig. 3 The 2020 CRF1100L Africa Twin STD



Fig. 4 The 2020 CRF1100L Africa Twin AS

2. Color Design Considerations for the 2016 to 2019 Models

The core of the livery theme during the development of the 2016 CRF1000L Africa Twin was the “revival of the Africa Twin brand.” A total of three color schemes were selected: the model’s representative schemes, Tricolor (red/blue/white) and CRF Rally (red/black/white), with monotones added as a new value proposition⁽³⁾. The livery concepts for these three types are shown below.

- Tricolor: The symbol of the Africa Twin brand’s revival
- CRF Rally: Expressing the prowess of the latest Dakar racer
- Monotones: New value as a tourer for adults

2.1. Production (sales) Ratio by Color Scheme

First, we confirmed the color history and the color ratio of the production volume since the model’s revival in 2016 (Fig. 5). Since 80% of the total production of more than 100,000 units is for the European market, the data mainly reflects the preferences of European users. Initially, the three color options were roughly equal. The popularity of Tricolor, which was positioned as a symbol of the revival of the Africa Twin brand, was increased thereafter. The success has been significantly influenced by the Adventure Sports (AS) variation added in 2018 came only in Tricolor, which was inspired by the first-generation model (Fig. 6).

2.2. User’s Thoughts Inspires the Color Designers

Since the launch of the 2016 model, we have observed the changes in the production volume of each of the above-

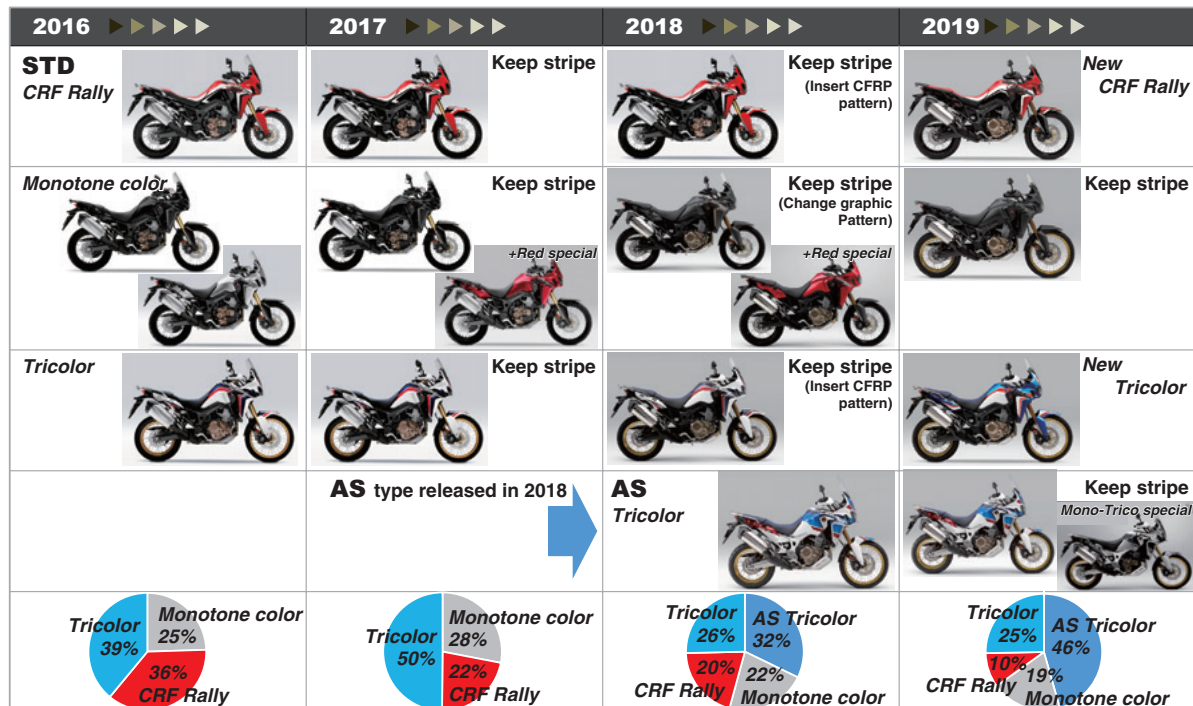


Fig. 5 Changes in color lineup and production ratio

mentioned colors and have continued to listen to the voices of customers around the world by means including the free description section of questionnaires. It was found that customers did not view Tricolor, CRF Rally, and monotone color schemes as simple color variations, but rather made their selections in conjunction with their primary use.

Since large motorcycles are highly hobby-oriented products, customers are likely to be particular about the colors they choose when purchasing. However, in the case of the Africa Twin, there was a clear and strong difference in the user's image of each color scheme, with some saying, "If it's not this color, it's not the Africa Twin," and others saying, "I love the model because of this color."

This was one of the unique aspects of the Africa Twin color variations.

2.3. Study for Each Color Scheme

2.3.1. Tricolor

The tricolor combination of red, blue and white was chosen as a symbol of the inheritance of the brand image in order to make a strong impression on the market of the revival of Africa Twin. This color scheme was worn by the original Africa Twin (Fig. 6), and in Europe, the customers have come to associate the image of the Africa Twin with the red/blue/white tricolor. We updated this color scheme to create an image that is appropriate for the new generation model with all new features, and adopted it for the 2016 model year.

The tricolor is also recognized as Honda's traditional color in racing⁽⁴⁾. Starting with the road racers in the 1970s, the color has been used for motocross team wear, the World Endurance Championship racers, the WGP racers and Paris-Dakar racers in the 1980s, and the latest racer replica models. Therefore, even customers who are not familiar with the first-generation Africa Twin will be able to feel the appeal of this traditional color scheme for racing.

The tricolor Africa Twin is a symbolic dedication to the



Fig. 6 The XR650, first generation Africa Twin launched in 1988

NXR750 (Fig. 7), which dominated the Paris-Dakar race on the African continent in this color⁽³⁾. It is a motorcycle that could travel through seemingly impossible terrain and it evokes that image of travel in people. Through repeated conversations with customers, such as older users who remember their enthusiasm for the Paris-Dakar race in their youth, it became clear that the Africa Twin in Tricolor is a combination that can evoke even the memories of their motorcycle life. From this, we understood that this color scheme has been chosen because it resonates with the most dedicated Honda fans and Africa Twin fans.

2.3.2. CRF Rally

The momentum of the latest Honda Dakar rally racer was expressed by incorporating the livery of the CRF450 Rally (Fig. 8), the works racer, to show its presence as an adventure model for a new era (Fig. 9).

According to the results of the questionnaire, many customers selected this color based on the image of the



Fig. 7 The NXR750 conquers African continent



Fig. 8 High-performance CRF450 Rally currently used in Dakar Rally

latest Dakar Rally racer as per the color concept, while others selected it based on the powerful and stylish image of the color red itself, and seeing red as a traditional color for Honda's off-road vehicles (Fig. 10).

Since the mid-1970s, Honda's off-road motorcycles and motocross racers have been promoting red as their image color. It was found that the simple elements of such images resonated with the customers, and they chose the products because of the sharp impression and the association with Honda being active in the racing scene.

2.3.3. Monotones

The selection of monotones is composed of stylish tones and colors with a strong, solid impression, as a coloring that is geared towards a wide range of mature lifestyles without being bound by a specific image (Fig. 11).

Monotones are often chosen to avoid the replica colors that tend to stand out, but in the case of the Africa Twin, it seems to have been chosen more proactively. Customers specifically choose this color scheme to match their lifestyles or riding styles, such as: "wanting to ride an adventure model but not off-road," "a businessman who wants a large on/off-road model for a quick ride to work," and "wanting to go on a long-distance touring in comfort wearing matching riding gear with a partner."



Fig. 9 The 2016 Africa Twin coloring design based on the CRF450 Rally



Fig. 10 The Honda CRF series

2.4. Exclusive Tricolor Livery for the New Adventure Sports (AS)

To further enhance the image and feel of the Africa Twin as an adventure sport model, the color selections for the Adventure Sports (AS) trim added to the lineup for the 2018 model year was considered based on the changes of the shipment ratio by color since the 2016 model, as well as feedback from Europe, its main market. In the most recent 2017 model year, Tricolor already accounted for half of the shipments, indicating its popularity (Fig. 12).

We thought that Tricolor would be the most suitable color for the AS, which is equipped with a big tank for more touring fun and reminds us of traveling.

Also, 2018 was a special year because it was exactly 30 years since the birth of the XRV650, the first Africa Twin, in 1988.

For these reasons, we decided to use a color scheme reminiscent of the tricolor of the first generation as the 30th anniversary color, and applied two-tone paint in many areas to create a livery suitable for a special model (Fig. 13).

In addition, the wreath design of the 30th anniversary commemorative mark was expressed in the tire pattern to



Fig. 11 The 2016 Africa Twin in monotone (silver)

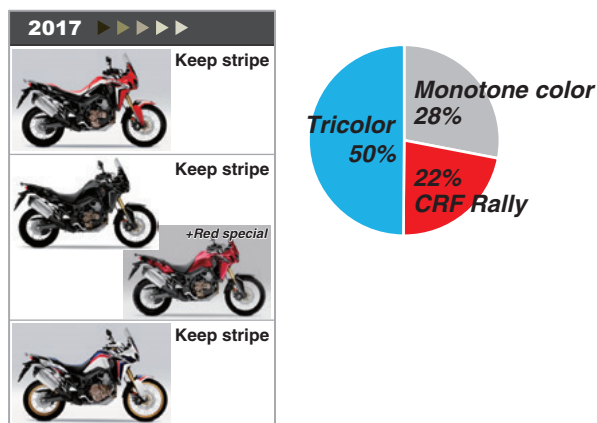


Fig. 12 Shipment volume for 2017 model by color

express our gratitude to the customers who have continued to ride and love the model for the past 30 years (Fig. 14).

As a result, the total number of both STD and AS in Tricolor in the 2018 model reached nearly 60% of the total (Fig. 15).



Fig. 13 The 2018 CRF1000L Africa Twin AS



Fig. 14 30th anniversary mark

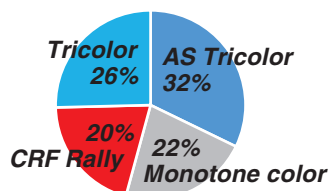


Fig. 15 Shipment volume of 2018 model by color and type

2.5. Africa Twin Color Variation Features and Brand Revival

We have taken the approach mentioned above towards the coloring design for the Africa Twin since 2016 as a way to strongly solidify the brand that was first established with the original model. The image that customers seek for the Africa Twin changes depending on the historical background of their exposure to motorcycles and the feelings that are fostered by the wide range of uses for on- and off-road vehicles. The iconic Tricolor, CRF Rally, and monotones fulfilled these individual wishes of the customers, and this combination of color schemes became the distinctive features of the Africa Twin. With sales exceeding 100,000 units in the five years since its launch, and the well-balanced acceptance of each color with Tricolor at its core, we believe that we have achieved the revival of the brand.

3. 2020 Model Livery Concept and Methodology

In considering the color schemes for the 2020 Africa Twin, we kept in mind that this is a rare model where the colors are given the role giving different identities to their respective Africa Twin.

The main feature of the 2020 model is that it has been differentiated into two distinctive types, Standard or STD (Fig. 3) for more enjoyable off-road riding and Adventure Sports or AS (Fig. 4) for more comfortable touring, with enhanced functions⁽²⁾ for each type. This is linked to the above “the colors are given the role giving different identities to their respective Africa Twin,” which means that each model concept can be accurately expressed in the coloring. Figure 16 shows a concept board showing the color scheme of each model.

The STD is interpreted as a new Africa Twin, an on/off-road model with a large but tight body that demands off-road mobility. The conventional CRF Rally color is used as the image color; a black monotone model with an urban extreme sports image was also made available.

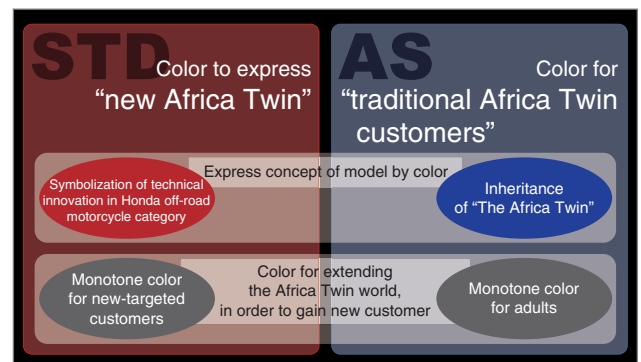


Fig. 16 Coloring concept of 2020 model

The AS is a tourer that inherits the impression of the Paris-Dakar model of the Africa Twin, which used to race through the African desert, and the traditional Tricolor was chosen as its image color. In addition, a monotone model has been created to take advantage of the characteristics of the AS, creating the image of a mature tourer that can handle a wide range of activities from urban use to touring.

The following is a description of the specific techniques used for each type and coloring.

3.1. The 2020 Africa Twin AS in Tricolor

The Africa Twin AS, which has evolved to enhance comfort in touring, is centered on the traditional tricolors, reminiscent of the first-generation Africa Twin that has traveled around the world with customers.

The livery concept was set as “New Interpretation of Heritage” and the tricolor arrangement was reworked to express a modern interpretation of the model’s heritage (Fig. 17).

The tricolor scheme of the AS type released in 2018 was expressed in graphics that flowed horizontally (Fig. 19), paying homage to the original Africa Twin (Fig. 18), as

mentioned earlier.

For the 2020 model, a geometric expression was adopted to make a modern update. Geometric graphics were arranged to accentuate the vehicle body’s front-to-back flow line to tighten the appearance of the AS type, which comes with a large gasoline tank (Fig. 20).

In the 2018 model, the blue paint was applied all the way down to the front edge of the middle cowling to create an imposing front-view impression in the horizontal direction. In the 2020 model, the front edge of the middle cowling was painted white to give a vertical impression in the same view (Fig. 21). This gives a slimmer look to the overall volume of the fairing (Fig. 22), which has increased with the installation of the cornering lights⁽⁵⁾. In contrast to the 2018 model, which has a more imposing impression, we tried to create a design that communicates ease of handling in touring.

Using these techniques, we further evolved the



Fig. 17 The 2020 Africa Twin AS in Tricolor



Fig. 18 The 2018 CRF1000L Africa Twin AS with the XRV650, first-generation Africa Twin



Fig. 19 Graphics accentuating lateral flow



Fig. 20 Geometric graphics accentuating longitudinal flow

traditional tricolor scheme by expressing the fusion of tradition and modernity as well as the ease of handling coming from the lighter body.

3.2. The 2020 Africa Twin STD in CRF Rally

The Africa Twin STD is slimmer and lighter for more enjoyable off-road riding. To show its link to the latest rally racers with high off-road performance, the CRF Rally color scheme was selected to be the main focus.

The livery of the latest CRF450 Rally has a greater proportion of red to give a stronger impression. Therefore, the livery concept was changed to “VIVID RED HONDA” to enhance the image of the powerful and light racer.

The areas of red, a color that symbolizes Honda’s motocross racers, has been increased to increase the image of aggressive strength, sportiness, lightness, and agility (Fig. 23).

In contrast to the previous CRF Rally color scheme, which were graphics of red and white placed adjacent to each other, black was inserted in between to give sharp

contrasts in brightness between the adjacent colors, resulting in a tighter color expression (Fig. 24).

By doing so, we were able to make the red stand out and make CRF Rally a more powerful color.

Utilizing these techniques allowed for the creation of graphics that look sporty, nimble, and agile, while at the same time giving a vivid impression of each color and expressing a more aggressive strength, deepening the impression of sharpness and the worldview of Honda as a racing company.

3.3. The 2020 Africa Twin AS and STD in Monotone

3.3.1. The AS in Monotone (black)

In creating the first monotone color scheme for the AS, we kept in mind the need to appeal to a wide range of adult



Fig. 21 Difference in impression in front view by their coloring design



Fig. 22 The 2020 Africa Twin AS equipped with cornering lights



Fig. 23 The 2020 Africa Twin STD in CRF Rally color scheme



Fig. 24 Differences in details of painted parts between 2016 and 2020 models

customers of today with diverse values.

The livery concept was set forth as “Adventure Elite,” and we were conscious of using dark colors to show a high level of quality as gear that would look good not only in chic touring attire, but also in daily use in the city, and that would give a sense of ownership status.

The contrast in textures created by the combination of the main color of gloss black and aluminum parts evokes the feeling of a sophisticated belonging of an adult, making this a distinguished adventure model with a cool impression (Fig. 25).

3.3.2. The STD in Monotone (black)

The monotone added to the color lineup for the STD type makes effective use of the red aluminum subframe also used in the CRF Rally color scheme, and the graphics are designed to convey a sense of crisp mobility.

The livery concept is “MODERN EXTREME SPORTS,” with linear graphics that express the speed of extreme sports for young-minded users.

To express urban sophistication, matte black, which has a high affinity with the aggressive image of extreme sports, was selected as the main color to achieve both a trendy look and a strong presence (Fig. 26).

These two black monotone color schemes are designed to appeal to a wide range of customers by presenting the world of Africa Twin differently from the Tricolor and CRF Rally colors. By using these techniques, the adventure model, which has a strong off-road image, has been given a high-tech, modern, and urban sophistication to match new lifestyle and riding styles.

As a result, the colors for all 2020 Africa Twin AS and STD models have been decided. Figure 27 shows the color variations corresponding to the concept board shown at the beginning of this section.



Fig. 25 The 2020 Africa Twin AS in monotone (black)



Fig. 26 The 2020 Africa Twin STD in monotone (black)



Fig. 27 Coloring variations of the 2020 Africa Twin STD and AS

4. Designing of Logotypes and Texture

As with the coloring described above, the logotype design and the texture design also play an important role in conveying the concept of the product. The following are the details that were worked on in order to further enhance the attractiveness of the Africa Twin.

4.1. Logotype Design

In the 2016 model, both the STD and AS types adopted the common Africa Twin logotype design (Fig. 28), and in the 2020 model year, the common Africa Twin logotype that was redesigned with a modern edge (Fig. 29) was used to create logotype mark exclusive to the AS with an iconic element representing the form of the African continent added to it (Fig. 30).

This design is intended to give the audience a sense of the Africa Twin's journey through the vast land of dreams,

just as the Paris-Dakar Rally once did. The design of the logotype symbolizes the comfort of long-distance travel and the spirit of adventure, which have been enhanced in the 2020 AS model.

4.2. Textured Pattern Design

Texture designing plays an important role in both functionality and feel of quality: its functional role is in adjusting the slipperiness of the material according to the degree of friction required, and in reducing the appearance of scratches, and its role in the feel of quality is to have a high-quality look from its appearance.

For this iteration of texture designing, we collaborated with an external design studio to pursue a new expression.

Figure 31 shows the three proposals that were narrowed down based on the theme of “a pattern that gives a sense of dynamism” to stimulate the owner’s senses and satisfy the desire to own the vehicle, as well as having the necessary functionality for full-scale off-road performance. In addition, we discussed how the pattern would look when applied to actual parts, and decided on a fine-tuned pattern based on Proposal B.



Fig. 28 Logotype of the 2016 Africa Twin



Fig. 29 Logotype of the 2020 Africa Twin



Fig. 30 Logotype mark of the 2020 Africa Twin AS

Figure 32 shows the textured pattern with an application example.

Proposal B was derived from Africa Twin’s basic concept of “Go anywhere,” taking the image of a vast and complicated course in a rally competition and processing it as a geometric pattern.

This pattern, named “Random Road,” was applied to the top cover of the tank and the covers around the speedometer, where it is most likely to be seen by the user, with the aim to stir excitement when riding the vehicle.

Because of the Africa Twin’s use in various scenes, it must be able to withstand the various conditions of nature, such as rain, wind, and sand. Therefore the ease of cleaning was also examined when adopting the new textured pattern.

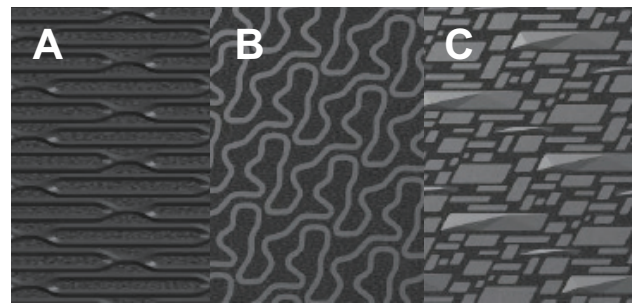


Fig. 31 Candidates for textured pattern

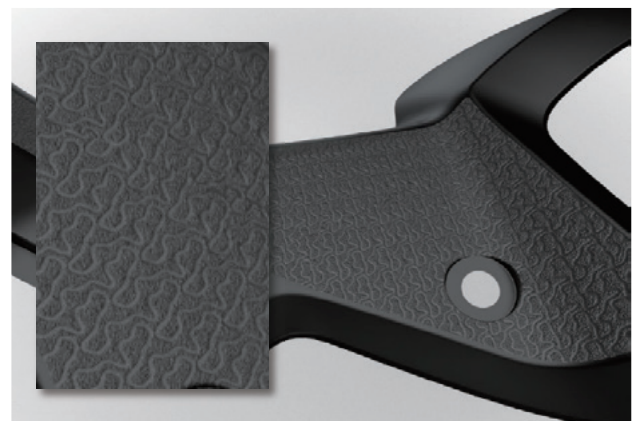


Fig. 32 Textured pattern and applied part

5. Summary

Since the 2016 model, the color variations of Africa Twin have been distinctive, with each livery having a different image and feel as felt by the customers.

This sense of each color becoming a brand on its own was the result of our effort in maintaining a consistent approach to the color schemes.

We aimed to enhance and further solidify the Africa Twin brand for the 2020 model by linking the characteristics of each livery with the STD and AS model concepts.

It is our hope that the Africa Twin will continue to “go everywhere” with its customers and remain a reliable lifelong companion.

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Active Sound Control Technology for Electrified Vehicles Based on Concept of Shepard Tones

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ABSTRACT

Active Sound Control technology for electrified vehicles was developed in order to realize vehicle interior sound levels matching the seamless acceleration that is characteristic of driving under electric motor power. This technology takes the fundamental approach of generating sound based on the conceptual approach of Shepard tones and synchronizing it with the vehicle velocity. The main tones generated according to the theory of Shepard tones are superimposed with multiple sub-tones at preset frequency ratios. This approach can produce acceleration sounds with further increased freedom. An acceleration sound that differs from engine sound and has sounds matched to the electrified vehicle has been realized by means of this technology.

1. Introduction

Among measures addressing global warming and other such environmental issues is the use of electrified vehicles (x Electrified Vehicle: xEV), which includes hybrid vehicles, fuel cell vehicles, and battery-powered electric vehicles. Advances are being made in the development and popularization of such vehicles. The electrification of power plants, however, has raised new challenges in the design of interior sound for vehicle cabins. When an EV is operating by motor, the absence of sound generated by an internal combustion engine makes the vehicle cabin quiet, but on the other hand, the feeling of acceleration that vehicle occupants gain from sound when the vehicle is accelerating is diminished⁽¹⁾. Furthermore, acceleration sound as one element that forms the identity of the vehicle is also lost.

The cabin interior sound from conventional engines is often sensed as noise. However, the sound functions not only to make vehicle occupants aware of vehicle acceleration and deceleration, but is also an element that can express the individual character of the particular automobile manufacturer. Each manufacturer has, therefore, been creating acceleration sounds to include as part of its own brand identity^{(2),(3)}. The authors have created an Active Sound Control (ASC) technology intended to enhance the acceleration feel of engine-powered vehicles as well as to construct sounds that are in line with the brand identity of

those vehicles, and they have applied the technology in the mass production of many vehicle models to date⁽²⁾.

Figure 1 shows the configuration of that ASC system. This technology generates engine order sound components synchronized with the engine speed that is acquired from the Controller Area Network (CAN). The sound source signals generated by the ASC Electronic Control Unit (ASC-ECU) are emitted by speakers in the vehicle cabin that are shared with the audio system, and there they combine with cabin interior sounds to become acceleration sounds.

In the case of an xEV, the sound produced by the motor when the EV is operating is comparatively small. New ASC technology capable of generating acceleration sounds suited

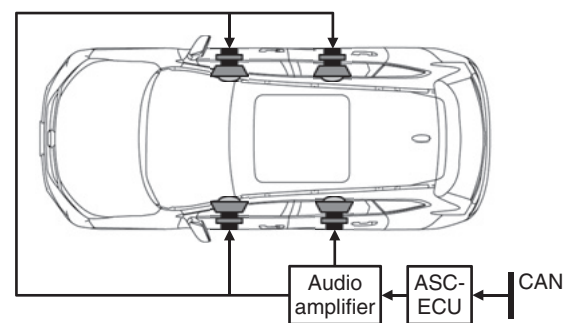


Fig. 1 ASC system configuration

¹ Innovative Research Excellence

to the characteristic experience of accelerating seamlessly from initial movement all the way up to high speed was, therefore, considered necessary.

This paper describes the concept for newly developed xEV-ASC technology, provides an overview of the system, and cites cases of its application in vehicles.

2. xEV-ASC Concept

The following three points served as guiding aims in investigating the xEV-ASC:

- (1) Realize a varying sound that is synchronized with vehicle velocity and acceleration
- (2) Realize sounds that can express the acceleration feel typically experienced in driving an EV
- (3) Modulate sounds with a high degree of freedom

2.1. Synchronization with Vehicle Speed

In order to express the acceleration of an EV operating under motor power, it is desirable to vary the quality of the sound that is synchronized with the changing vehicle velocity itself. The speed of the motor, which is the source of driving power when an EV is in operation, is also proportional to the vehicle velocity. The xEV-ASC, therefore, generates acceleration sounds that have the vehicle velocity as a reference signal.

The relationship between the frequency of the acceleration sound and the vehicle velocity is shown in Eq. (1).

$$f(v) = R \times v + F0. \quad (1)$$

Here, v is the vehicle velocity, R is the frequency change rate, and $F0$ expresses the segment on the frequency axis. Figure 2 shows examples of acceleration sound frequency settings according to Eq. (1). Since frequency change rate is one of the factors that influence acceleration feel⁽⁴⁾, the acceleration feel is harder to sense when the frequency change with respect to the vehicle velocity change shown in Ex. 1 of Fig. 2 is gradual. With the higher frequency change rate in Ex. 2, on the other hand, the sound will be at a high frequency when the vehicle velocity is high, making it unpleasant to hear. Under these circumstances, setting the sound to ascend to frequencies that are stepped as in Ex. 3 can make it possible to produce sounds in frequency ranges that will not be unpleasant to the ear while maintaining a

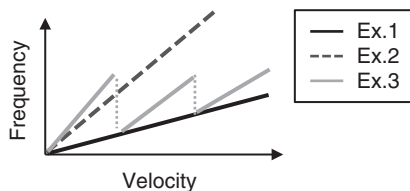


Fig. 2 Typical sound settings according to Eq. (1)

high frequency change rate. However, this will produce sounds like those of a vehicle with automatic or manual transmission (AT/MT), which changes gears, and it cannot readily express the acceleration feel typical of driving an EV with a motor, which accelerates seamlessly from initial movement all the way up to high speed.

For such an ASC that is synchronized with vehicle velocity, therefore, the technical issue is expressing a seamless acceleration feel while keeping the acceleration sounds within a frequency range that will not be unpleasant to the ear.

2.2. Realization of xEV Sound Quality by Application of Shepard Tones

In order to resolve the above technical issue, an approach was conceived that would apply Shepard tones⁽⁵⁾, which are also used for sound effects in music and films.

Shepard tones were devised by R. N. Shepard as sounds consisting of superimposed sine waves that are separated by octave units^{(5), (6)}. When these sounds are reproduced repeatedly, they cause an auditory illusion that makes the pitch seem to be continually rising.

Figure 3 shows the general musical scale and Shepard tones on a keyboard. The progression on the general musical scale, as shown in Fig. 3(a), is toward the right side of the page as the pitch rises by half tones, so that progressing from do (C) by 12 steps ends at C one octave higher. Shepard tones, however, are composed of multiple sounds that are an octave apart, as shown in Fig. 3(b). When these sounds are synchronized and reproduced so as to rise progressively by one octave, then in the case of a single sound, it seems to have risen one octave, but in the case of Shepard tones, it seems to have returned to the original sound. In other words, continuously reproducing a sequence of Shepard tones creates the illusion that the sound is continuing to rise higher.

Figure 4(a) shows a schematic diagram of Shepard tones as a way of understanding this phenomenon. The vertical direction represents the height of the frequency and the circumferential direction represents the height of the musical scale. The red frame marks the chord of C in Shepard tones, and the other tonal scales are arrayed in the circumferential direction. Reproducing each tonal scale

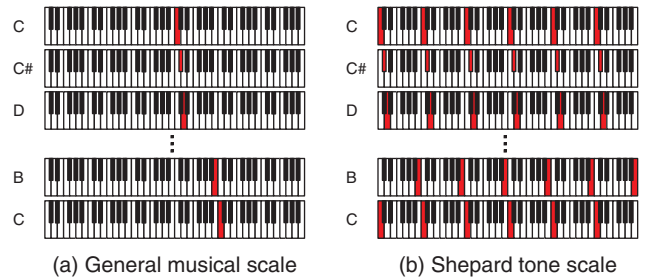


Fig. 3 Musical scale on keyboard for piano

continuously in a counterclockwise direction gives rise to the illusion that the sound is rising continuously like the spiraling arrow shown in the figure. Something that uses a similar illusion is the kind of sign pole shown in Fig. 4(b), which is widely used as a barber's pole or other such advertising sign. In the case of the sign, its rotation causes the visual illusion that the red and blue stripes are continuously rising up.

Reasoning that these Shepard tones could be used to resolve the issue in Section 2.1., development of xEV-ASC technology for generating acceleration sounds by the application of Shepard tones synchronized with vehicle velocity was undertaken.

2.3. Modulation of xEV Sound Quality by Tone Setting

Since Shepard tones are superpositions of sounds that are an octave apart⁽⁵⁾, there are limits to the sound that can be realized. Consequently, the sound from conventional

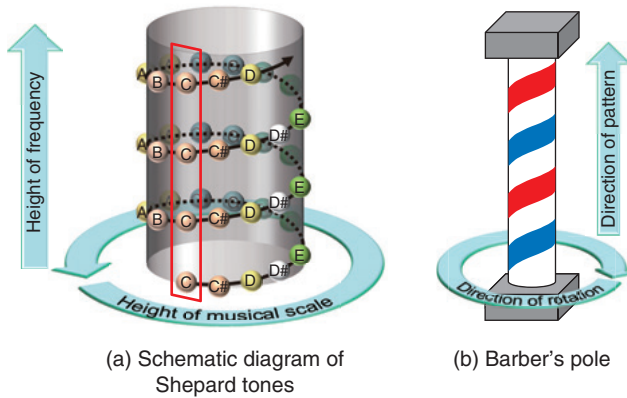


Fig. 4 Shepard tones and barber's pole

Shepard tones alone is insufficient for expressing the various identities of different vehicles.

As a way to enhance the freedom of sound modulation, an approach was conceived for applying the methods for forming chords in music theory to the generation of acceleration sounds while keeping the characteristics of Shepard tones. The set of sine waves that are in octave relationship in the original Shepard tones are defined as the main tones. Tones with a certain frequency ratio with respect to these main tones are defined as sub-tones. It was reasoned that generating multiple sub-tones in addition to main tones would realize a greater abundance of sounds.

3. xEV-ASC System

Figure 5 shows a block diagram of the xEV-ASC system. This system is made up of four modules: the vehicle state acquisition, sound creation, cabin interior acoustic field compensation, and volume control modules. The sound creation module utilizes ASC technology that generates sounds applying newly developed Shepard tones synchronized with the vehicle velocity.

3.1. Vehicle State Acquisition

The vehicle state acquisition module, as shown in Fig. 5, acquires from the CAN the vehicle velocity, accelerator pedal (AP) position, and information on the vehicle dynamic mode (normal, sport, and so on), which are needed to generate the acceleration sounds. The vehicle velocity is also used to perform internal calculation of the vehicle acceleration.

3.2. Sound Creation

The tonal quality of an acceleration sound is determined

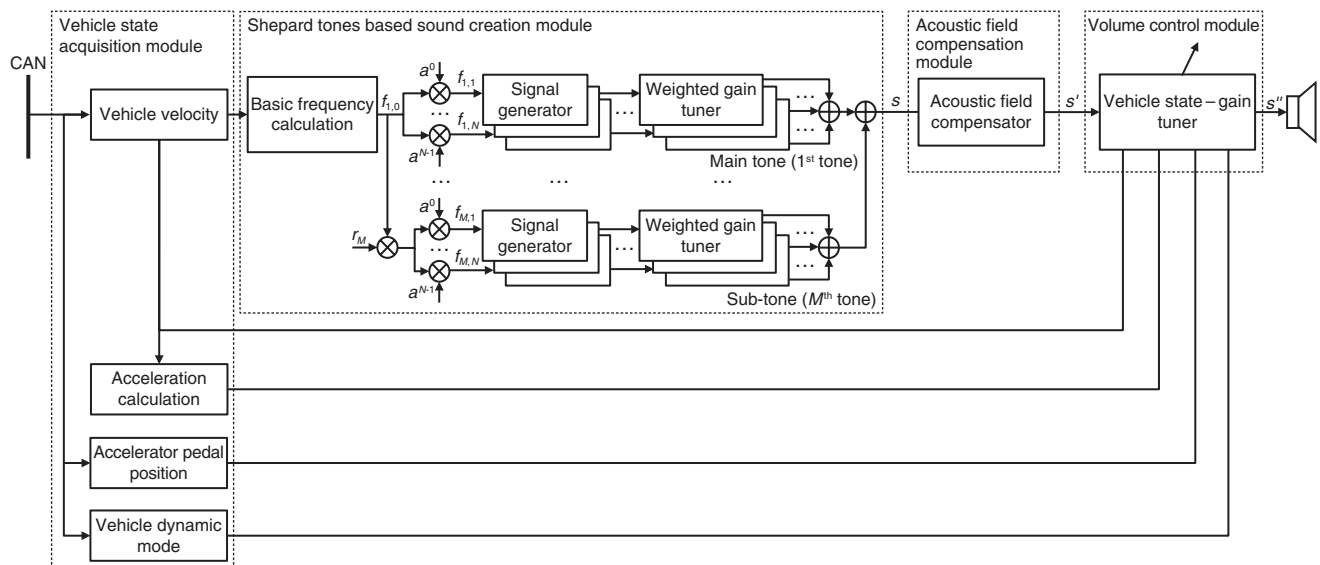


Fig. 5 Block diagram of xEV-ASC system

by its component frequencies and the magnitude of each frequency component. As shown in Fig. 5, the sound creation module calculates the component frequencies based on Shepard tones, generates sine signals for each frequency, and modulates the amplitude of the sine signals. By these three processes, it generates the main tones and sub-tones and configures the sounds.

3.2.1. Creation of main tones

For the creation of main tones, the basic frequency f_0 is calculated as shown in Eqs. (2) through (5).

$$f_0(n) = F_{\min} \times a^{\left(\frac{v(n) - V(n)}{k}\right)}, \quad (2)$$

$$\text{If } f_0(n) \geq F_{\max}, V(n) = v(n), \quad (3)$$

$$\text{Else if } f_0(n) < F_{\min}, V(n) = v(n) - \Delta V(n), \quad (4)$$

$$\text{Else, } V(n) = V(n - 1). \quad (5)$$

Here, n is the discrete time, $F_{\min}$ and $F_{\max}$ are the lower limit frequency and upper limit frequency, respectively, a is the base of the exponential function of vehicle velocity v , V is the vehicle velocity when the basic frequency f_0 reaches the upper limit frequency, and k expresses the frequency change rate modulation coefficient. Of these, k , a , $F_{\min}$, and $F_{\max}$ are control parameters. It can be determined from the above that the basic frequency f_0 varies exponentially between $F_{\min}$ and $F_{\max}$ according to the vehicle velocity. When f_0 exceeds $F_{\max}$ as acceleration occurs, the vehicle velocity v is set to V when $f_0 = F_{\max}$, according to Eq. (3), and this returns f_0 to $F_{\min}$. When f_0 drops below $F_{\min}$ during deceleration, V is set to $v - \Delta V$ in order to bring f_0 to $F_{\max}$. Here, ΔV expresses the amount of change in the vehicle velocity when f_0 rises from $F_{\min}$ to $F_{\max}$, and it can be calculated as shown in Eq. (6).

$$\Delta V = k \log_a \frac{F_{\max}}{F_{\min}}. \quad (6)$$

ΔV is calculated using k , a , $F_{\min}$, and $F_{\max}$, which are decided in advance as control parameters.

The N th component frequency of the main tones is calculated from f_0 , as shown in Eqs. (7) and (8).

$$f_N(n) = f_0 \times a^{N-1}, \quad (7)$$

$$\text{If } f_N(n) \geq F_{\max}, f_N(n) = f_N(n) \times \frac{F_{\min}}{F_{\max}}. \quad (8)$$

The number of necessary component frequencies $N_{\max}$ is determined by a , $F_{\min}$, and $F_{\max}$.

$$N_{\max} = \log_a \frac{F_{\max}}{F_{\min}}. \quad (9)$$

According to Eqs. (7) and (8), the ratio of any two adjoining component frequencies will consistently be the constant a . When $a = 2$, the component frequencies of the acceleration sounds are the original Shepard tones, which consistently maintain an octave relationship, producing a

harmonious sound. Figure 6 shows an example of Shepard tone frequency components that include six components calculated by Eqs. (2) to (8).

The sine signal s_N for each frequency component is generated by the signal generator according to the respective frequency. The magnitude of the respective sine waves is determined by modulating the two weighted gains shown in Fig. 7.

$G_S(f)$ is a weighted gain for the purpose of causing auditory illusion by means of the Shepard tones by causing the low-frequency and high-frequency sounds in the range between $F_{\min}$ and $F_{\max}$ to fade in and fade out smoothly. Figure 8 shows an example of this configuration. By the use of $G_S(f)$ and Eqs. (2) through (8), the acceleration sound that has the Shepard tones characteristics shown in

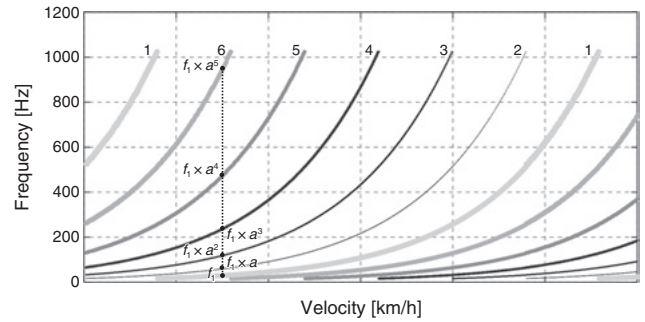


Fig. 6 Example of calculated frequencies

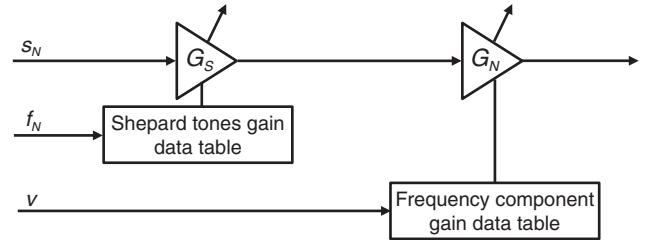


Fig. 7 Block diagram of weighted gain tuner

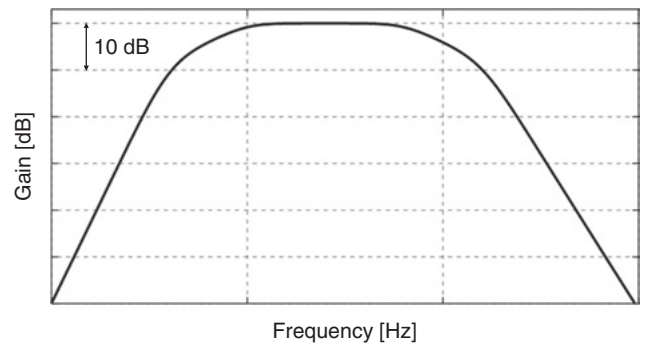


Fig. 8 Example of Shepard tones gain $G_S(f)$

Fig. 9 can be generated in synchronization with the vehicle velocity.

$G_N(v)$ is the weighted gain of each frequency component that is based on vehicle velocity. As shown by the configuration example in Fig. 10, the sound can be modulated by changing the ratio of frequency component magnitudes according to the vehicle velocity.

3.2.2. Creation of sub-tones

In creating sub-tones, when the ratio between the basic frequencies of the M th sub-tone and the main tone is set to r_M , the component frequency $f_{M,N}$ can be calculated as shown in Eq. (10).

$$f_{M,N}(n) = r_M \times f_{1,0}(n) \times a^{N-1}. \quad (10)$$

It is possible to set r_M on the basis, for example, of music theory⁽⁷⁾. Table 1 shows the triads, which are the basic chords made up of three sounds together with the impressions⁽⁸⁾ of the sounds that are expressed by those triads. Major and minor triads can express bright and dark sounds. It is said that suspended triads can give an impression of the fantastic. These can be configured for use according to the characteristics of the vehicle. A diminished triad is said to have an unstable sound, which may conceivably have uses when encouraging caution. When configuring a sound with three tones based on a major triad

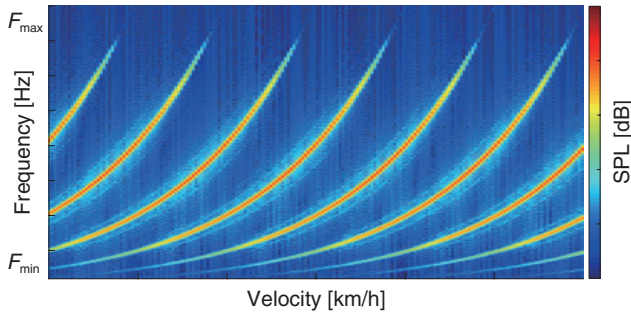


Fig. 9 Example of Shepard tones based acceleration sound

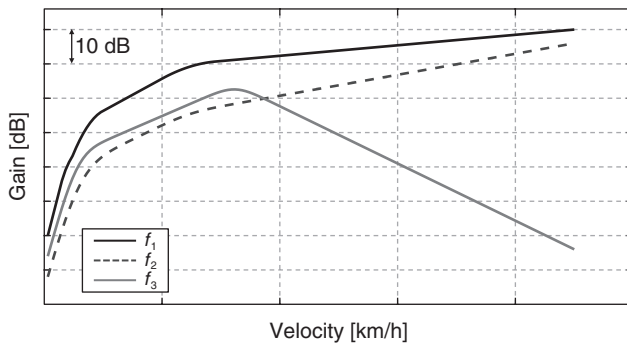


Fig. 10 Example of frequency component gain $G_N(v)$

Table 1 Typical triads and impressions of triads

Chord type	Frequency ratio	Impression
Major	1:1.25:1.5	Bright/Pleasant
Minor	1:1.2:1.5	Dark/Sad
Suspended	1:1.33:1.5	Fantastic
Diminished	1:1.2:1.42	Unstable/Transient
Augmented	1:1.25:1.6	Unstable/Transient

to give a bright impression, for instance, this can be done by setting the frequency ratio $r_1:r_2:r_3$ of the main tones and two sub-tones to 1:1.25:1.5.

The signal s that is the output of the sound creation module is calculated by adding together the various frequency component signals for each tone, as in Eq. (11). In this way, it is possible to assign multiple sounds that have freely selectable frequency ratios.

$$s(n) = \sum_{M=1}^{ALL} \sum_{N=1}^{ALL} G_N(v(n)) \times G_S(f_{M,N}(n)) \times G_C(f_{M,N}(n)) \times s_{M,N}(n). \quad (11)$$

3.3. Cabin Interior Acoustic Field Compensation

As indicated by the gray line in Fig. 11, the gain characteristics of the acoustic response from the speaker to the vehicle occupant's head as influenced by the acoustic field inside the vehicle cabin have peaks and valleys. The acceleration sounds transmitted to vehicle occupants vary in the magnitude of the sound components, depending on their frequencies, and thus sounds cannot be guaranteed to be exactly as configured in advance. In order to realize the acceleration sound quality, as configured, at the vehicle occupant's location, therefore, the magnitude of each frequency component is compensated by using the inverse $G_C(f)$ of the cabin interior acoustic response gain characteristics, indicated by the black line in Fig. 11.

3.4. Volume Control

In order to achieve a balance between quietness when cruising and acceleration feel when accelerating, as well as to produce acceleration sounds that are coordinated with the behavior of the vehicle and operations performed by vehicle

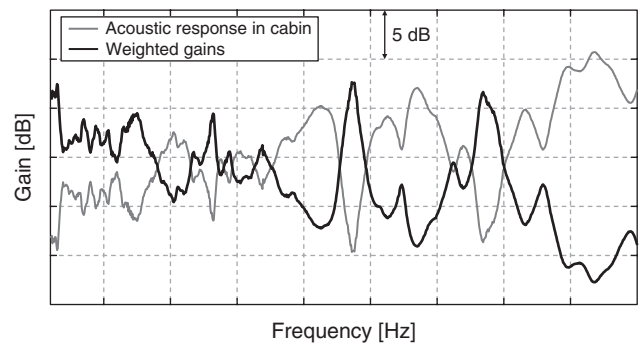


Fig. 11 Example of acoustic compensation gain $G_C(f)$

occupants, a means is provided to modulate the overall volume of the acceleration sounds according to the vehicle's velocity, acceleration, and AP position. By arranging the system so that the acceleration sound volume can be set for each of the vehicle dynamic modes selected by vehicle occupants, such as normal, sport, and so on, the system can also be switched between cabin interior sound settings that emphasize quietness or that emphasize acceleration feel, depending on the vehicle dynamic mode.

Figures 12 through 14 show examples of settings for vehicle velocity gain $G_V(v)$, acceleration gain $G_{Acc}(\Delta v)$,

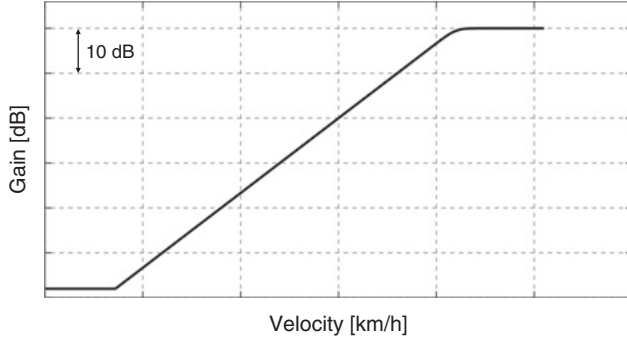


Fig. 12 Example of velocity gain $G_V(v)$

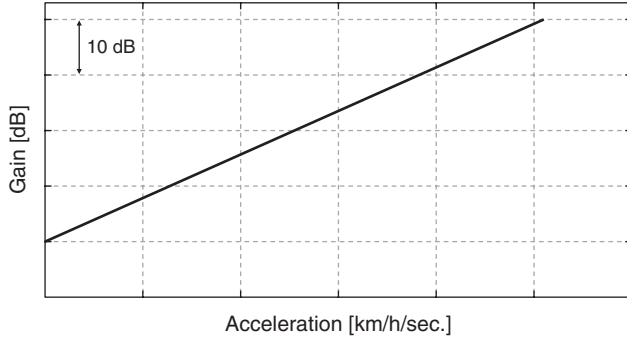


Fig. 13 Example of acceleration gain $G_{Acc}(\Delta v)$

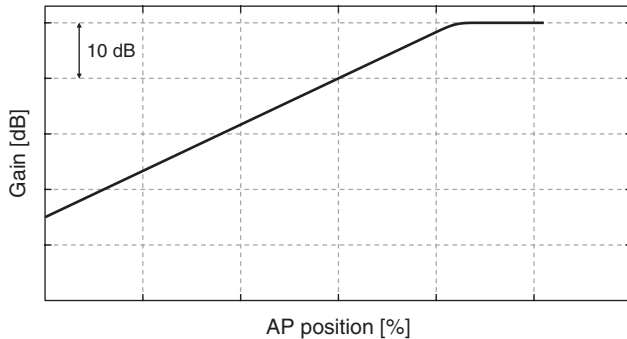


Fig. 14 Example of accelerator pedal position gain $G_{AP}(p)$

Table 2 Example of vehicle dynamic mode gain

Vehicle dynamic mode	Dynamic mode gain $G_M(m)$
Comfort	-90 dB
Normal	0 dB
Sport	+6 dB
...	...

and AP position gain $G_{AP}(p)$, respectively. These can be set so that the sound volume increases with increases in the vehicle velocity and acceleration and with the AP opening. Table 2 shows examples of settings for vehicle dynamic mode gain $G_M(m)$. These can be set so that in comfort mode, no sound is output, while in sport mode, the sound volume is set to a high level to emphasize the acceleration feel.

The acceleration sound signal s'' is output from the speakers after first undergoing volume control as shown in Eq. (12) with respect to signal s' , which has undergone acoustic field compensation.

$$s''(n) = s'(n) \times G_M(m(n)) \times [\alpha \times G_A(\Delta v(n)) + (1 - \alpha) \times G_V(v(n)) \times G_{AP}(p(n))]. \quad (12)$$

Here, α is a parameter that modulates the ratio of acceleration gain and AP position gain. It satisfies the condition $0 \leq \alpha \leq 1$.

4. Cases of Application in Vehicles

Here, the case of application of this system in an SUV Plug-in Hybrid EV (PHEV) for the China market that is scheduled to go on sale in 2021 will be introduced. The system is configured in the same way shown in Fig. 2. The ASC-ECU generates acceleration sound signals based on vehicle information acquired from the CAN. The signals are emitted in the vehicle cabin from speakers that are shared with the audio system. In this way, the system acts to enhance the acceleration feel of the subject vehicle during EV operation.

4.1. System Settings

The first item was to investigate how to set the sub-tones. A number of settings based on the triads in Table 1 were tried, and eventually the configuration of major triad with bright sounds was adopted. As stated in Clause 3.2.2., the ratio was set as $r_1:r_2:r_3 = 1:1.25:1.5$ with the aim of creating a bright acceleration sound. Then, on the premise that this will be the sound, the parameters for modulating the sound and volume were tuned by repeated testing in an actual vehicle.

Next, the range of frequencies was investigated. Since the upper limit frequency expresses the enjoyable quality of EV driving, it was reasoned that this frequency should be

made somewhat higher. From the experience of ASC tuning in conventional engine-powered vehicles, it was reasoned that the high frequency around the 8th-order sound of a four-cylinder, four-cycle engine would be needed. Since that 8th-order sound was 800 Hz at 6000 rpm, the upper limit frequency was set to $F_{\max} = 800$ Hz. Based on the lower limit frequency that can be reproduced by speakers, the lower limit frequency was set to $F_{\min} = 50$ Hz. As a result, there were four main tones generated at the same vehicle velocity according to parameters a , $F_{\min}$, and $F_{\max}$ and Eq. (9).

Regarding parameters k and a , which are used to modulate the frequency change rate, these were tuned to match them to the acceleration performance of the subject vehicle. They were set to $k = 25$ km/h and $a = 2$. It is apparent from Eq. (6) that a single sine wave is generated so as to repeat at a frequency between $F_{\min}$ and $F_{\max}$ at intervals of $\Delta V = 100$ km/h. Since one tone is composed of four sine waves, this also means that the frequency components of the tone are repeated each 25 km/h.

In order to make the various frequency components fade in and fade out smoothly, the gain $G_S(f)$ setting shown in Fig. 8 was used. The gain $G_N(v)$ of each frequency component was set as shown in Fig. 15 so as to emphasize the linearity of acceleration sounds and put the gain of each frequency component at the same value. Given these conditions, the gain was set to rise with increasing vehicle velocity.

The volume control was configured to coordinate the acceleration sound volume with the acceleration of the vehicle and AP operation by vehicle occupants. The vehicle velocity gain $G_V(v)$ was set to 0 dB throughout the entire vehicle velocity range. The acceleration gain $G_{Acc}(\Delta v)$ and AP position gain $G_{AP}(p)$ were set as shown in Figs. 13 and 14 so that the volume would rise with increases in acceleration and with greater AP opening by vehicle occupants. In order to emphasize quietness when driving in normal mode while also providing a strong acceleration feel during acceleration in sport mode, the vehicle dynamic mode gain $G_M(m)$ was set to deliver

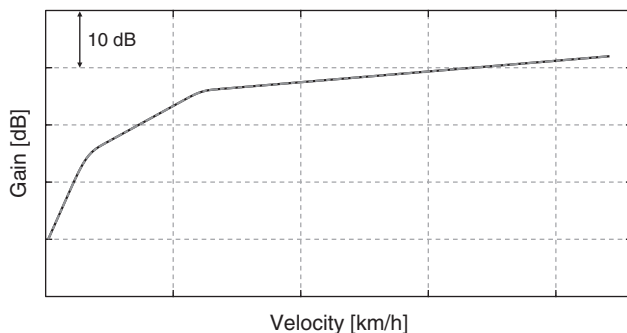
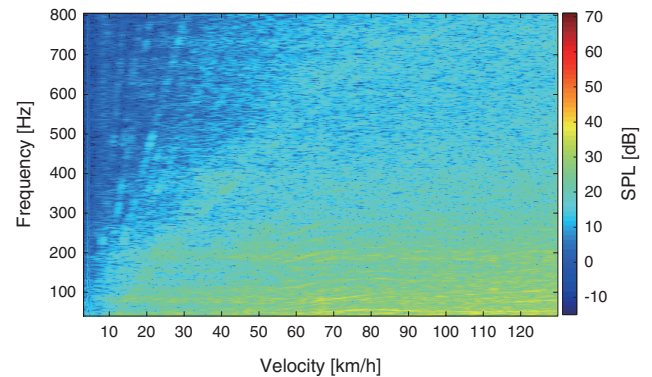


Fig. 15 Frequency component gain $G_N(v)$ for test car

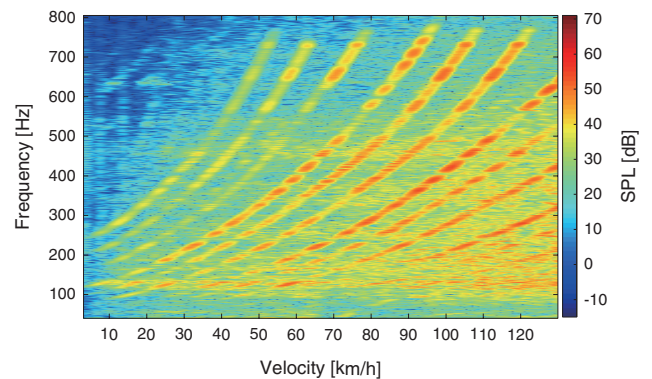
acceleration sounds that would be felt when driving in sport mode.

4.2. xEV-ASC Control Effects

Figure 16 shows spectrograms of cabin interior sound with and without the xEV-ASC system. When without the xEV-ASC system, there are fewer sound components that change frequency as the vehicle velocity increases. When with the xEV-ASC system, on the other hand, acceleration sounds with Shepard tone characteristics, meaning they are repeated every 25 km/h between $F_{\min}$ and $F_{\max}$, are generated in synchronization with vehicle velocity. Test rides of the vehicle equipped with the xEV-ASC system were conducted in-house. The results confirmed that the xEV-ASC system can enhance the acceleration feel that vehicle occupants receive when accelerating during EV operation of the vehicle. The xEV-ASC system is capable of generating acceleration sounds with a quality that matches the characteristics of EV driving, which delivers a seamless acceleration feel. It was successfully confirmed that the system can be used to produce distinctive xEV acceleration sounds.



(a) Without xEV-ASC system



(b) With xEV-ASC system

Fig. 16 Interior sound spectrogram of test car

5. Conclusion

This paper reported on newly developed xEV-ASC technology. This technology uses the concept of Shepard tones to generate acceleration sounds that are synchronized with vehicle velocity, thereby realizing a sound that can express the seamless acceleration feel experienced during motor-powered EV operation. The technology further achieves sound modulation with a high degree of freedom by the configuration of main tones and sub-tones. This technology was also applied, and its effectiveness was confirmed, in an SUV PHEV for the China market that is scheduled to go on sale in 2021.

For the xEV of the future, this technology is thought to have the potential to become an important element of the technologies that will be used to help form a vehicle's identity.

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Technology for Prediction of Contactor Noise for Electric-powered Vehicle Batteries

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ABSTRACT

Electric-powered vehicles have a high-voltage battery unit mounted in the vehicle body, and the sound made by operation of the electromagnetic contactor inside the unit can be unpleasant for vehicle occupants. A method was created for predicting this noise from the excitation force of the high-voltage battery unit on its own and from the acoustic transmission characteristics of the vehicle body structure. The adoption of component-based transfer path analysis made it possible to separate vibration sources from transfer systems and predict noise in the fully assembled vehicle state by using the load transferred from the stand-alone high-voltage battery unit to the vehicle body side and a transfer function that combines the vehicle body structure transfer and the cabin acoustic transfer. A computer-aided engineering model was also created for predicting the load from the stand-alone high-voltage battery unit based on the load from the junction board, which is a sub-unit of it. This made it possible to predict the excitation force of the high-voltage battery unit at the drawing stage. By means of the above technology, it has become possible to consider noise evaluation in the fully assembled vehicle state at the performance design stage.

1. Introduction

Calls to reduce the burden on the environment from automobiles have been heightening in recent years. Every automobile manufacturer has been taking measures to reduce CO₂ emissions by enhancing fuel economy performance and by developing and popularizing electric-powered vehicles.

Honda has been developing a variety of electric-powered vehicles to promote their popularization^{(1), (2)}. These electric-powered vehicles are equipped with a high-voltage battery unit (hereinafter, unit)⁽³⁾⁻⁽⁵⁾ for the purpose of storing electrical energy in batteries. Installed inside the unit is an electromagnetic contactor, which is a control device that turns the current on and off in order to supply electric power. It operates when the vehicle starts moving and when the vehicle comes to a stop. The engine is normally stopped when the vehicle starts moving, and the background noise level is low, so that the sound of the unit operating is heard as an unpleasant noise. Because this noise has been evaluated in a fully assembled vehicle state, issues often emerge in later stages of development that leave no option but to rework development or take additional measures.

There is demand, therefore, for the creation of technology to predict noise in the initial stages of development.

Transfer path analysis (TPA) is one method used for analyzing this kind of noise. The noise in a fully assembled vehicle state can be predicted by multiplying together the input from the unit, which is the vibration source, and the structural acoustic transfer function on the vehicle body side, which is the response system. When the input system and response system are close to being rigidly connected, the method commonly used in traditional TPA to identify the input is to use a transfer function matrix for the response system together with the response obtained when in actual operation. Measurements are made using the actual vehicle body and unit, however, so this method cannot be applied in the initial design stages when a prototype unit does not exist.

For this paper, therefore, a method was created for predicting noise in a fully assembled vehicle state by using component-based TPA to allow the unit and the vehicle body to be evaluated separately. This approach was used together with computer-aided engineering (CAE) to create a method for predicting input from the unit without using a prototype unit.

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² Estech Corp.

2. Electromagnetic Contactor Operating Noise

2.1. Excitation Caused by Electromagnetic Contactor

The electromagnetic contactor is one of the control devices used to turn large electric currents on and off. Figure 1 shows a schematic view of this electromagnetic contactor. It controls the on-off state of the electric current by using electromagnetic force to change the position of a movable iron core and open or close a contact. The contact that occurs when this is done is a vibration source, and the vibration is transmitted from the unit to the vehicle body, producing noise.

2.2. High-Voltage Battery Unit Configuration

Figure 2 shows an example of unit components. The electromagnetic contactors are mounted on the junction board, which has the safety function of breaking electrical connections and current flow. The configuration has this junction board attached to the battery frame, and the unit including this component attached to the vehicle body frame.

2.3. Operating Noise in a Fully Assembled Vehicle

The operating noise of an electromagnetic contactor in a fully assembled vehicle is an impact noise that occurs for a brief period of time. Figure 3 shows the results from frequency analysis of this operating noise at a vehicle occupant's ear location. It is apparent that there is a peak from around 100 Hz to 600 Hz. Taking into account the frequency range close to this peak together with the fact that the lower limit of the audible frequency range is generally about 20 Hz, the frequency range for analysis was set from 20 Hz to 1000 Hz.

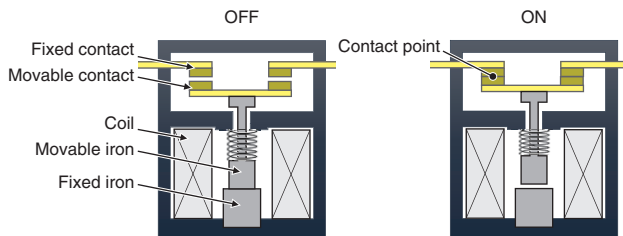


Fig. 1 Schematics of electromagnetic contactor

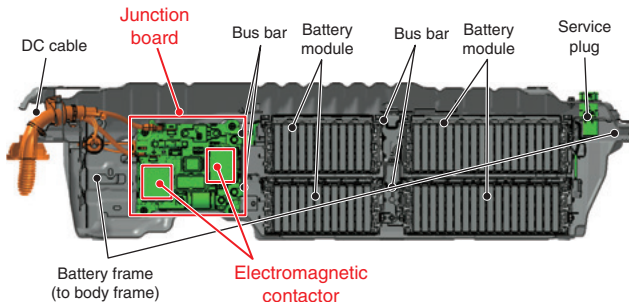


Fig. 2 High-voltage battery unit components

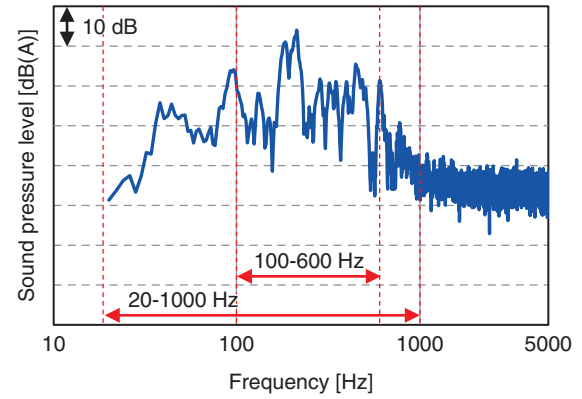


Fig. 3 Cabin noise of electromagnetic contactor

3. Component-Based TPA

3.1. Differences from Traditional TPA

TPA has long been in frequent use for the analysis of noise and vibration. This is a method for analyzing the degree of contribution by sound sources and the respective transmission paths based on input from the engine, motor, and other such vibration sources together with the structural acoustic transmission characteristics of the vehicle body and so on that form the response system^{(6), (7)}.

Component-based TPA is a method that makes it possible to measure input from the unit discretely when it is detached from the response system on the vehicle body side⁽⁸⁾. In traditional TPA, measurements of unit input had to be made with the unit and the vehicle body in a combined state. In component-based TPA, measurements of structural acoustic transmission characteristics are made with the unit and the vehicle body in a combined state, allowing measurement of unit input from the unit, detached from the vehicle body side. Table 1 shows a comparison with traditional TPA. This has become a very actively utilized method of analysis in recent years because it allows a target load value to be set for the unit and it also fits with the ongoing trend toward accelerated flow of model-based development.

3.2. Transmission Force from Unit

Three main methods are known for measuring input loads in component-based TPA⁽⁹⁾. The first is the direct force method, in which the unit is mounted rigidly in place and the load transmitted from the vibration source is measured directly. The second is the hybrid method, in which the unit is fixed in a jig, and the load it transmits is measured and combined with the response to transmission in that system to identify the equivalent load. Third is the free velocity method, in which the unit is in a free state, and the response transmitted from the vibration source is measured and converted into load. Figure 4 shows these methods in schematic form. Although the second and third methods are frequently used, they require the acquisition

Table 1 Traditional TPA and component-based TPA

Method	Input force (F)	Transfer function (H)
Traditional TPA	Contact force	Unit separation
Component-based TPA	Blocked force	Unit combine

of a transfer function for separate measurement systems, which necessitates a procedure to convert the measurement load to equivalent external force. With the first, direct force method, mounting the unit rigidly in place does become an issue, but since the measured placement reaction force can itself be taken as the equivalent external force, this method has the advantage of a simpler measurement procedure.

The theory of component-based TPA in the direct force method can be explained as follows. The equation of motion for the system made up of input system and response system is considered in dynamic stiffness notation. This dynamic stiffness is fixed for each transmission path. If the notation is D_{sr} , for example, then this means a dynamic stiffness that is derived from the response-side response during source-side excitation. This is thought of as being in a combined state (non-operation), being in a combined state (under operation), and being in a rigidly-joined state (under operation), as shown in Fig. 5, and the placement reaction force for the rigidly-joined state (under operation) is derived from each equation of motion.

In a combined state, the equation will be as follows:

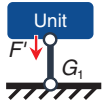
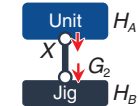
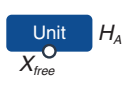
$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} x_r \\ x_s \end{bmatrix} = \begin{bmatrix} f_r \\ f_s \end{bmatrix} \quad (1)$$

D : Dynamic stiffness s : Source
 x : Displacement r : Response

An equation is also set up similarly and expanded for the combined state (under operation).

$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} x_{ra} \\ x_{sa} \end{bmatrix} = \begin{bmatrix} 0 \\ f_s \end{bmatrix} \quad (2)$$

s_a : Source in operating state
 r_a : Response in operating state

(1) Direct Force	(2) Hybrid	(3) Free Velocity
		
$F' = G_1$	$F'^{eq} = G_2 + H_A^{-1} \cdot X$	$F' = H_A \cdot X_{free}$

G : Response force
 X : Receiver

Fig. 4 Force measurement of component-based TPA

$$x_{sa} = D_{ss}^{-1} (f_s - D_{sr} x_{ra}) \quad (3)$$

$$D_{rs} D_{ss}^{-1} f_s = D_{rs} D_{ss}^{-1} x_{ra} - D_{rr} x_{ra}$$

Another equation is set up similarly and expanded for the rigidly-joined state (under operation).

$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} 0 \\ x_{s0} \end{bmatrix} = \begin{bmatrix} f_{r0} \\ f_s \end{bmatrix} \quad (4)$$

s_0 : Source in rigid state

$$f_{r0} = D_{rs} D_{ss}^{-1} f_s \quad (5)$$

Equation (5) is derived from Eq. (4). Plugging Eq. (3) into Eq. (5) yields the placement reaction force f_{r0} .

$$f_{r0} = (D_{rs} D_{ss}^{-1} D_{sr} - D_{rr}) x_{ra} \quad (6)$$

Next, an equivalent external force that reproduces the response of the combined state (under operation), of the kind shown in Fig. 6, is envisaged.

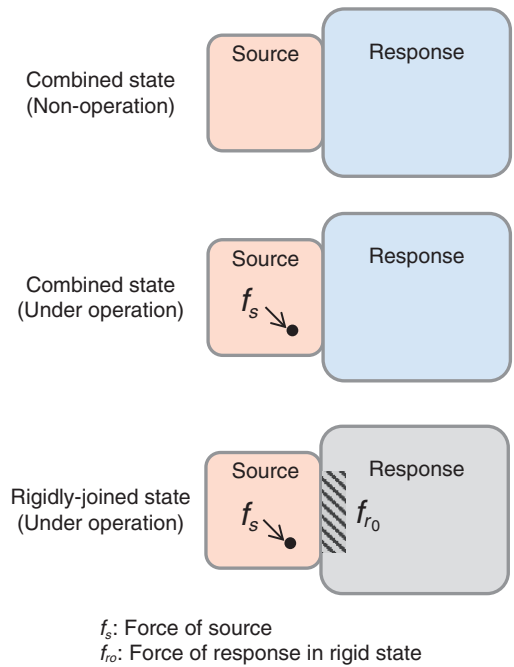


Fig. 5 Equation of motion

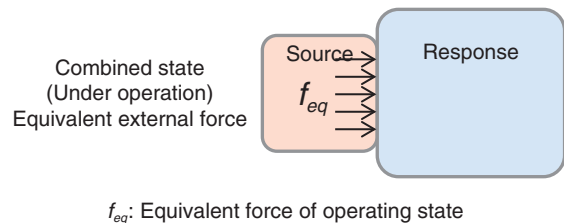


Fig. 6 Equation of motion by equivalent external force

An equation of motion in dynamic stiffness notation is set up, yielding Eq. (7) with respect to the equivalent external force.

$$\begin{bmatrix} D_{rr} & D_{rs} \\ D_{sr} & D_{ss} \end{bmatrix} \begin{bmatrix} x_{ra} \\ x_{sa} \end{bmatrix} = \begin{bmatrix} f_{eq} \\ 0 \end{bmatrix} \quad (7)$$

$$f_{eq} = -(D_{rs}D_{ss}^{-1}D_{sr} - D_{rr})x_{ra}$$

It is apparent that this equivalent external force is opposite in direction but equal in size to the placement reaction force of Eq. (6). The equivalent external force calculated from the transfer function matrix when combined is, therefore, equal to the reaction force when the vibration source is positioned at the point where combined.

When using the direct force method, the input load from a unit that is rigidly connected and fixed in place in a jig can be measured and that value used as the component-based TPA input value.

3.3. Application to Electromagnetic Contactor Operating Noise

The operating noise of an electromagnetic contactor will be described first in terms of the transmission path. As shown in Fig. 7, the vibration of the electromagnetic contactor when it operates is transmitted from the junction board, which is a sub-unit, to the unit. Up to this point is taken as the input side. The unit is fastened to the vehicle body frame with bolts. The vibration is transmitted from this join to the vehicle body and to the cabin interior space. If the characteristics of input from the unit and the structural acoustic transmission characteristics of the vehicle body and cabin interior space are known, then the cabin noise can be predicted using TPA. The load on the join can be substituted with the unit load when rigidly connected, as discussed in the preceding section.

3.4. Test Configuration

The configuration of the unit test of electromagnetic contactor operating noise is described here. In order to confirm that verification can be performed with the unit detached from the vehicle body side, the testing was implemented on a unit installed at a different location in the vehicle body. Figure 8 shows unit measurement. The unit

is fixed in place on a jig using bolts and fastened to it under the specified torque conditions for fastening to the vehicle body side. The fixture used here was designed with a higher degree of stiffness so that the lowest order of natural frequency could be three times or higher than 1000 Hz. This keeps vibration of the jig from influencing the analysis target frequencies from 20 Hz to 1000 Hz. Load sensors were also placed between the unit's joins to the frame and the jig to measure the placement reaction force from the unit to the jig when an electromagnetic contactor operates.

3.5. Test Results

The results from verification of unit evaluation are described here. Figure 9 shows the results from measurement of unit load by the installed location of the unit in the vehicle body. Differences in the load paths within the unit yielded corresponding differences in the frequency characteristics of the load.

Next, Figs. 10 and 11 show the noise prediction results from unit measurements by unit installed location in the vehicle. These are compared with the results for noise in a fully assembled vehicle. This successfully confirmed that the predicted noise represented the peaks of sound from 100 Hz to 600 Hz in fully assembled vehicle noise, regardless of the installed location. The noise levels at the frequencies from 20 Hz to 1000 Hz targeted for analysis were also confirmed.

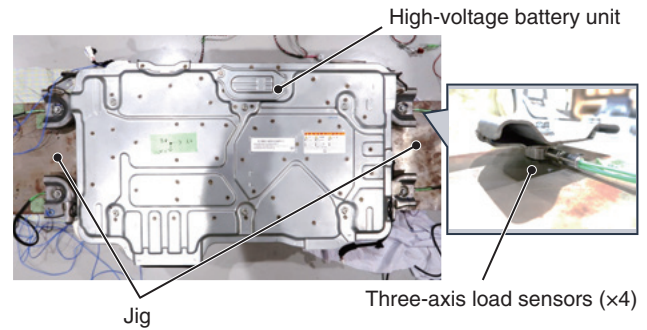


Fig. 8 Force response test of high-voltage battery unit

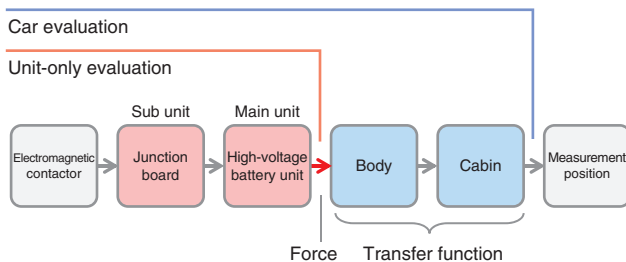


Fig. 7 Transmission path of contactor noise

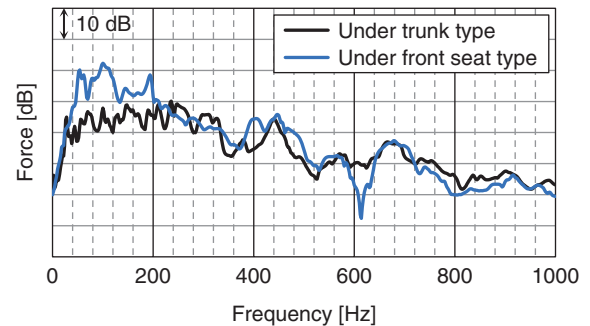


Fig. 9 Input force from unit

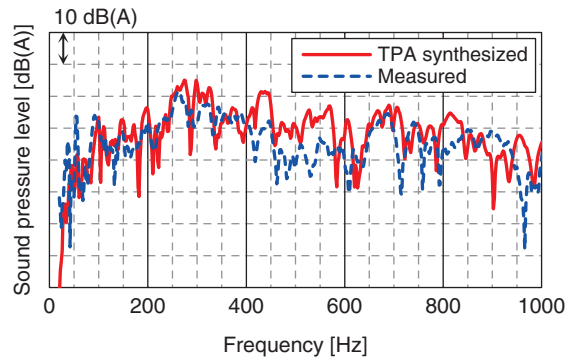


Fig. 10 Sound pressure level (Under trunk type)

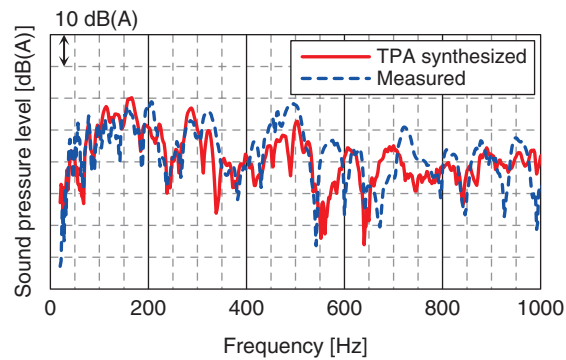


Fig. 11 Sound pressure level (Under front seat type)

4. Unit Transmission Force According to CAE

4.1. CAE Modeling Method

For the operating noise of an electromagnetic contactor in a fully assembled vehicle state, the unit load can be made the target value by calculating back from the target value for cabin noise based on TPA results. If it were possible to predict those load characteristics by CAE at the unit design stage, then development could be advanced more efficiently by putting it on a non-prototype basis. A CAE model was thus created that would calculate the load transmitted to the vehicle body from a unit. The actual measurement values of load transmitted from the junction board to the unit were used in the input conditions.

Figure 12 shows a model based on the finite element method (FEM). The junction board has a complex shape, so it was expressed using concentrated mass elements to reduce the burden of calculation, and the frequency response analysis was implemented with the unit fixed rigidly in place and the boundary conditions of the unit join portions taken as totally constraining.

Using actual measurement values for the input from the junction board, analysis of the load transmission was carried out with loads from two units having different structures,

unit A and unit B. The main structural difference was in the location where the junction board was attached to the battery frame. Figure 13 shows a schematic view. Unit A has the junction board attached to the side surface of the unit close to the vehicle body join. Unit B has the junction board attached to the rear of the unit. In order to verify the validity of this approach, the testing in coordination with CAE was carried out with equal rigid combined state, as unit tests (Fig. 8), and the results were compared.

4.2. Results of Verification by CAE

The CAE analysis results for differing unit loads produced by the same input conditions as compared with actual measurement results are shown in Figs. 14 and 15.

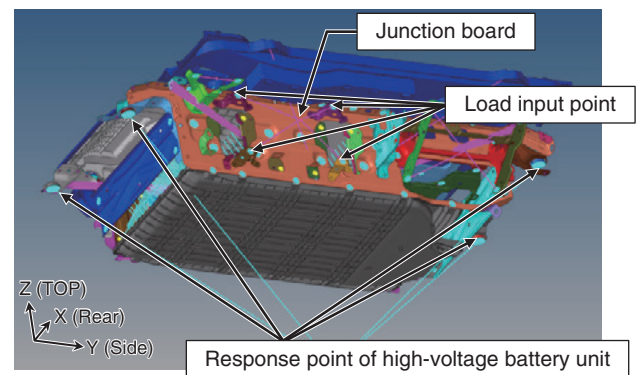


Fig. 12 CAE modeling of high-voltage battery unit

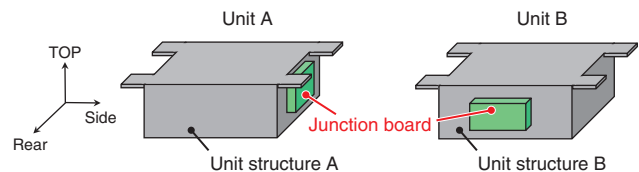


Fig. 13 Junction board mounting position

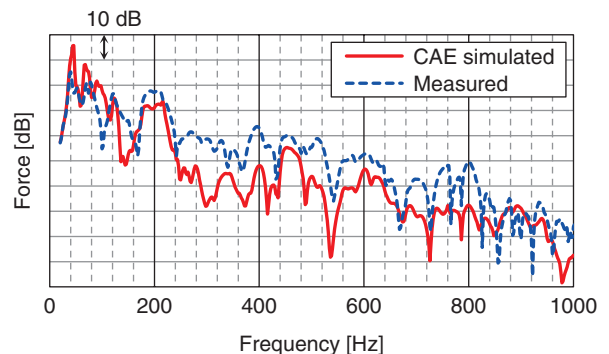


Fig. 14 Force CAE-analysis (unit A)

The difference between unit A and unit B in junction board installation location resulted in differing vibration modes in the battery frame during operation of the electromagnetic contactors. With unit A, there was a peak due to resonance in the vicinity of 200 Hz. Similarly, with unit B, there was also a resonance point in the vicinity of 200 Hz, but its vibration characteristics were distributed more widely across the entire range. This difference can also be observed in the frequency characteristics of the join load values of the units. The CAE results reproduce this feature well, confirming the validity of the CAE modeling here.

The unit load values analyzed by CAE were also used to predict noise in the fully assembled vehicle state. The structural acoustic transfer functions for the vehicle bodies use the actual measurement values for vehicles of the same class. The results for noise in the fully assembled vehicle state, for noise predicted by calculation from unit testing, and also for noise predicted by calculation from CAE predicted unit load values were compared. The blue dotted line shows values for noise measured in the fully assembled vehicle state. The green dotted line shows values for noise predicted from unit testing. The red solid line shows values for noise predicted from the unit load obtained by CAE. The results for unit A in Fig. 16 show that the resonance point

in the vicinity of 200 Hz is successfully reproduced. It is apparent from the results for unit B in Fig. 17 that the broad distribution from 200 Hz to 700 Hz has been reproduced. The sound pressure levels in each frequency band have been successfully verified, and this confirms the validity of CAE model utilization in investigations of design addressing noise.

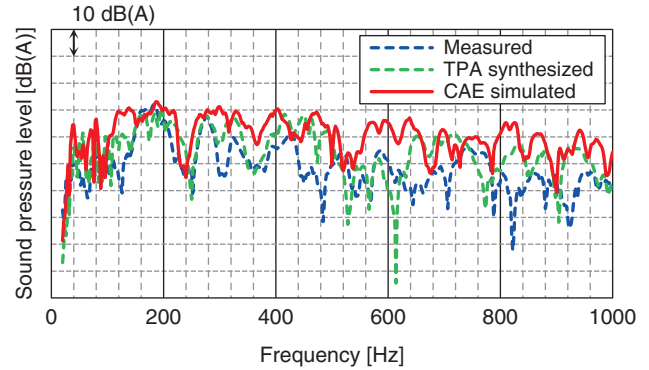


Fig. 17 CAE simulated noise (unit B)

5. Conclusion

- (1) The prediction of noise in the fully assembled vehicle state was successfully accomplished by using the direct force method of component-based TPA to isolate the unit that is the vibration source from the vehicle body side and then using the unit load measurements with the structural acoustic transmission characteristics of the vehicle body.
- (2) A model that utilizes CAE was created to analyze the unit transmission force, and noise in the fully assembled vehicle state was successfully predicted from the results of junction board load measurement.

The present investigation has enabled advance development of the unit in the initial stages when no fully assembled vehicle exists by working from target values for noise in the fully assembled vehicle state and substituting the target values for the unit load. A model was created that predicts the unit load by means of CAE. Prediction of noise in the fully assembled vehicle state from the junction board load measurement results has become possible at a stage when a unit prototype does not exist, allowing even earlier investigation of design.

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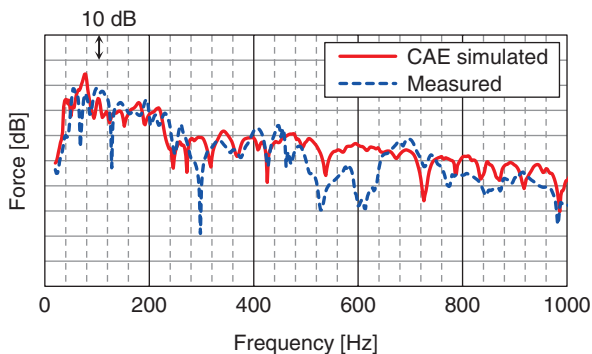


Fig. 15 Force CAE-analysis (unit B)

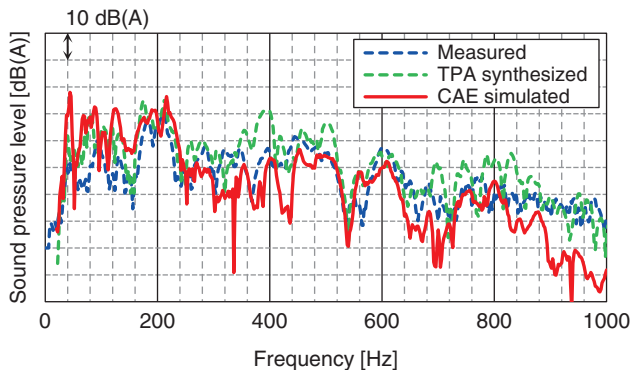


Fig. 16 CAE simulated noise (unit A)

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Proposal and Verification of Friction Coefficient Calculation Model by True Contact and Oil Film (Evaluation of Piston Ring and Sleeve)

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ABSTRACT

The investigation of sliding parts takes into account the coefficient of friction of the parts. When the parts are in a relatively high-speed region, such as the piston rings and sleeves in an engine, sliding test performance itself is a challenge and the tribological properties cannot readily be determined. Therefore, surface roughness and waviness after initial familiarity were applied to a stochastic method proposed by Liu, et al., and the oil film thickness reduction coefficient of Gupta, et al., was used in high-speed regions. In addition, a new calculation model was proposed that takes into sliding, which becomes a determining factor in high-speed regions. As conventionally performed, sliding tests could not readily be implemented in high-speed regions. However, a newly developed drum cam test apparatus has made such testing possible to implement. The validity of this model was verified by comparison and the results of sliding tests up to 8 m/s. The results verified that the coefficient of friction in this model match very closely with the results of tests using ordinary sleeve material of cast gray iron (FC250) in high-speed regions up to 8 m/s. In addition, it has become possible to obtain the coefficient of friction in high-speed regions, which had not been possible to determine up to now. It has also become possible to predict the coefficient of friction in high-speed regions where the velocities are equal to or higher than in the verification tests.

1. Introduction

Computer-aided engineering (CAE) technology has now become a necessity on the front lines of engine development. Meanwhile, for the characteristics of sliding parts that are subject to friction and wear, the figures needed to perform CAE analysis are still being taken from test results and entered into the program, but there are cases when the characteristics are not for the speed ranges in actual use, or differ from the true contact pressures, and so on. This is often the case because testing to obtain the tribological properties cannot readily be implemented. Figure 1 shows the results of reciprocating sliding tests implemented in order to evaluate piston rings and sleeves.

The horizontal axis shows the peak values of sliding velocity, which changes sinusoidally as reciprocating movement occurs. The vertical axis shows the coefficient of friction, and this is the friction force, the changes of which form a rectangular wave, divided by the applied load. The coefficient of friction of the cast gray iron (FC250) used in the sleeve is higher than that of Nikasil coating at 1 m/

s, but this relationship changes drastically as the velocity approaches 2 m/s.

There are, however, no reports on tribological properties in high-speed regions up to 8 m/s, which is an engine's normal operating range. The challenges involved in

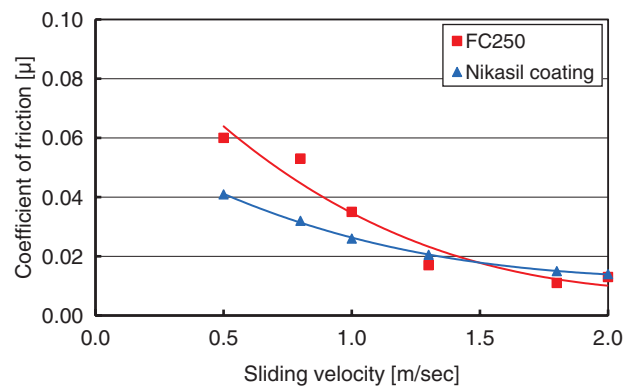


Fig. 1 Relationship between sliding velocity and coefficient of friction

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fabricating evaluation test equipment can be considered a factor in this. For the present research, a new model was created with the capability for calculating tribological properties in speed ranges where actual measurements cannot readily be made using a reciprocating test apparatus. An original high-speed reciprocating test apparatus was developed to conduct verification, and the results are reported herein.

2. Calculation Model for Determining Tribological Properties

2.1. Overview of Calculation Methods

Various researchers have carried out testing and analysis on the question of how the coefficient of friction differs with structures of differing kinds⁽¹⁾ as well as with roughness on machined surfaces⁽²⁾. The distinctive features of the present research lie in the following three points: (1) For speed regions that do not involve heat generation, calculations are performed by the stochastic method of Liu et al.⁽³⁾. (2) For the surface roughness and waviness used in calculation, actual measured values from sliding surfaces after the initial familiarity period following reciprocating sliding tests are used. (3) In high-speed ranges, a new calculation model is used that adds an original calculation taking into account the decrease in oil film thickness due to heat generation caused by sliding. Verification was carried out using these methods. Related calculation models are described below.

2.2. Division of Load Between Oil Film Portion and Direct Contact Portion

As shown in Fig. 2, the load applied to sliding parts is considered to be divided into two parts, the oil film portion and the convex portion of the sliding surface that has direct contact (true contact portion). When the total load applied between pin and plate is P , the contact load on the convex portion of asperity is P_a , and the load generated on the oil film portion is P_h , and their relationship is expressed by Eq. (1).

$$P = P_h + P_a \quad (1)$$

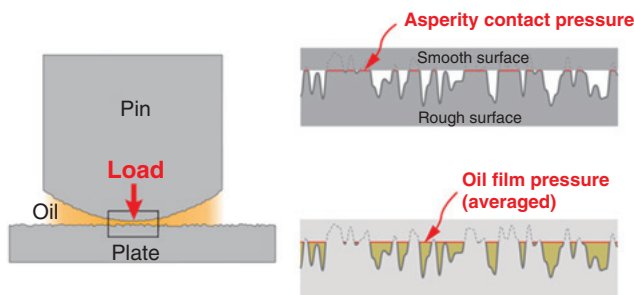


Fig. 2 Division of contact pressure by asperity and oil film

For the ratio of P_h and P_a in P differs according to the sliding conditions. These were, therefore, treated as the two variables γ_h and γ_a , which are the load fraction ratios as defined in Eq. (2), and determined by calculation.

$$\gamma_h = \frac{P_h}{P}, \gamma_a = \frac{P_a}{P} \quad (2)$$

2.3. Method for Deriving Tribological Properties of Oil Film Portion

In order to obtain the coefficient of friction of the oil film portion, the shear stress generated on the oil film is needed. Determining the shear stress requires first that the oil film thickness be determined.

The oil film thickness was determined using the approximation of oil film thickness in elastic fluid lubrication by Nijenbanning et al.⁽⁴⁾. Taking into account that the load P_h , that is applied to the oil film, takes a form in Eq. (2) that includes the variable γ_h , the dimensionless oil film thickness H_c is expressed by Eq. (3) and Eq. (4) below.

$$H_c = \gamma_h^{\frac{1}{2}} \left\{ \left[\gamma_h^{\frac{9}{4}} H_{RI}^{\frac{3}{2}} + \left(\gamma_h^{-\frac{2}{3}} H_{EI}^{-4} + H_{00}^{-4} \right)^{-\frac{3}{8}} \right]^{\frac{2}{3}s} + \left(\gamma_h^4 H_{RP}^{-8} + \gamma_h^4 H_{EP}^{-8} \right)^{-\frac{s}{8}} \right\}^{\frac{1}{s}} \quad (3)$$

This equation is an approximation of the oil film thickness at the central portion under load as obtained from the oil film thickness distribution under different conditions of load and viscosity property.

$$s = 1.5 \left[1 + \exp \left(-1.2 \frac{H_{EI}}{H_{RI}} \gamma_h^{-\frac{7}{3}} \right) \right] \quad (4)$$

Here, H_{RI} , H_{EI} , H_{RP} , and H_{EP} are dimensionless film thicknesses in a region of rigidity and equal viscosity, a region of elasticity and equal viscosity, a region of rigidity and high-pressure viscosity, and a region of elasticity and high-pressure viscosity. H_{00} is a constant.

In general, when sliding velocity increases, heat generation becomes conspicuous, and oil film thickness shows a tendency to decrease due to heat generation. Heat generation of this kind could also conceivably influence oil film thickness at the sliding speed range of pin and sleeve. The calculation model of Liu et al.⁽³⁾, however, is for the low-speed, high-load range, and it does not take this influence into account. For the present research, therefore, the oil film thickness reduction coefficient of Gupta et al.⁽⁵⁾,

shown in Eq. (5), was applied to the calculation of oil film thickness in high-speed regions.

$$\Phi_T = \frac{1 - 13.2 \left(\frac{p_0}{E'} \right) L^{0.42}}{1 + 0.213(1 + 2.23S^{0.83})L^{0.640}} \quad (5)$$

Here, L is a thermal load parameter that is a function of speed, pressure, oil viscosity coefficient, and so on. S is the ratio of sliding and rolling. With plain rolling, heat generation is around zero, but when sliding occurs, then heat generation increases according to that ratio.

For the shear stress that occurs in the oil film, it was decided to follow the viscosity model of Ree and Eyring⁽⁶⁾, shown in Eq. (6).

$$\tau_h = \tau_0 \operatorname{arcsinh} \left(\frac{\eta \dot{\gamma}}{\tau_0} \right) \quad (6)$$

τ_0 is a constant for stress that depends on the temperature. $\dot{\gamma}$ is a shear rate obtained when sliding velocity is divided by oil film thickness. η is the viscosity of lubricating oil, and the pressure, temperature, and viscosity property of Roelands et al.⁽⁷⁾ were used.

2.4. Method for Deriving Tribological Properties of Convex Portion

The calculation accuracy of the model here is increased by using the surface roughness and waviness obtained by actual measurement made after initial familiarity is achieved by sliding.

Figures 3 and 4 show the surface contour data from measurements of roughness and waviness made when obtaining data for the coefficient of friction in relation to sliding velocity in Fig. 1. The measurements were made using a surface texture and contour measuring instrument (SURFCOM 5000DX manufactured by Tokyo Seimitsu Co., Ltd.).

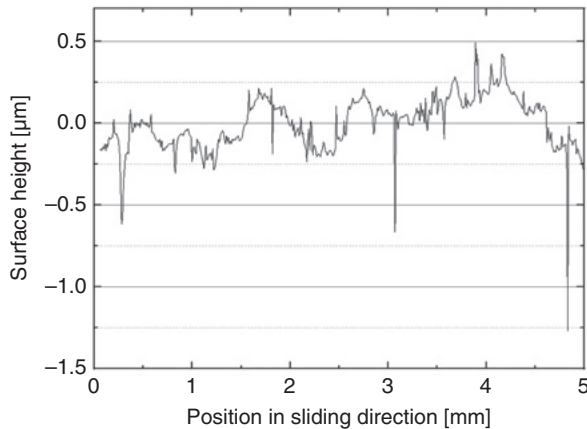


Fig. 3 Surface contour of FC250 after test

Comparison of roughness shows that FC250 is Ra 0.025 while Nikasil coating is Ra 0.007. The latter can be considered to have a smoother surface. As shown in Fig. 5, however, the Nikasil coating surface exhibits waviness that is of low amplitude but has a long period. The influence

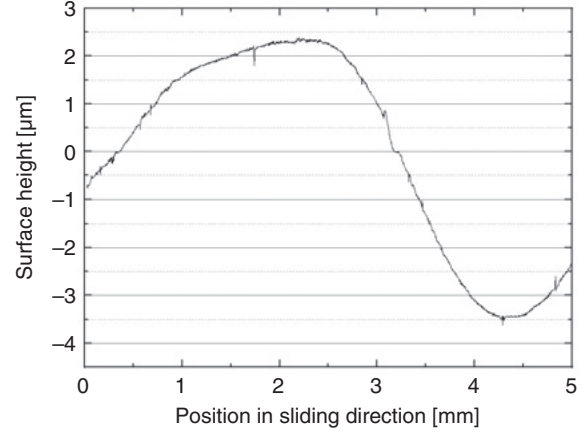


Fig. 4 Surface contour of Nikasil coating after test

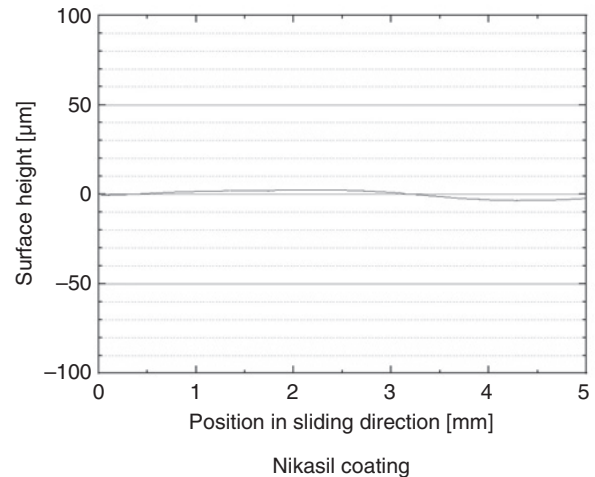
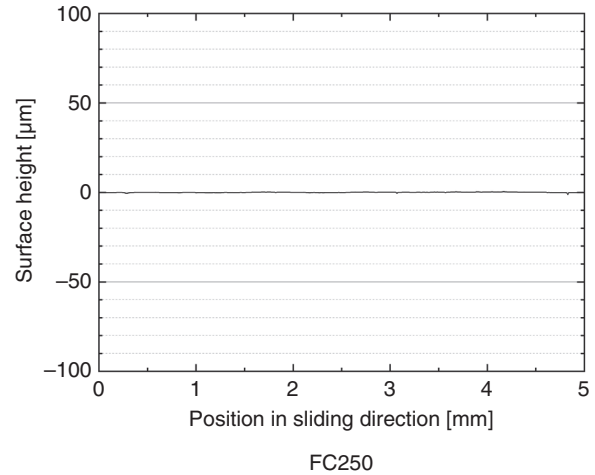


Fig. 5 Comparison of surface contours

of this kind of surface characteristics on the tribological properties was taken into consideration.

Table 1 shows the material parameters for sliding surfaces as extracted from the sliding surface contour curves. The calculation for the coefficient of friction was derived using these conditions, and verification of the model calculations was carried out as a comparison of the velocity dependence of the coefficient of friction with the test figures.

The probability density distribution of this waviness and roughness after sliding appeared generally as a Gaussian distribution. It was assumed, therefore, that the convex portion with Gaussian distribution $\phi_s(z)$ as in Eq. (7) would come in contact with a completely smooth surface.

$$\phi_s(z) = \frac{1}{\sigma_s \sqrt{2\pi}} e^{-\frac{z^2}{2\sigma_s^2}} \quad (7)$$

z is the protrusion height from the mean position, and σ_s is the standard deviation for the protrusion height. An equivalent σ_s was calculated from the contour measurement results for the pin and plate, which show a Gaussian distribution, and this was inserted into the formula.

2.5. Method for Calculating Contact Load of Convex Portion

The convex portion that is in contact bears the load P_a only on the peaks and in some cases may undergo elastic deformation in which the height is lowered or convex portions may be raised higher than h_{ss} . Equation (8) from Johnson et al.⁽⁸⁾ was therefore used for the mean contact pressure applied to the area of true contact, which is the convex portion.

$$p_{a,av} = \frac{2}{3} n \beta \sigma_s E' \sqrt{\frac{\sigma_s}{\beta}} F_{\frac{3}{2}} \left(\frac{h_{ss}}{\sigma_s} \right) \quad (8)$$

h_{ss} is the height of the contact surface shown in Fig. 6. n is the density of the convex portion. β is the radius of the peaks. E' is the equivalent Young's modulus of the material expressed as in Eq. (9).

$$\frac{2}{E'} = \left(\frac{1 - \nu_1^2}{E_1} + \frac{1 - \nu_2^2}{E_2} \right)^{-1} \quad (9)$$

Here, E_1 , E_2 , ν_1 , and ν_2 are the Young's modulus and Poisson's ratio for the pin and plate. Function F in Eq. (8) is expressed as follows:

$$F_{\frac{3}{2}}(u) = (2\pi)^{-\frac{1}{2}} \int_u^\infty (t-u)^{\frac{3}{2}} e^{-\frac{t^2}{2}} dt \quad (10)$$

Ordinarily, model calculations do not consider changes

Table 1 Calculation conditions for surface irregularities of sliding parts

	σ_s [μm]	n [m^{-2}]	β [μm]	E' [GPa]
Nikasil coating	0.064	2.25×10^{10}	27.0	247
FC250	0.170	3.40×10^{10}	42.5	263

in the surface state due to initial familiarity. The calculation model here, however, has taken waviness with a long period and asperity after testing into consideration. In order to include their influence in the calculations, the pressure concentration factor (P.C.F.) of Seabra et al.⁽⁹⁾ was used. This is expressed as shown in Eq. (11).

$$\text{P.C.F.} = C1 \left(\frac{\lambda}{\text{Amp}} \right)^\alpha \left(\frac{a}{R} \right)^\beta \left(\frac{\lambda}{a} \right)^\gamma \quad (11)$$

Here, $C1=4.3884$, $\alpha=-0.4234$, $\beta=-0.4204$, and $\gamma=-0.0155$. λ and Amp are the wavelength and amplitude, respectively, of surface waviness. a is Hertzian contact half length and R corresponds to the equivalent radius of curvature of the pin. At this time, the influence of waviness causes the area of Hertzian contact to be reduced by the amount of the reduction of area (R.A.) in the coefficient below. In other words, in the Hertzian contact region, which is reduced in area by the amount of this coefficient, pressure on the convex portion is exerted by the amount of the P.C.F. multiplied by the mean contact pressure ($p_{a,av}$).

$$\text{R.A.} = \ln \left[C2 \left(\frac{\lambda}{\text{Amp}} \right)^\theta \left(\frac{a}{R} \right)^\eta \left(\frac{\lambda}{a} \right)^\Psi \right] \quad (12)$$

Here, the constants are $C2=0.9404$, $\theta=0.3802$, and $\Psi=0.0395$. The waviness assumed in this model is somewhat smaller than in the Hertzian contact region, and it is larger than the period of asperity.

2.6. Method for Calculation of Shear Force of Oil Film and Surface Roughness

The shear stress τ_{ci} that is generated in the contact region i of an asperity surface is determined as shown in Eq. (13) using the value for the coefficient of friction f_{ci} (Fig. 1) obtained in a boundary lubrication area, or in other words, low-speed-region sliding tests.

$$\tau_{ci} = f_{ci} p_{ci} \quad (13)$$

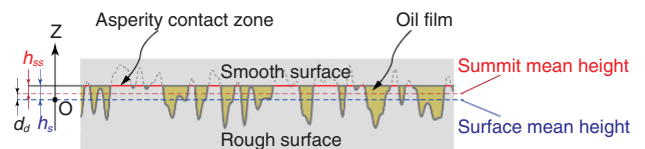


Fig. 6 Relationship of surface parameters

The shear stress in the oil film and the friction force in the true contact portion caused by surface asperity are divided and determined as the respective quantities in this way, and consequently, the net coefficient of friction f is taken to be the sum of these quantities divided by the load P as expressed in Eq. (14).

$$f = \frac{\sum_{i=1}^N \iint_{A_{ci}} \tau_{ci} dA_{ci} + \iint_{A_h} \tau_h dA_h}{P} \quad (14)$$

Here, A_c indicates the load-bearing area of the protrusion contact portion, and A_h that of the oil film-forming region. Figure 7 shows the calculation flow.

First, the load fraction ratios γ_h and γ_a are assumed. This determines the relative distances of the uneven surface and the smooth surface, the pressure on the convex portion is determined, and the oil film thickness can be determined from this pressure.

The pressure applied to the convex portion can also be derived from the load P_a divided by the area A_{nom} of the pressure-generating region. When the convex contact portion pressures obtained by the two methods are identical, the assumed values for γ_h and γ_a are considered to be

correct, and the coefficient of friction was determined from Eq. (14).

Since the present research involves calculations for high-speed ranges, the original step was taken of adding Eq. (5), Eq. (11), and Eq. (12).

3. Comparison of Test Results and Calculation Results for Coefficient of Friction

3.1. High-Speed Reciprocating Test Apparatus

In the case of a test stroke of 50 mm, the reciprocating movement here started where the edge velocity was zero. On advancing 25 mm, the highest velocity is reached, and upon arrival at the edge 50 mm ahead, the velocity becomes zero. This is treated as one cycle, and the reciprocating action is continued while applying a load.

With the piston in an actual engine, there is an air spring effect from the combustion gases and air-fuel mixture at top dead center and bottom dead center, the positions where the velocity is zero. No vibration is generated due to the friction caused by the sealing of combustion gas or crank deflection.

These effects cannot readily be reproduced in the reciprocating sliding tests, however, so vibration is generated in the test piece, centered on the point where

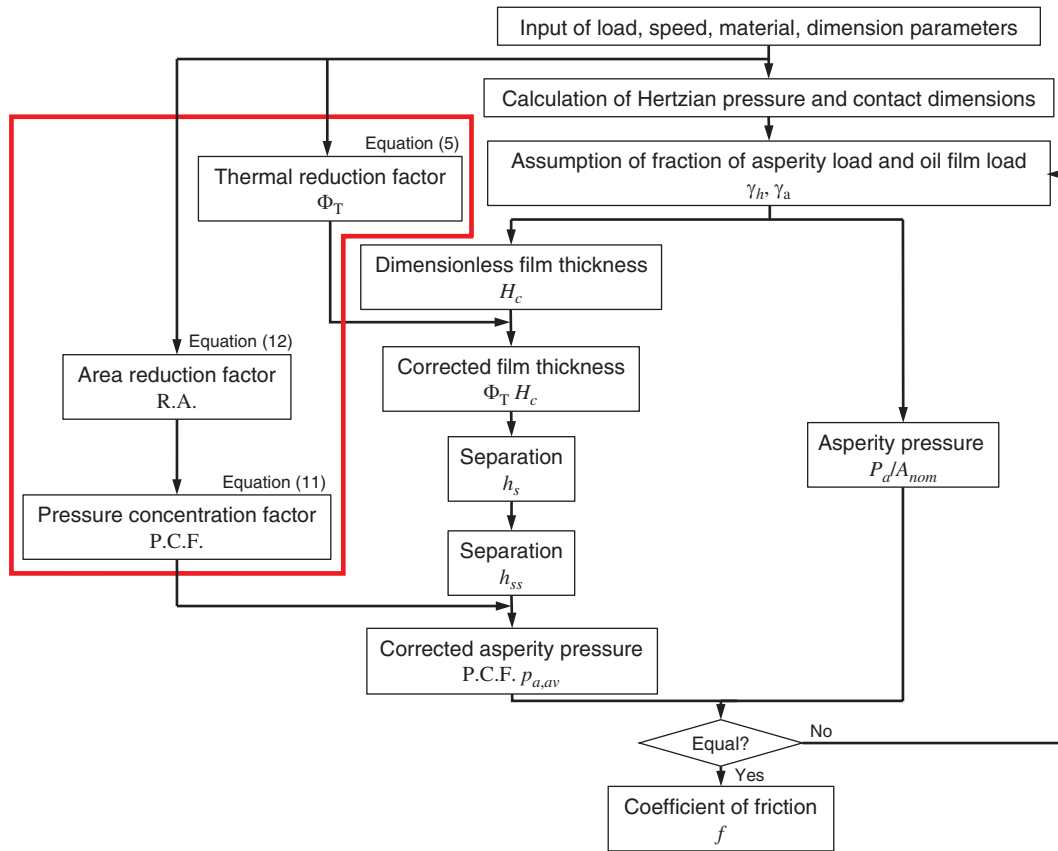


Fig. 7 Calculation flow

the load is applied. In some cases the test apparatus itself shakes back and forth in a large motion. In order to avoid this, most tests⁽¹⁰⁾⁻⁽¹³⁾ are implemented at speed ranges up to 2 m/s where the mean velocity provides for reproducibility of results and the reciprocating sliding test apparatus is stable in screening tests. These velocities are one order of magnitude lower than normal maximum mean piston velocity (about 18 m/s).

This was addressed by reducing the weight of the holder that supports the test piece, which is the plate, and also by adopting a drum cam system to drive the sliders in parallel via ball bearings placed in a helical trench made in the rotating drum. This made it possible to achieve high-speed reciprocating movement. Figure 8 shows the test apparatus mechanism. Table 2 shows the test apparatus specifications.

3.2. Sliding Tests

The sliding tests are implemented as virtual engine piston rings and sleeves. The test conditions are shown in Table 3.

The material used for the piston rings was SUS440C with the usual material properties and with nitriding treatment applied. The material used for the sleeve was FC250 fabricated by spin casting and with Nikasil coating, which has also come into frequent use on mass-production vehicles in recent years, applied on the aluminum parent material.

The lubricant used in testing was the ordinary, genuine Honda brand oil (Ultra Mild) supplied at room temperature at the rate of 1 ml per minute from the point of a needle next to the pin. Figure 9 shows testing underway with high-speed reciprocating movement.

As to the test time, testing was continued until the pin and plate had undergone wear, and after initial familiarity had been achieved when a stable coefficient of friction could be obtained.

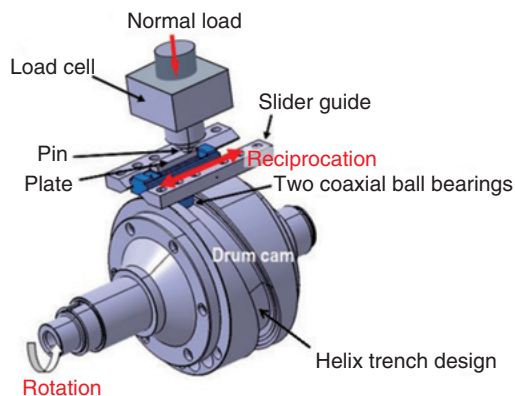


Fig. 8 Mechanism to generate reciprocating movement

Table 2 Specifications of apparatus

Sliding speed	0.1 m/s to 8.0 m/s
Reciprocation stroke	50 mm
Normal load	30 to 200 N
Pin size	φ 15 mm × 25 mm
Plate size	17 mm × 70 mm × 9 mm

Table 3 Test conditions

Sliding speed	0.5 to 8.0 m/s (Peak in reciprocating cycle)
Pin material	Nitriding Treatment on SUS440C
Plate material	FC250 (Cast gray iron) Nikasil coating on Cast aluminum
Normal load	100 N
Lubricant	Ultra Mild 10W-30

3.3. Comparison of Test Results and Calculation Results

The calculation results for the coefficient of friction with respect to sliding velocity using FC250 and Nikasil coating are shown in Figs. 10 and 11. The horizontal axis is the sliding velocity. The vertical axis is the mean coefficient of friction. The test results are also overlaid on the figures for the purpose of comparison. With regard to the FC250, the calculated value for the coefficient of friction largely

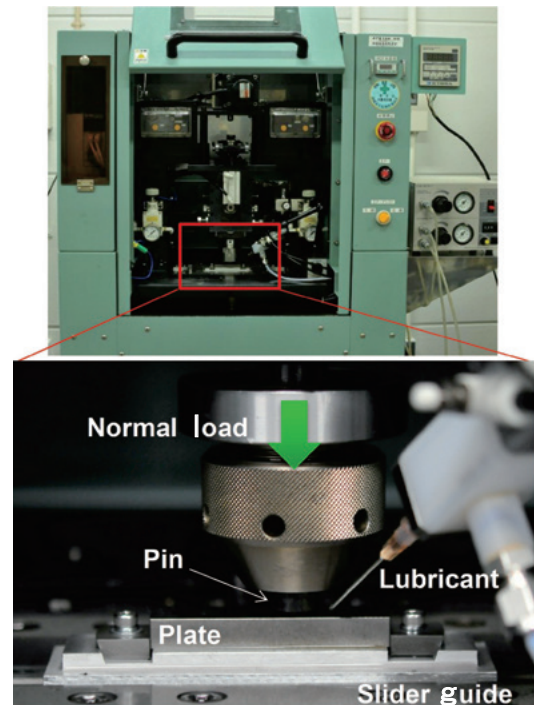


Fig. 9 Sliding part during reciprocating frictional test (4 m/s)

matched the experiment value throughout in the lubricated state.

As shown in Fig. 11, on the other hand, the coefficient of friction calculated for the Nikasil coating showed marked differences in the region up to 2 m/s. This is conceivably because the Nikasil coating surface layer and the base surface have differing hardness. It is also apparent that virtually no difference is seen when the influence of waviness shown in Eq. (6) and Eq. (7) is taken into account. As to methods for analyzing the coating surface structure by this kind of stochastic friction analysis, further investigation is probably needed.

Figure 12 shows the Stribeck curves for the results of testing and calculation performed here.

The calculation results obtained using the calculation model created here are shown by lines, while the test results are shown by points. The horizontal axis shows the velocity (m/s) just as it did in Figs. 10 and 11.

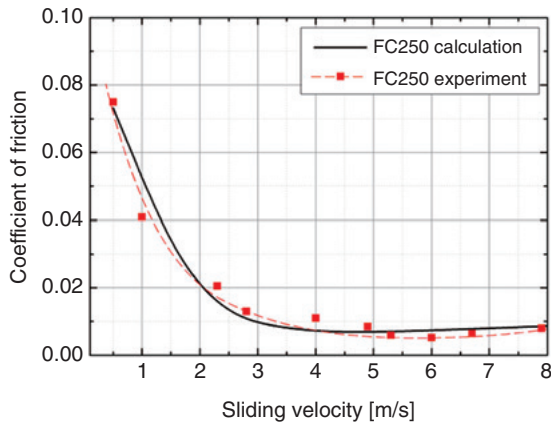


Fig. 10 Comparison of calculated and measured coefficient of friction to sliding velocity, FC250

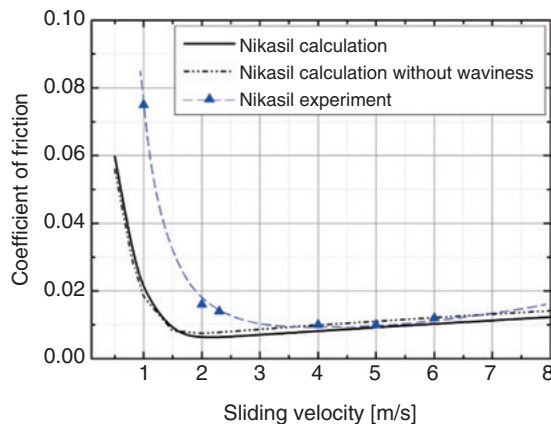


Fig. 11 Comparison of calculated and measured coefficient of friction to sliding velocity, Nikasil coating

There are also regions where the calculation results and test results do not match at velocities of 2 m/s or less. It is apparent, however, that results generally match at subsequent speed ranges. Moreover, this model made it possible to derive values at speed ranges that could not be tested experimentally.

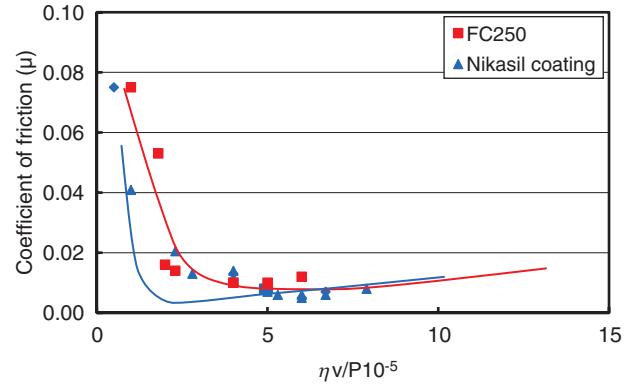


Fig. 12 Comparison of calculated and measured coefficient of friction to sliding velocity

4. Conclusion

Surface roughness and waviness after initial familiarity has been achieved were applied to the stochastic method proposed by Liu et al. A new calculation model was created to take into account slippage, which becomes a determining factor in higher-speed regions.

An apparatus was developed that makes it possible to implement stand-alone sliding at 8 m/s, which is the normal operating range for actual engines.

In this way it has become possible to obtain the coefficient of friction in high-speed regions where it has been unable to derive up to now. It has also become possible to predict the coefficient of friction in high-speed regions where the velocities are equal to or higher than in the verification tests.

With coatings, the hardness of the surface layer differs from that of the base surface below it. For this reason, although the present model was able to make the calculations, they did not match with the test results. Going forward, the model will be rebuilt so that it also takes these material properties into consideration, and the matter of enhancing the accuracy of calculation of the coefficient of friction at low speeds will be investigated.

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Heat Pipe with High Heat Transfer Rate by Reciprocating Motion

(Examination of Application to Automotive Engine Piston)

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ABSTRACT

The flow of gas and liquid in heat pipes is generally impaired by factors such as oscillation and inclination, with the result that the heat transfer becomes excessively low. For this reason, there are no known cases of heat pipe use in cars and motorcycles, etc.

The authors, therefore, proposed a new heat pipe that controls the two-phase flow of gas and liquid without reducing the amount of heat transport, by reducing the friction energy loss inside the pipe and forcibly inducing self-oscillation.

Measurement results in the condition with oscillation applied by reciprocating motion showed an increase in the heat transfer coefficient by a factor of 1.6 compared with that at standstill. That mechanism is thought to be as follows. In the initial stage, the liquid sealed in the heat pipe is broken up into fine droplets by reciprocation. The droplets then acquire drive force in a constant direction macroscopically while contacting the gates, producing a unidirectional flow. Further, a loop flow channel enables transfer of gas and liquid from condensed areas to evaporation areas without gas-liquid collision.

This study performed thermal analysis of the case when applied to an engine piston. The results showed that the temperature at the piston head center was reduced by 39 K and ΔT was also reduced from 140 K to 75 K, and thus thermal stress reduction effects can be anticipated.

1. Introduction

With electric vehicles (EV) and hybrid electric vehicles (HEVs) targeting better energy efficiency and environmental compatibility, a cooling/heating system for the motor, power control unit (PCU), battery, etc. is an increasingly crucial subsystem of vehicles for reasons such as performance improvement and suppression of deformation⁽¹⁾⁻⁽³⁾. Temperatures are usually controlled by direct and indirect methods such as an oil jet to motor surfaces and coolant in a cooling channel. However, thermal conductivity of currently used cooling media lower than the specific heat of H₂O and NH₃, resulting in reduced cooling effect⁽⁴⁾.

Meanwhile, it is well known that the thermal conductivity of heat pipes used in computers and air conditioners is 10 or more times higher than that of the above-noted cooling media⁽⁵⁾⁻⁽⁸⁾. Due to the structural characteristics of heat pipes, however, the flow of gas and liquid is impaired by factors such as axial accelerations, with the inevitable result that the amount of thermal conductivity becomes excessively low⁽⁹⁾. For this reason,

there are no known reports of their use for cooling of automotive parts.

The objective of this study is to investigate of a new cooling heat pipe that controls the two-phase flow of gas and liquid and maintains a high heat transfer by (1) friction control inside the pipe, and (2) forced self-oscillation. Verification of prototype design used reciprocating motion, which is relatively easy to control, as an applied force, and was conducted using a high-speed reciprocation apparatus with a stroke width of 50 mm.

The design concept of the heat pipe was then applied to cooling passage in an engine piston of an internal combustion engine (ICE). Analysis results of the heat transfer performance in the piston are also reported herein.

2. Design and Prototyping of New Heat Pipe

Figure 1 shows a commercially available heat pipe and the newly designed heat pipe. The commercially available heat pipe has a metal mesh-type wick inside. Specimens with the same shape were used for attachment to the high-

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speed reciprocation testing apparatus.

The investigation initially planned to compare the amounts of thermal conductivity between the newly designed heat pipe and a commercially available heat pipe with a metal mesh-type wick inside. As described in a past report⁽²⁰⁾, however, when the commercially available heat pipe is oscillated, the thermal conductivity decreases by the cross-section integral of the pipe, so the test results were compared with those of a bulk aluminum cylinder. The aluminum cylinder material was aluminum 4000 NP12P.

Figure 2 shows the working principle of the commercially available heat pipe⁽¹⁰⁾ which transfers heat as follows: a small amount of working fluid sealed in the vessel evaporates in the evaporator, the vapor passes through the center of the pipe to the condenser and the condensed water vapor then flows back to the evaporator due to the capillary force of the fine metal mesh wick attached to the inner wall of the vessel.

Figures 3 and 4 show the structure⁽¹¹⁾ and the cross-section of the newly designed heat pipe. The pipe has an internal structure with gate-shaped protrusions at regular intervals that control the flow of liquid and gas. The geometrical design enables the liquid to move along the inner wall of the pipe under an oscillation, and generate fine droplets by collision. The resultant two-phase flow transfers heat energy efficiently.

Table 1 shows specifications of the heat pipe.

Figure 5 shows the prototype process of the heat pipe.

The prototype was prepared by adding pure water as a coolant into the pipe at room temperature using a fluid injector (Fig. 5, top).

Table 1 Heat pipe specifications

Pipe length	144 mm
Pipe size	Φ8 mm
Number of gates	10
Gate size	D9 x T5 x V5.3, θ15°

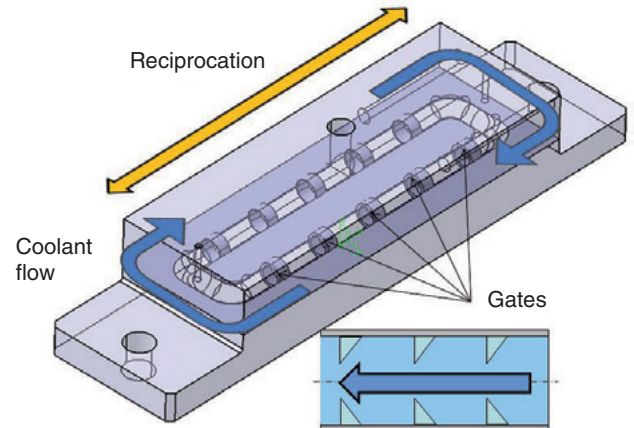


Fig. 3 Newly designed heat pipe

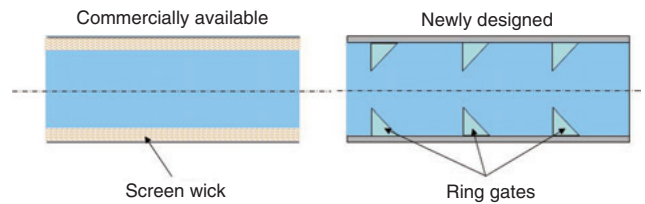


Fig. 4 Inner structures of heat pipes

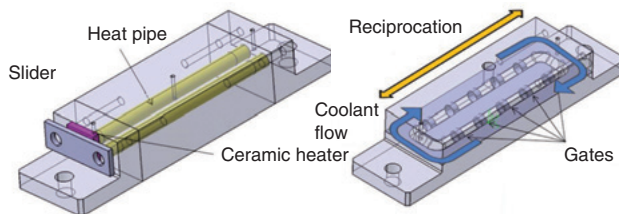


Fig. 1 Structures of specimen using commercially available heat pipe (left) and specimen using newly designed heat pipe (right)

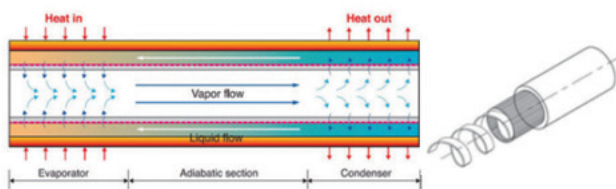


Fig. 2 Working principle of wick heat pipes

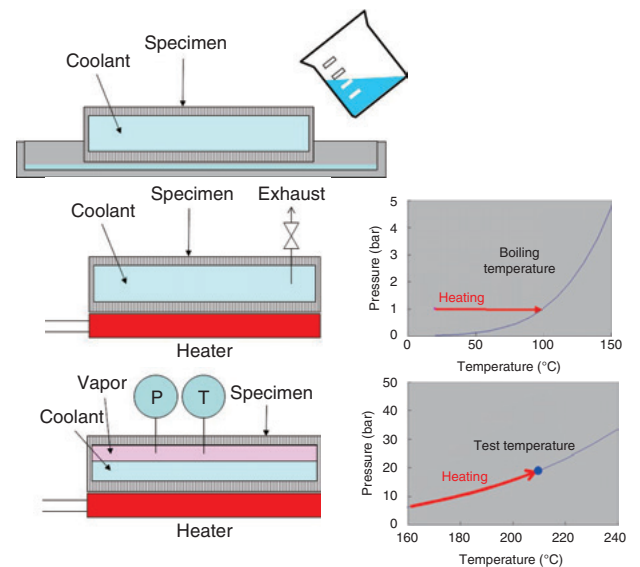


Fig. 5 Prototype process of newly designed heat pipe

The pressure and temperature were measured while heating the bottom side of the aluminum specimen at atmospheric pressure (Fig. 5, middle), internal vapor was exhausted while measuring the specimen mass, and the pipe was then sealed by inserting an iron ball into the hole at the prescribed coolant mass. After sealing, the specimen was heated to the test temperature, and the saturated vapor pressure (Fig. 5, bottom) was confirmed. The heat pipe was attached to a high-speed reciprocation testing apparatus as shown in Fig. 6, and thermocouples were attached to the specimen in three locations. A ceramic heater was used to apply heat. Heat radiation was performed using a cooling fin for personal computer CPUs. Temperature variations at the measurement points and heat transfer coefficient were examined while oscillating the heat pipe in the axial direction.

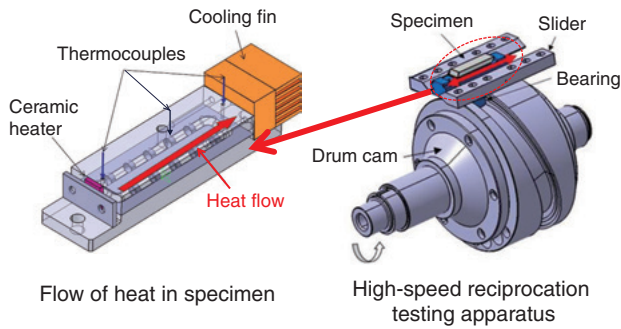


Fig. 6 Flow of heat in specimen and high-speed reciprocation testing apparatus

3. High-speed Reciprocation Test (Reciprocating Motion)

Table 2 shows the conditions.

A commercially available heat pipe and three newly designed heat pipes with respective water-to-air ratios of 50/50, 70/30, and 80/20 were prepared to determine the optimal ratio.

In addition, a bulk aluminum specimen of the same shape without a heat pipe was also tested for comparison (Fig. 7).

In the test, a constant sliding speed was maintained until temperature at each measurement point reached an equilibrium, after which the speed was changed to the test conditions. The temperatures were then measured at prescribed speed.

The heat source was a ceramic heater in close contact with the specimen, and a cooling fin was fixed to the opposite side. A commercially available silver paste was applied to the interface between the heater and the specimen. The heat input was set to 30 Watt.

Table 2 Conditions of reciprocation test

Reciprocating speed range	0.0 to 3.0 m/sec
Reciprocating stroke	50 mm

The tests were conducted using a high-speed reciprocation testing apparatus⁽¹²⁾. The specimen was covered by an aluminum cover and an insulator to suppress a thermal radiation outside the specimen. Figure 8 shows the specimen and its surroundings configurations.

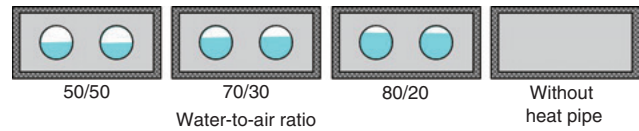


Fig. 7 Comparison of heat pipes with different water-to-air ratios

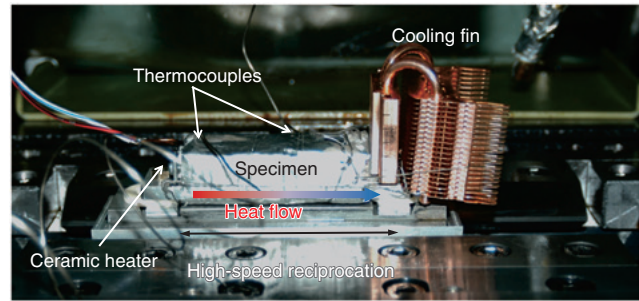


Fig. 8 Specimen during high-speed reciprocation test (3 m/sec)

4. High-speed Reciprocation Test Results

The heat flux was calculated by Eq. (1) and Eq. (2) below.

$$q = \lambda_e A_e \frac{\Delta T}{L} \quad (1)$$

q : Heat flux (W/m^2)

λ_e : Heat transfer coefficient ($\text{W/m}^2\text{K}$)

A_e : Cross-sectional area

L : Length

Calculation was made for two different cross-sections (aluminum specimen with and without a heat pipe inside). Heat radiation from the specimen was assumed to be

uniform. The ratio for the heat balance calculation was calculated from the cross-section.

$$q = (\lambda_1 A_1 + \lambda_2 A_2) \frac{\Delta T}{L} \quad (2)$$

λ_1 : Heat transfer coefficient of aluminum

A_1 : Cross-sectional area of aluminum

λ_2 : Heat transfer coefficient of heat pipe

A_2 : Cross-sectional area of heat pipe

Figure 9 shows the heat pipe test results during high-speed reciprocation.

The effective thermal conductivity of the bulk aluminum specimen without a heat pipe inside is constant at 140 W/m K under the test speed.

Meanwhile, the thermal conductivity at standstill in the specimen with a water-to-air ratio of 70/30 and a heat pipe ratio to the bulk base area ratio of 10% in the heat balance calculation is lower than that of bulk aluminum specimen. This is thought to be because the air inside the heat pipe lowers the thermal conductivity and reduces the cross-section integral⁽¹³⁾⁻⁽²³⁾.

The thermal conductivity is slightly higher than that of the bulk aluminum specimen at a sliding speed of 2 m/sec, and reaches 620 W/m K at speed of 3 m/sec. Recalculating this effect for the heat pipe alone results in thermal conductivity of 4900 W/m K at a speed of 3 m/sec.

For reference, the thermal conductivity of the bulk aluminum specimen is 140 W/m K, and many commercially available heat pipes have a thermal conductivity at standstill of around 3000 W/m K, so the newly designed heat pipe exhibited thermal conductivity 35 times that of bulk aluminum and 1.6 times that of commercially available heat pipes. Figure 10 shows the effect of the heat pipe filling ratio.

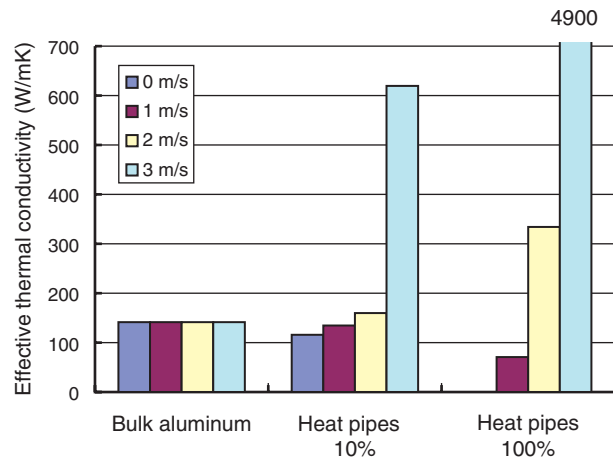


Fig. 9 Effectiveness of heat pipes during high-speed reciprocation

At a water-to-air ratio of 50/50, the effective thermal conductivity increases with the sliding speed. Furthermore, although the thermal conductivity at a water-to-air ratio of 70/30 is lower than that of a ratio of 50/50 up to a sliding speed of 2 m/sec, it rises sharply to 620 W/m K at a speed of 3 m/sec. At a water-to-air ratio of 80/20, the highest thermal conductivity of 235 W/m K appears at a speed of 1 m/sec, but drops to 180 W/m K at a speed of 3 m/sec.

Figure 11 shows a conceptual diagram of droplets inside the newly developed heat pipe.

The reason why the newly designed heat pipe exhibited high heat conduction is under investigation. However, it is thought that in the initial stage, the fluid sealed inside the heat pipe is broken up into fine droplets by reciprocation. The droplets then acquire drive force in a constant direction macroscopically while contacting the gates, producing a unidirectional flow. Further, use of a loop flow channel enables transfer of gas and liquid from condensed areas to evaporation areas without gas-liquid collision.

This made it possible to exhibit higher performance under high-speed reciprocating conditions compared to the heat transfer amount of bulk aluminum at standstill.

As the above results showed that increasing the oscillation inertial force is an effective means of heat transport, application to the cooling of ICE engine pistons was then investigated.

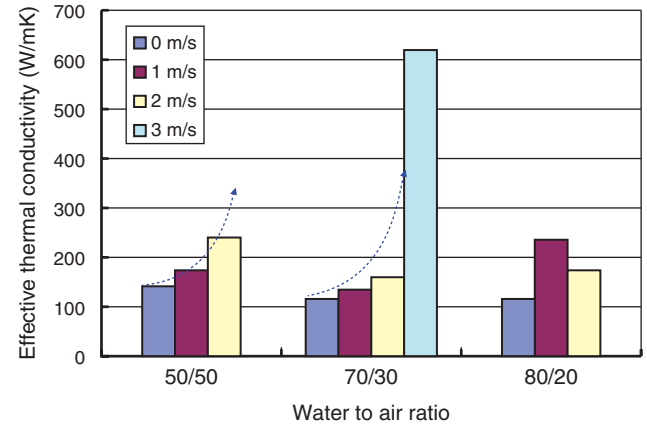


Fig. 10 Effectiveness of heat pipe filling ratio

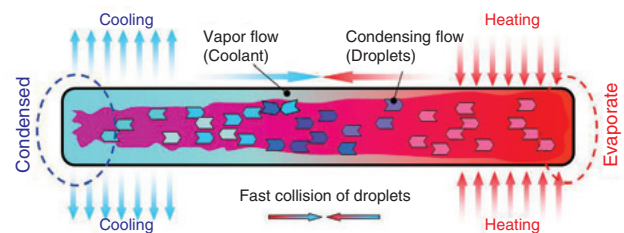


Fig. 11 Diagram of droplet movement

5. Application to Engine Pistons

Application to engine pistons was investigated based on the above data, and thermal analysis was performed⁽²⁴⁾⁻⁽²⁷⁾.

Wang et al. incorporated heat pipes into the skirt area of a piston to verify the effects, and reported that the high thermal conductivity of 3980 W/m°C was achieved. However, the structure used in that study produces a skewed working fluid distribution due to the angle of inclination of the cylinder, and the heat conduction efficiency may be non-uniform. Therefore, the structure shown in Fig. 12 below was adopted and a prototype piston with heat pipes arranged based on this drawing was prepared.

The heat pipes are arranged to transfer heat from the piston top, where cooling is most needed, to the piston skirt.

The heat pipes use the shape shown in Fig. 3, with backflow-reducing gates arranged inside the pipe to control the flow of gas. A copper alloy piston ring was installed in the skirt area to transfer heat from the piston to the sleeve.

Figure 13 shows actual prototypes of a piston produced by optical molding and an aluminum alloy piston produced using a 3D printer. In addition, Fig. 14 shows a CT scan image of the interior of the piston with heat pipes arranged. This shows that the gates provided inside the piston are formed with directionality.

5.1. Calculation Method

Thermal conduction calculations (numerical solution of a steady-state three-dimensional heat conduction equation)

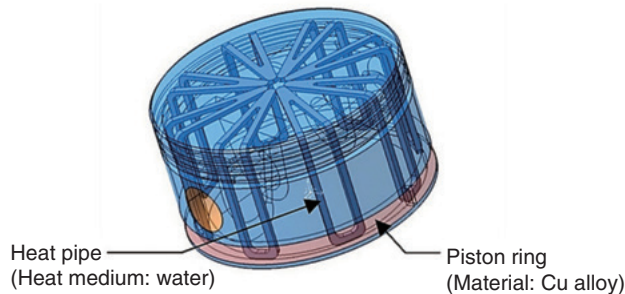


Fig. 12 Piston with built-in heat pipe



Fig. 13 Prototype produced by optical molding (left), prototype produced by metal 3D printer (right)

were made for a piston with heat pipes embedded from the top to the skirt area, and the heat radiation characteristics of the piston were estimated as described below. The thermal conduction of the heat pipes was set to 2000 W/m K and the half value of 1000 W/m K based on the data obtained in Fig. 9, the thermal conductivity of the piston ring raw material, and the thermal conductivity obtained from measurements during operation⁽²⁸⁾.

The basic formula (3) is shown below.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (3)$$

The boundary conditions are shown below. (Bulk Body = BULK)

Piston bore diameter: $\phi 110$

Thermal conductivity of base material: 150 W/m K

Thermal conductivity of heat pipe: 1000 W/m K, 2000 W/m K

Shape: Piston (1/4 model)

Figure 15 shows different areas of the piston and an example of thermal analysis.

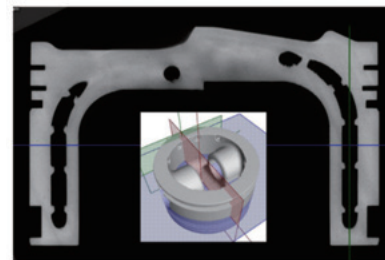


Fig. 14 Sectional image of piston with built-in heat pipes

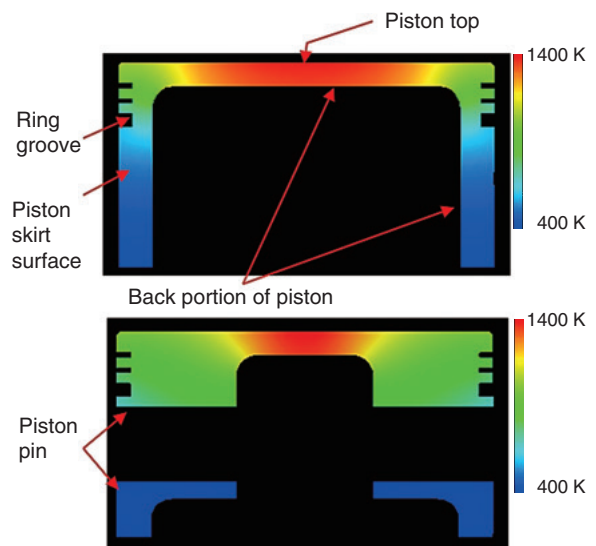


Fig. 15 Example of thermal analysis

The thermal conductivity and temperature within the cylinder were determined as time averages from the in-cylinder pressure data using the Woschni model. Although it is preferable to introduce a contact thermal resistance model, for simplicity this study applied the same thermal conductivity scheme to the metal contact areas.

Table 3 shows the heat transfer boundary conditions of different areas.

Uniform temperature in the heat pipe insertion area was assumed and a constant temperature was used for calculation.

A piston top area temperature of 200 K was set as the design target in this calculation.

Figure 16 shows the arrangement of heat pipes in the piston.

5.2. Calculation Results

Figure 17 shows the results of heat transfer calculation for a single piston without heat pipes.

The temperature reached 583 K (310°C) in the central piston top area and 523 K (250°C) at the piston top edge. The temperature in the skirt area was 443 K (170°C). The difference between the highest and lowest temperatures on the piston was $\Delta T = 140$ K. Figure 18 shows the results of heat transfer calculation for a single piston with heat pipes (1000 W/m K) installed.

The temperature reached 557 K (284°C) in the central piston top area and 518 K (245°C) at the piston top edge.

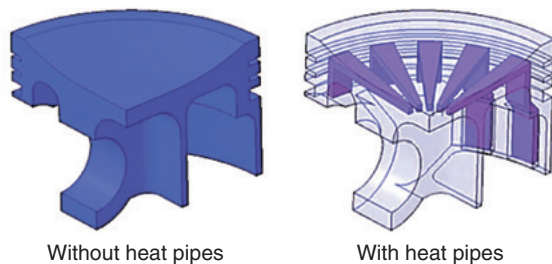


Fig. 16 Arrangement of heat pipes in piston

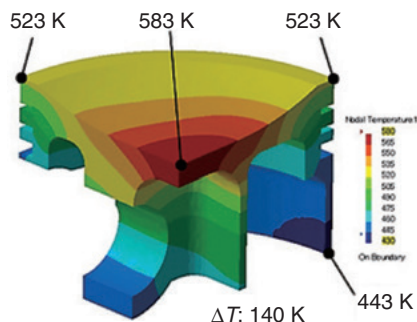


Fig. 17 Results of heat transfer calculation without heat pipes

Table 3 Heat transfer boundary condition

Area	Heat-transfer coefficient (W/m ² K)	Temperature (K)
Piston top	423	1373.15
Ring groove	2878	403.15
Piston skirt surface	300	403.15
Piston pin	1471	403.15
Back portion of piston	232	403.15

The temperature in the skirt area reached 461 K (188°C) due to heat transfer by the heat pipes. The difference between the highest and lowest temperatures on the piston was $\Delta T = 96$ K.

Figure 19 shows the results of heat transfer calculation for a single piston with heat pipes (2000 W/m K) installed.

The temperature reached 544 K (271°C) in the central piston top area and 517 K (244°C) at the piston top edge. The temperature in the skirt area reached 469 K (196°C) due to heat transfer by the heat pipes. The difference between the highest and lowest temperatures on the piston was $\Delta T = 75$ K.

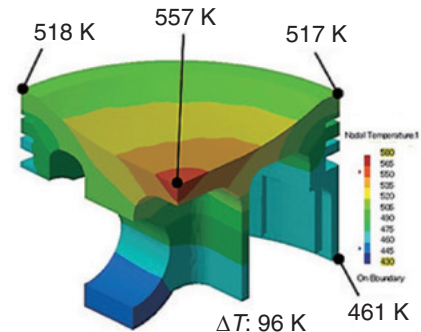


Fig. 18 Results of heat transfer calculation for piston with heat pipes (1000 W/m K)

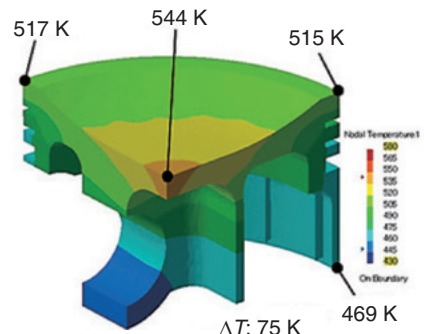


Fig. 19 Results of heat transfer calculation for piston with heat pipes (2000 W/m K)

Figure 20 summarizes these calculation results.

This shows that the temperature of the central piston top area, that is to say the highest temperature on the piston, dropped due to heat transfer by the heat pipes.

Conversely, the temperature of the piston skirt area increased slightly due to the presence of heat pipes. This shows that heat pipes have the effect of reducing thermal stress on the piston by equalization of the piston temperature distribution.

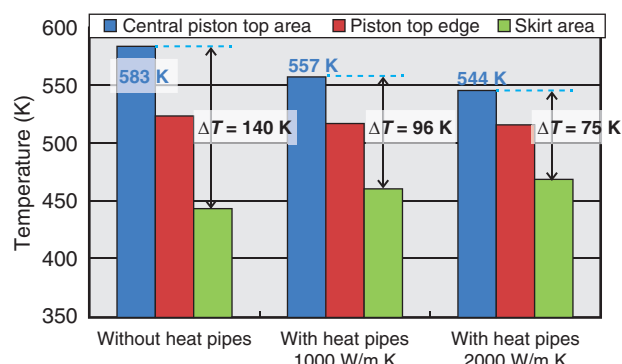


Fig. 20 Comparison of calculation results

6. Conclusion

- (1) The thermal conductivity of a heat pipe that uses protrusions at regular intervals to control the flow of liquid and gas during reciprocation tends to increase sharply as the reciprocating sliding speed increases.
- (2) Component unit conversion indicates that the newly designed heat pipe has thermal conductivity 1.6 times that of a commercially available heat pipe at standstill.
- (3) Although water was used as the working fluid in the calculations, the temperature of the central piston head area of an ICE piston was reduced by 39 K, and ΔT was also reduced from 140 K to 75 K.

The above results indicate effectiveness in reducing the thermal stress on the piston. In addition, structural modification was also found to effectively increase the amount of heat transfer. However, various issues are of course anticipated, such as the impact of heat pipe installation on strength, development of a structure that can withstand long-term use, and increased weight due to increased wall thickness in the skirt area where heat pipes are incorporated.

Nevertheless, it is thought to be potentially feasible in principle to develop this approach into an extremely advantageous engine cooling system through creative efforts in the future⁽²⁹⁾⁻⁽⁴³⁾.

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Kenji MATSUMOTO

Reduction of Internal Resistance in High Capacity Lithium-ion Batteries with 3D Lattice-structured Electrode

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ABSTRACT

After applying a 3D metal lattice structure to the current collectors, enhancements to the cathode were examined in small cells, and an increase in volumetric energy density was demonstrated in laminated cells, with the goal of increasing the energy density of lithium-ion batteries.

Countermeasures were implemented to address two issues with the cathodes of small cells. The efficacy of these measures was confirmed, and the causal factors were cataloged. The first issue is enhancing the contact between the collectors and the active materials. This was addressed by coating the surface of the collectors with conductive carbon. The second issue is enhancing the creation of electron-conductive paths. This was addressed by applying a fine particle conductive agent in the form of a liquid dispersant. The results confirmed that each of these countermeasures had the effect of suppressing resistance and enhancing durability. Moreover, to ascertain the primary cause of these effects, the conductivity of the active material was evaluated using scanning probe microscopy (SPM). The results showed that it is because the countermeasures are suppressing the interruption of electron-conductive paths.

Increasing the thickness of the electrodes in laminated cells reduced the number of electrode layers, and resulted in a 9.8% increase in energy density of cell elements for a cell using 3D lattice-structured electrodes (674 Wh/L), compared with a cell using foil-coated electrodes (614 Wh/L).

1. Introduction

Enhancing fuel economy through electrification of automobiles, and achieving full widespread adoption of electric vehicles, are key measures toward the realization of a low-carbon society^{(1), (2)}. In order to meet the increase in demand, increasing the volumetric energy density of lithium-ion batteries has become a crucial issue^{(3), (4)}.

Volumetric energy density is calculated as the product of battery capacity and average voltage divided by volume. Battery capacity is determined by the capacity per unit volume of active material in the electrodes, and the amount of active material filling the cell. The number of electrode layers can be reduced by increasing the thickness of the electrodes. As a result, the separator and collector amounts used can be reduced. This increases the ratio of active material in the cell, and makes it possible to increase the energy density of the battery.

A study was made of applying a 3D lattice structure to the collectors (3D collectors) of lithium-ion batteries, as a technology to increase the thickness of electrodes by increasing the amount of active material filling the cell. A 3D collector has a porosity of 90% or higher, making it possible to increase the loading by filling the voids with active material^{(5), (6)}. As a result, compared with the usual foil-coated electrodes, electrodes with 3D collectors (3D electrodes) make it possible to reduce the number of electrode layers within a cell. Because the number of electrode layers is reduced, the number of separator layers and the amount of collector used decreases as well. This serves to increase the ratio of active material inside the cell. Consequently, it becomes possible to increase the energy density of a battery through the application of 3D electrodes.

In the previous paper, a prototype cathode using a 3D collector (3D cathode) was fabricated, and the characteristics of the electrode were assessed. This revealed

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its effectiveness at suppressing internal cell resistance and increasing durability compared with foil-coated cathodes⁽⁷⁾. In doing so, two issues were identified with regard to suppressing internal resistance. The first is that enhancement of the collector surface is needed in order to increase contact between the active materials and the collectors. The second is that enhancement of the dispersion characteristics of the conductive agent is needed to increase formation of electron conductive paths between the active materials⁽⁷⁾.

Therefore, remedial measures were considered for each of the two aforementioned issues, with the aim of suppressing the internal resistance of the 3D electrodes. In order to increase contact between the active material and the collector, a 3D electrode with a coating of conductive carbon particles on the collector surface was explored. In order to increase the formation of electron conductive paths between the active materials, the application of a fine particle conductive agent in the form of a liquid dispersant was explored.

Furthermore, a laminated cell was fabricated with 3D collectors applied to both poles, and the increase in energy density was examined.

2. Examination of Cell Structure

2.1. Examination of Contact between Cathode Active Material and Collector

Figure 1 shows the results for a scanning electron microscope (SEM) observation of a cross section of a 3D electrode. As the broken line in the figure shows, a portion of the active material near the collector aluminum of the 3D electrode contains gaps where it is not in direct contact with the collector. Electrons are supplied directly to the active material that is in contact with the aluminum, but the supply of electrons at locations that are not in contact occurs through the mediation of other active materials or conductive agents. This causes the resistance to increase.

A method for coating the surface of aluminum with conducting carbon particles has been proposed as a means of increasing contact between the active materials and the

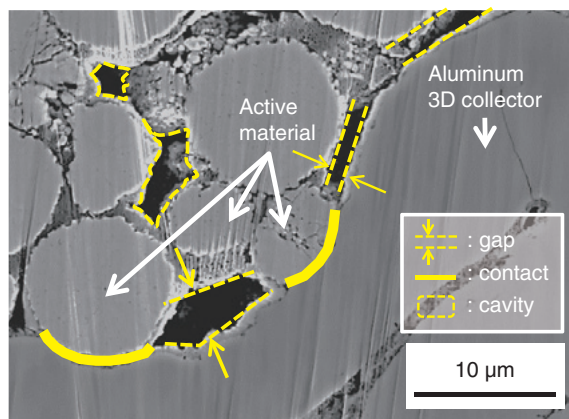


Fig. 1 Cross-section SEM image of 3D cathode

collectors in typical foil-coated electrodes⁽⁸⁾⁻⁽¹⁰⁾. Enhancing the contact between the active materials and the collectors by forming a carbon coat layer decreases interface resistance between the aluminum surface and active materials, while also making it possible to reduce variability in resistance⁽¹⁰⁾. Coating the surface of the aluminum framework of the 3D collector with carbon is expected to eliminate these gaps and effectively increase contact between the active material and the collector. On the other hand, due to the plasticity of the graphite, which is the active material in the anode, there is no issue with contact between it and the collector.

2.2. Examining Electronic Conductivity between Active Materials

In the electrodes of typical lithium-ion batteries, increasing the dispersive properties of the conductive agent is known to help the conductive agent to fill pores evenly, thereby enhancing electronic conductivity between active materials⁽¹¹⁾. Figure 2 shows the measurement results for pore size distribution in a foil-coated cathode and 3D cathode. It can be seen that the pore sizes are smaller in the 3D cathode than in the foil-coated cathode. Moreover, as shown by the broken outlines in Fig. 1, it is clear that there are cavities between the active materials where the conductive agent has not penetrated between the particles of each active material. As the dispersion of the conductive agent decreases, the electronic conductivity within the electrode decreases, causing the electrical resistance to increase⁽¹¹⁾. To counteract this, it is possible to suppress agglutination and enhance the fill of conductive agent into pores, by applying a conductive agent that has been dispersed within a solvent beforehand, instead of a conventional conductive agent powder. Moreover, decreasing the size of the particles

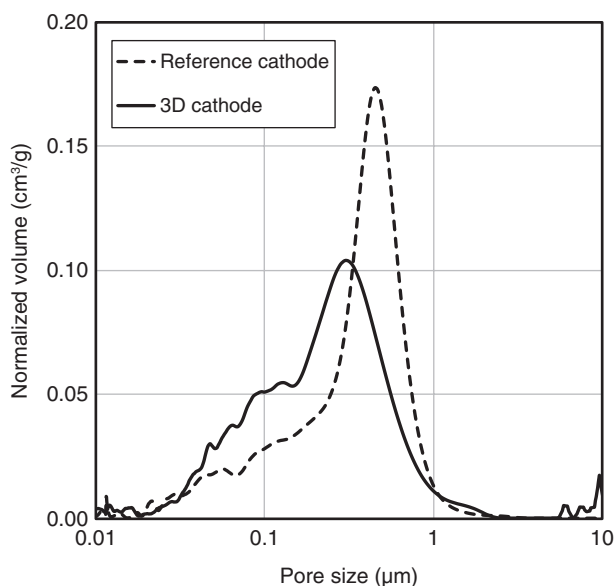


Fig. 2 Cathode pore distribution

in the conductive agent can be expected to have the effect of increasing penetration between the particles of active material, and enhancing electronic conductivity between the particles of active material.

2.3. Examining Energy Density

The previous paper presented the results of calculation of the increase in energy density in a cell to which 3D electrodes have been applied. For the cell size used in vehicles (360-mL volume), the relationship between electrode loading and collector porosity, which makes it possible to surpass the energy density achieved using foil-coated electrodes, was resolved. The results were: 97% or higher porosity at a loading of 90 mg/cm², 93% or higher at 120 mg/cm², and 89% or higher at 150 mg/cm²⁽⁷⁾. For 3D electrodes, the decrease in components due to the decrease in number of layers, which is made possible by thicker electrodes, increased energy density regardless of cell size.

As Fig. 3 shows, lithium-ion battery cells can be divided into a layered element composed of electrodes and separators, and an exterior body of tabs, laminate film, etc. If the active materials are fixed in place, the capacity of the battery is determined by the capacity of the element, regardless of the shape of the cell. Therefore, the effects on energy density of enhancements to the electrodes can be assessed by measuring the capacity per element and comparing the energy densities.

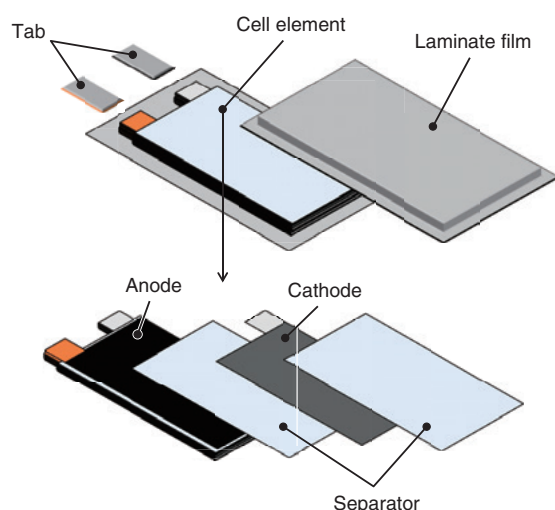


Fig. 3 Internal structure of lithium-ion battery

3. Testing Method

3.1. Cell Components

3.1.1. 3D collector

For the collector, Celmet manufactured by Sumitomo Electric Industries, Ltd. was used^{(5), (6)}. In the interest of battery potential, and because of their stability when used as collectors, aluminum Celmet was used for the cathode,

Table 1 Physical properties of Celmet

	Aluminum Celmet	Copper Celmet
Porosity (%)	97	97
Average pore size (μm)	550	550
Specific surface area (m ² /m ³)	5500	5500
Thickness (μm)	1000	1000
Area density (g/m ²)	100	200

and copper Celmet was used for the anode. Typical physical properties are listed in Table 1.

A 3D collector was fabricated and its aluminum surface coated with a carbon coat layer as shown in Fig. 4. First, a 10-wt% carbon black solution was prepared using N-Methyl-2-pyrrolidone as the solvent. The aluminum 3D collector was then immersed in this solution. Next, a blade was used to remove excess carbon black, and then air was blown over the collector. Finally, this was placed in a vacuum dryer at 120°C to create a carbon-coated 3D collector.

Three types of collectors were created, with carbon coatings of 0.1 mg/cm², 0.5 mg/cm², and 1.0 mg/cm². However, at 0.1 mg/cm² the aluminum surface was not coated evenly, and at 1.0 mg/cm² the voids in the 3D lattice were clogged with carbon. Owing to this, only the evenly coated 0.5 mg/cm² type was made into electrodes.

3.1.2. Cathode

The ternary layered oxide LiNi_{1/3}Co_{1/3}Mn_{1/3}O₂ (NCM) was used as the active material, acetylene black (AB) was used as the conductive agent, and polyvinylidene difluoride (PVDF) was used as the binder. These were combined with a composition ratio of NCM/AB/PVDF = 94/4/2 wt%. The aluminum 3D collector was filled with composite slurry to have a loading of 90 mg/cm². The cathode was then pressed in a roller press at 120°C so that the electrode density would be 3.2 g/cm³, and fabrication of the electrode was completed. The carbon-coated 3D collector was applied, and a cathode was fabricated in the same way as outlined above. In addition to AB, CSB-2 was used. This is a fine particle conductive agent dispersed in a N-Methyl-2-pyrrolidone solvent, from the Conductive Slurry for Battery (CSB) Series manufactured by Mikuni-Color Ltd.; and a cathode was fabricated in the same way as outlined above. Typical physical properties for each conductive agent are listed in Table 2. Because CSB-2 has a smaller particle size

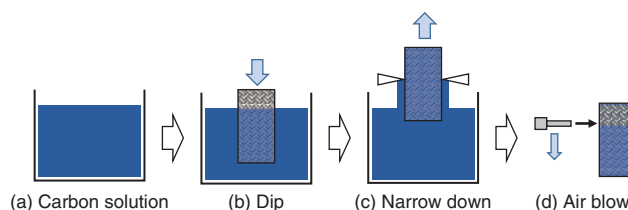


Fig. 4 Schematic view of electrode carbon coating process

Table 2 Physical properties of conductive agent

	AB	CSB-2
Particle size (nm)	48	23
SSA (m ² /g)	41	133
DBP absorption (ml/100g)	114	220
State	Powder	Dispersion

than AB, the specific surface area increases. Accordingly, the amount of di-n-butyl phthalate (DBP) supplied (which indicates solution permeability) is increased. This can also be expected to have the effect of enhancing the permeability of the electrolyte. The foil-coated cathode was fabricated to have an electrode density of 3.2 g/cm³ by coating both sides of a 15- μ m sheet of aluminum foil, so that the loading on each side would be 90 mg/cm² and 45 mg/cm², respectively.

3.1.3. Anode

For the active material, natural graphite (Gr) was used; for the conductive agent, AB; for the binder, styrene butadiene rubber (SBR); and for the thickening agent carboxymethylcellulose (CMC). These were combined in a composition ratio of Gr/AB/SBR/CMC = 96.5/1/1.5/1 wt%. This composite slurry was used to fill both sides of a copper 3D collector so that the loading on each side would be 45 mg/cm² and 22.5 mg/cm², respectively. The anode was then pressed in a roller press at room temperature so that the electrode density would be 1.5 g/cm³, and fabrication of the electrode was completed.

Meanwhile, the foil-coated collector anode was fabricated by coating both sides of a 10- μ m sheet of copper foil, so that the loading on each side would be 45 mg/cm² and 22.5 mg/cm², respectively. The anode was then pressed in a roller press at room temperature so that the electrode density would be 1.5 g/cm³, and fabrication of the electrode was completed.

3.1.4. Separator

A microporous polyethylene film 15 μ m thick was used.

3.1.5. Electrolyte

A mixture of ethylene carbonate (EC), dimethyl carbonate (DMC), and ethyl methyl carbonate (EMC) was used for the solvent at a composition ratio of EC/DMC/EMC = 30/40/30 wt%. The supporting salt lithium hexafluorophosphate (LiPF₆) was dissolved in 1.2 mol concentration in the solvent to form the electrolyte.

3.1.6. Cell exterior body

A laminate film with a thickness of 150 μ m was used.

3.2. Cell Manufacturing Method

3.2.1. Small cell evaluation

A small cell evaluation was conducted for the purpose of evaluating the internal resistance and cycling properties

of the 3D cathode. Small cells can be easily prototyped with high reproducibility. Also, it is possible to perform a relative comparison of internal resistance and initial durability, making them useful when considering electrode design. Four types of cathodes were subject to investigation: a cathode with a composite-coated collector foil (foil-coated cathode), a cathode with a 3D collector filled with composite (3D cathode (standard)), a 3D cathode coated in a carbon layer (3D cathode (C coating)), and a 3D cathode to which a CSB-2 conductive agent has been applied (3D cathode (CSB-2)). The cathodes were punched out to be 30 mm $\times$ 40 mm in size, the anodes 34 mm $\times$ 44 mm in size, and the separators 40 mm $\times$ 50 mm in size. As Fig. 5 shows, the cell elements were fabricated by placing electrodes and separators in layers. The laminate film was punched out to be 88 mm $\times$ 220 mm in size, then folded in half. The elements were placed inside it and electrolyte injected, then defoamed and sealed to fabricate the laminate cells. Three of each type of cell were prepared and the average values they yielded were used as the evaluation results. Each configuration is also shown in Table 3.

3.2.2. Laminated cell evaluation

A laminated cell evaluation was conducted for the purpose of empirically studying the energy density when 3D electrodes are used for the cathode and anode, and to clarify the resistance in such a cell. With laminated cells, the energy density for the cell can be confirmed, and the resistance value for the cell including tabs and components can be made clear. The cathode was punched out to be 71 mm $\times$ 81 mm in size, the anode 75 mm $\times$ 85 mm in size, and the separator 80 mm $\times$ 90 mm in size. As Fig. 6 shows, the reference electrode cell and 3D electrode cell were each fabricated by placing electrodes and separators in layers. The laminate film was punched out to be 125 mm $\times$ 135 mm

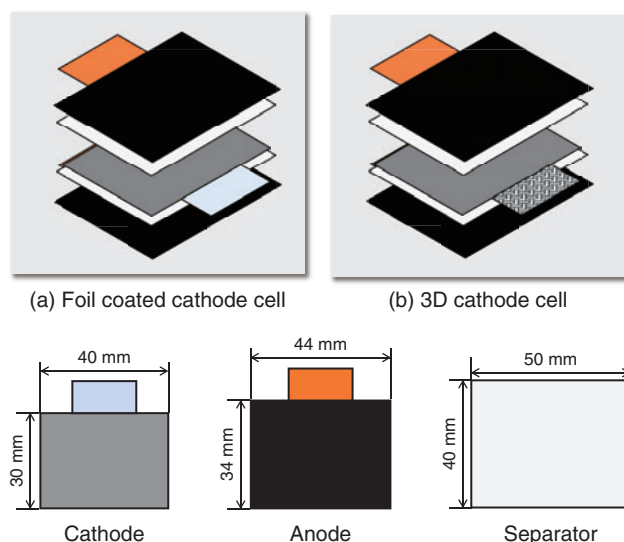


Fig. 5 Small cell element

Table 3 Small cell components

	Foil coated cathode cell	3D cathode cell
Cathode active material	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$	
Cathode active material content	94 wt%	
Cathode loading	45 mg/cm ²	90 mg/cm ²
Cathode density	3.2 g/cm ³	
Cathode collector	Aluminum foil	Aluminum Celmet
Anode active material	Graphite	
Anode active material content	96.5 wt%	
Anode loading	22.5 mg/cm ²	
Anode density	1.5 g/cm ³	
Anode collector	Copper foil	
Electrolyte	1.2 mol LiPF ₆ EC/DMC/EMC = 30/40/30 wt%	
Separator	15 μm	
Negative/Positive ratio	1.2	

Table 4 Multilayer cell components

	Reference cell	3D cell
Cathode active material	$\text{LiNi}_{1/3}\text{Mn}_{1/3}\text{Co}_{1/3}\text{O}_2$	
Cathode active material content	94 wt%	
Cathode loading	45 mg/cm ²	90 mg/cm ²
Cathode density	3.2 g/cm ³	3.2 g/cm ³
Cathode collector	Aluminum foil	Aluminum Celmet (C coating)
Anode active material	Graphite	
Anode active material content	96.5 wt%	
Anode loading	22.5 mg/cm ²	45 mg/cm ² , 22.5 mg/cm ²
Anode density	1.5 g/cm ³	1.5 g/cm ³
Anode collector	Copper foil	Copper Celmet
Number of electrodes	9	5
Electrolyte	1.2 mol LiPF ₆ EC/DMC/EMC = 30/40/30 wt%	
Separator	15 μm	
Negative/Positive ratio	1.2	

in size, placed on the top and bottom of the element, and sealed on three sides. Electrolyte was then injected, and then defoamed and sealed to fabricate the laminate cells. Three of each type of cell were prepared and the average values they yielded were used as the evaluation results. The cell configuration is also shown in Table 4.

3.3. Cell Evaluation Method

3.3.1. Rated discharge test

A rated discharge test was conducted to confirm cell capacity. As an aging treatment, the cells were placed in a thermostatic chamber at 25°C and charged at 0.1 C under constant current (CC), with the upper voltage limit at 4.2 V. After charging under constant current-constant voltage

(CCCV) for a constant voltage (CV) time of one hour, the cells were rested for one hour, then discharged at CC at 0.2 C, with the lower voltage limit at 2.5 V. This constituted one cycle and a total of five cycles were carried out. Cell capacity was defined as the capacity after CC charging at 0.3 C with the upper voltage limit at 4.2 V, charging for a CV time of one hour, then resting for one hour, after which the cell was discharged at CC at 0.3 C, with the lower voltage limit at 2.5 V. For the definition of the C-rate, the current value for full discharge in one hour is taken to be 1 C, where C is the cell capacity divided by the full discharge time. In other words, for a cell with constant capacity, 0.5 C is the current value for full discharge in two hours, and 2 C is the current value for full discharge in 0.5 hour.

3.3.2. 10-second direct current resistance (10-sec DCR)

A 10-sec DCR test was conducted to evaluate the internal resistance of the cell. The state of charge (SOC) of the cell was adjusted to 50%. Next, the cell was discharged for 10 seconds at each set current value and the voltage was measured at 0.1 second, 1 second, and 10 seconds of discharge time. The set current values were 0.3 C, 0.5 C, 0.75 C, 1.0 C, 1.5 C, 2.0 C, and 2.5 C. The voltage at each time with respect to each current value was plotted, with the horizontal axis as the current value and the vertical axis as the voltage. The slope of that curve was taken as the resistance, and the resistance at 10 seconds was taken as the overall resistance. Resistance was viewed as having these primary components: the resistance at 0.1 second (0.1-sec DCR), which was taken to be electronic resistance (Resistance A); the resistance from 0.1 to 1 second ((1-0.1)-sec DCR), which was taken to be reaction resistance (Resistance B); and the resistance from 1 to 10 seconds ((10-1)-sec DCR), which was taken to be ionic diffusion resistance (Resistance C)^{(12), (13)}.

3.3.3. Cycle test

A cycle test was conducted to evaluate cell durability. Measurements were made with the cells placed in a thermostatic chamber at 45°C, the upper voltage limit set at

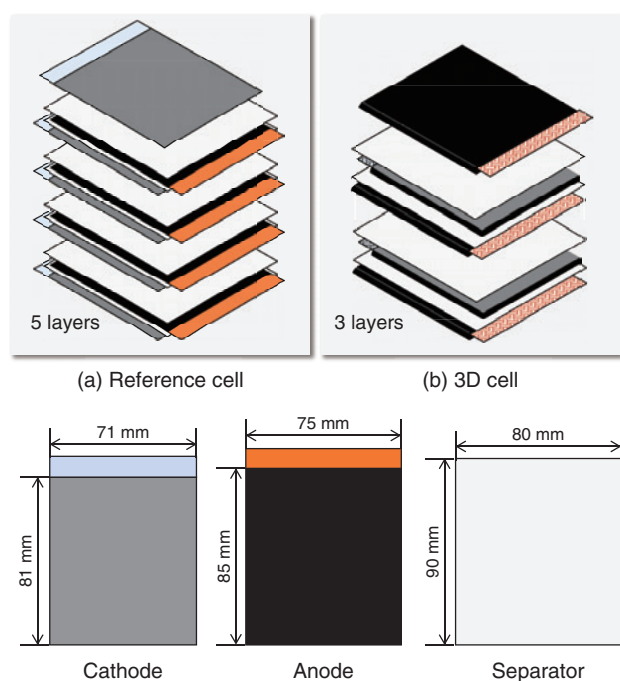


Fig. 6 Multilayer cell element

4.2 V, and the lower voltage limit at 2.5 V, and then subjected to CC discharge at 0.5 C and CCCV charging at 0.5 C for CV time of one hour and rest time of one hour. Every 200 cycles, the thermostatic chamber was set to 25°C and the capacity for the rated discharge test was confirmed. At the completion of 600 cycles, the 10-sec DCR was measured.

3.4. Analysis of Electrodes

3.4.1. SEM

Cross sections were prepared using a cross-section polisher and observed using an ULTRA 55 SEM from Carl Zeiss NTS GmbH to confirm the state of active material contact with the collector in the electrode.

3.4.2. Electron probe microanalyzer (EPMA)

Cross sections were prepared using a cross-section polisher and observed using a JXA-8500F from JEOL Ltd. to confirm the state of dispersion of each material in the electrode.

3.4.3. Pore distribution measurement

Measurements to quantify pore distribution in the electrodes were carried out by the mercury penetration method using a POREMASTER 60-GT fully automatic pore distribution measurement device manufactured by Quantachrome Instruments.

3.4.4. Scanning probe microscope (SPM)

Electrode cross sections were prepared using argon ion milling, and observed using an SFT-3500 fully automatic Nano Search microscope from Shimadzu Corporation, to quantify changes in the electron conductive paths to the active materials in the cathode before and after the cycle test. As the schematic diagram in Fig. 7 shows, each active material particle is touched with the probe, an 8-V bias voltage sufficient for stable measurement of resistance in the active materials is applied, and the resistance is calculated from the current value.

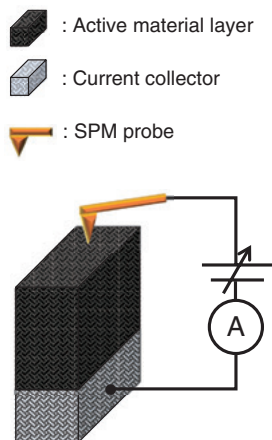
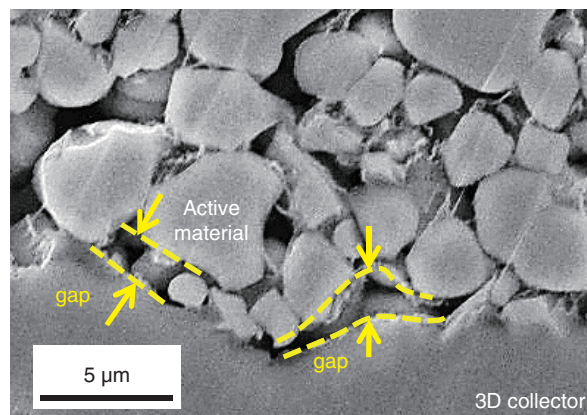


Fig. 7 Schematic diagram of SPM

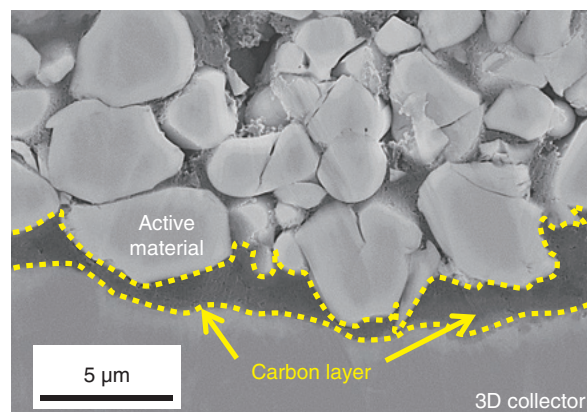
4. Results and Discussion

4.1. Results of Observation of Cathode Cross Sections

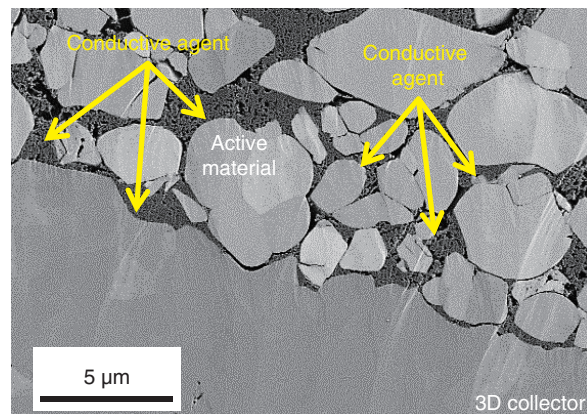
Figure 8 shows the results of observation by SEM of cross sections of (a) 3D cathode (standard), (b) 3D cathode (C coating), and (c) 3D cathode (CSB-2). Figure 9 shows the element mapping of carbon and fluorine in the 3D cathode (standard) and 3D cathode (CSB-2) observed using the EPMA.



(a) 3D cathode (standard)



(b) 3D cathode (C coating)



(c) 3D cathode (CSB-2)

Fig. 8 Cross-sectional SEM images of 3D cathodes

It is apparent from Fig. 8 that in (a) there are gaps where the active material does not directly contact the collector, and some active material is isolated. This causes an increase in electronic resistance. As the broken lines in the figure show, in (b) there is a carbon layer on the surface of the collector. Thus, it was confirmed that the active material is contacting this collector evenly through the conductive carbon layer. Consequently, enhancing the electronic conductivity between the collector and the active material can be expected to have the effect of suppressing electronic resistance in the electrode.

In Fig. 8(c) it was confirmed that the conductive agent has penetrated the gaps between the particles of active material and is well dispersed. It is thought that because the 23-nm primary particle size of the CSB-2 conductive

agent is less than half the 48-nm primary particle size of the regular AB conductive agent, its ability to fill the gaps was enhanced.

From Fig. 9, it can be confirmed that for the entire electrode, the dispersion of carbon (representing the conductive agent) and fluorine (representing the binder) is increased in (c) compared with (a). This is thought to be because the dispersion of each material was enhanced by applying the conductive agent dispersed within a solvent rather than as a powder. In light of these analysis results, it is expected that enhancing electronic conductivity within the electrode composite will reduce resistance in the electrode. In addition, it is known that because the binder used to enhance electrode binding does not itself contribute to the battery reaction, resistance will increase if dispersion

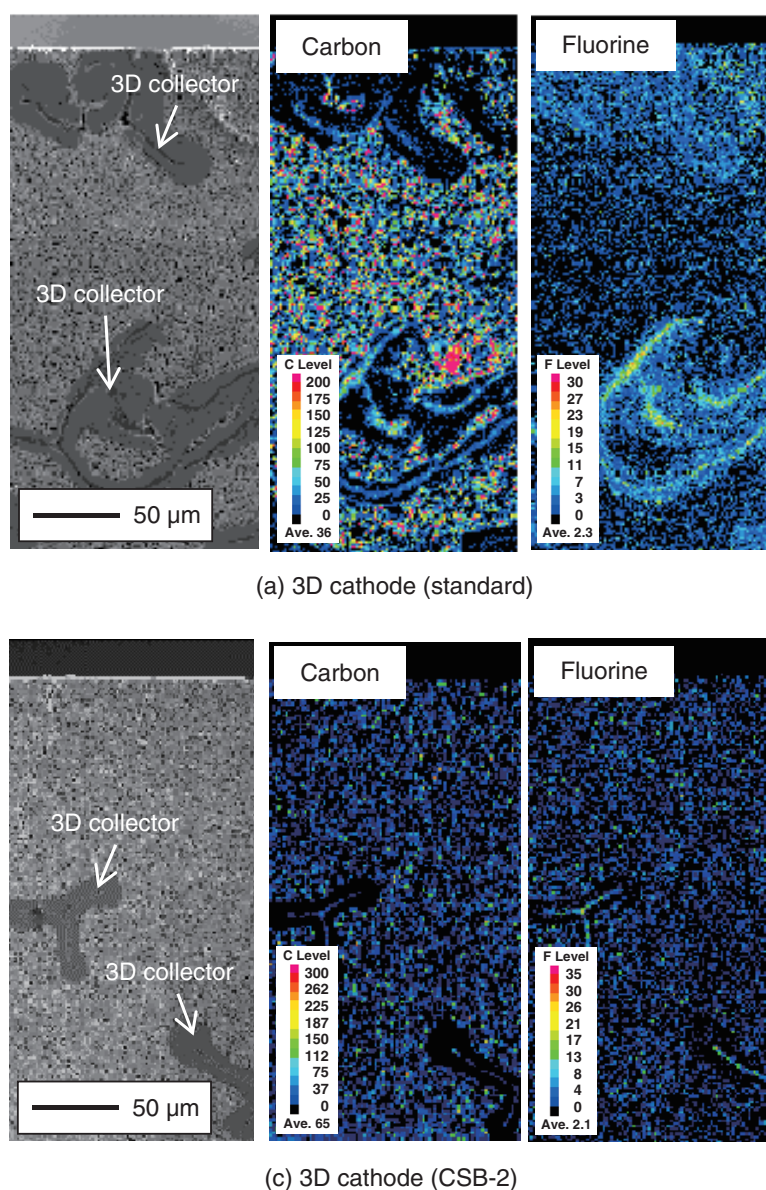


Fig. 9 EPMA elemental mapping analysis of 3D cathode

is low⁽¹¹⁾. However, increasing dispersion of the binder in (c) 3D cathode (CSB-2) can be expected to reduce reaction resistance in the electrode.

4.2. Measurement Results of Cathode Initial Resistance

Figure 10 shows the 10-sec DCR results for each cathode. This confirms that the resistance for all 3D cathodes is suppressed relative to the foil-coated cathode.

In Resistance A, the primary component of resistance is electronic resistance, and was $8.8 \Omega\cdot\text{cm}^2$ for the 3D cathode (standard) compared with $10.4 \Omega\cdot\text{cm}^2$ for the foil-coated cathode. Thus, it was confirmed that the 3D collector effectively reduced resistance by $1.6 \Omega\cdot\text{cm}^2$. Moreover, the resistance was $7.9 \Omega\cdot\text{cm}^2$ for the 3D cathode (C coating), and $7.2 \Omega\cdot\text{cm}^2$ for the 3D cathode (CSB-2), confirming that they further reduce resistance relative to the 3D cathode (standard). As was confirmed by the cross-section SEM image in Fig. 9, in the 3D cathode (C coating), it is thought that increasing the contact at the interface between the collector and active material has the effect of increasing the electronic conductivity between the active materials and the collector. In the 3D cathode (CSB-2), it is thought that the fill of conductive agent between the active materials had the effect of increasing electronic conductivity between the active materials. From these results, it was confirmed that both of these remedial measures were able to reduce electronic resistance in the electrodes.

In Resistance B, the primary component of resistance is reaction resistance, which was $1.6 \Omega\cdot\text{cm}^2$ for the 3D cathode (standard), $1.7 \Omega\cdot\text{cm}^2$ for the 3D cathode (C coating), and $0.8 \Omega\cdot\text{cm}^2$ for the 3D cathode (CSB-2), compared with $0.9 \Omega\cdot\text{cm}^2$ for the foil-coated cathode. Thus, it was confirmed

that the 3D cathode (standard) and 3D cathode (C coating) increased resistance, while the 3D cathode (CSB-2) reduced it. It is apparent from the fluorine element mapping by the EPMA in Fig. 10 that the 3D cathode (standard) contains areas where the binder has low dispersion and is unevenly distributed. This is thought to be increasing reaction resistance. The 3D cathode (C coating) uses the same slurry, and thus has a similar tendency. By contrast, because the binder in the 3D cathode (CSB-2) has been confirmed to be evenly distributed with high dispersion, this is thought to be suppressing reaction resistance in the electrode.

In Resistance C, the primary component of resistance is ionic diffusion resistance, which was $1.9 \Omega\cdot\text{cm}^2$ for the 3D cathode (standard), $1.4 \Omega\cdot\text{cm}^2$ for the 3D cathode (C coating), and $1.3 \Omega\cdot\text{cm}^2$ for the 3D cathode (CSB-2), compared with $1.7 \Omega\cdot\text{cm}^2$ for the foil-coated cathode. Thus, it was confirmed that the CSB-2 conductive agent has a considerable effect in reducing resistance. As shown by the physical properties of each conductive agent in Table 2, using the CSB-2 conductive agent increases specific surface area to $133 \text{ m}^2/\text{g}$, compared with $41 \text{ m}^2/\text{g}$ for AB. Also, the DBP absorption, which shows the penetrability of the solution, increases to $220 \text{ ml}/100\text{g}$, compared with $114 \text{ ml}/100\text{g}$ for AB. Based on this, it is thought that increasing the penetration of electrolyte solution into the pores of the electrode makes it easier to supply lithium ions to the active material, suppressing ionic diffusion resistance in the electrode.

4.3. Results of Cathode Durability Evaluation

Figure 11 shows the rate of change in capacity every 200 cycles from the cycle test at 45°C . In contrast to the foil-coated cathode, which had a capacity retention of 79% after 600 cycles, the capacity retention of the 3D cathode (standard) was 84%, the 3D cathode (C coating) 85%, and

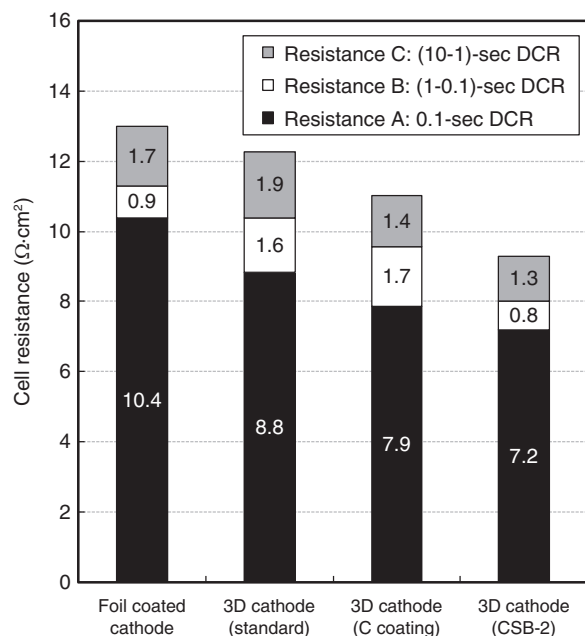


Fig. 10 Results of 10-sec DCR for cathodes

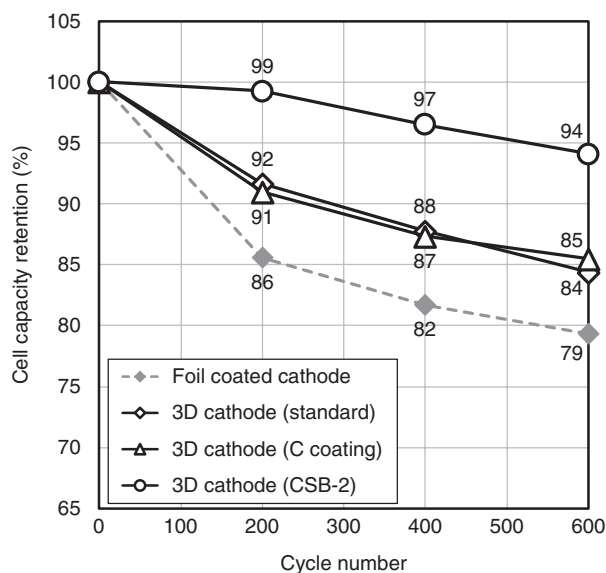


Fig. 11 Capacity retention performance of cathodes

the 3D cathode (CSB-2) 94%. This confirms that capacity retention is heightened for all 3D cathodes. This is thought to occur because the aluminum frame that forms the 3D lattice structure maintains its structure during cycle testing. Also, maintaining the binding of the various constituent materials throughout the electrode keeps the active material from detaching. The 3D cathode (C coating) increased contact between the collector and active material, with the effect of suppressing electronic resistance at their interface. However, because the frame structure of the electrode and the contents of the electrode composite were unchanged, it was equivalent to the 3D cathode (standard) with respect to capacity degradation. On the other hand, the 3D cathode (CSB-2) not only effectively suppressed deterioration of the 3D lattice structure, but the enhanced dispersive properties of the conductive agent suppressed the interruption of conductive paths between the active materials, and the enhanced ionic diffusion suppressed interruption of ion paths. These are thought to have enhanced the suppression of capacity degradation.

Figure 12 shows the change in 10-sec DCR before and after 600 cycles of the cycle test at 45°C, while Table 5 shows the values of each component of resistance. Figure 12 and Table 5 confirm that for all 3D cathodes, the increase in 10-sec DCR resistance is suppressed relative to the foil-coated cathode. For the 3D cathodes, it was confirmed that suppressing the increase in Resistance A caused the increase in overall resistance to be suppressed. Resistance A more than doubled for the foil-coated cathode following the durability test, changing from 10.4 $\Omega\cdot\text{cm}^2$ before to 26.5 $\Omega\cdot\text{cm}^2$ after. By contrast, the 3D cathode (standard) changed from 8.8 $\Omega\cdot\text{cm}^2$ to 12.3 $\Omega\cdot\text{cm}^2$, confirming that the

Table 5 Change in cathode resistance

		Reference cathode	3D cathode (standard)	3D cathode (C coating)	3D cathode (CSB-2)
Resistance A ($\Omega\cdot\text{cm}^2$)	Before	10.4	8.8	7.9	7.2
	After	26.5	12.3	8.3	8.8
Resistance B ($\Omega\cdot\text{cm}^2$)	Before	0.9	1.6	1.7	0.8
	After	4.7	5.0	4.4	3.2
Resistance C ($\Omega\cdot\text{cm}^2$)	Before	1.7	1.9	1.4	1.3
	After	3.2	2.6	2.3	1.8

increase in resistance was suppressed. Furthermore, the 3D cathode (C coating) changed from 7.9 $\Omega\cdot\text{cm}^2$ to 10.4 $\Omega\cdot\text{cm}^2$, and the 3D cathode (CSB-2) changed from 7.2 $\Omega\cdot\text{cm}^2$ to 8.8 $\Omega\cdot\text{cm}^2$, confirming an even greater effect in suppressing the increase in resistance relative to the 3D cathode (standard). Because the primary component of resistance in Resistance A is electronic resistance, it is conceivable that the aluminum frame of the 3D cathode is suppressing the increase in resistance by reducing the interruption of electron conductive paths caused by separation of the active material from the collector during cycling. It is thought that the 3D cathode (C coating) is particularly effective at suppressing the interruption of electron conductive paths, due to the tight contact between the active material and the collector imparted by the conductive carbon particles.

4.4. Results of Active Material Conductivity Evaluation

Figure 13 shows the results of the active material conductivity evaluation conducted using SPM for both the foil-coated cathode and 3D cathode (C coating) before and after 600 cycles of the cycle test at 45°C. The particles in the SEM cross-section images of each electrode are active materials. The SPM probe touched each particle of active material and applied a bias voltage of 8 V, after which the resistance was calculated based on the current value. The measured active materials were sorted into resistance values of less than 50 M Ω , 50 M Ω or more, 500 M Ω or more, and 1000 M Ω or more. Figure 14 shows a graph indicating the ratio of resistance in the active materials of each electrode. Figure 15 shows the results of measurements taken near the aluminum collector of the 3D cathode (C coating) using SPM.

From Fig. 13 and Fig. 14, it was confirmed that the ratio of active material with a high resistance in (a) the foil-coated cathode had increased following the cycle test compared with before. In short, it is conceivable that the internal structure of the electrode in (a) the foil-coated cathode, an electrode with a thickened coating, was changed with each cycle repetition. This would result in decreased electronic conductivity to the active material and increase resistance following each cycle. This result agrees with that seen in Fig. 12, where there was a large post-cycle increase in Resistance A, whose primary component of resistance is electronic resistance.

The pre/post cycle change for (b) the 3D cathode (C coating), in the 50 M Ω or more range of active materials, amounted to a marginal increase. Therefore, it was

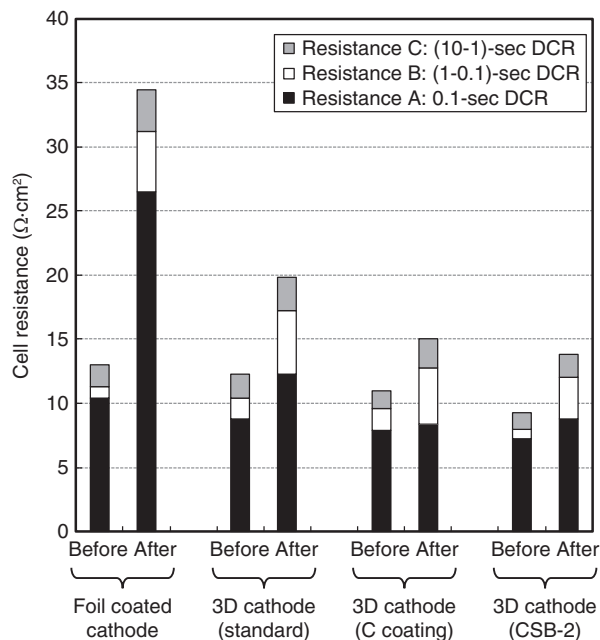
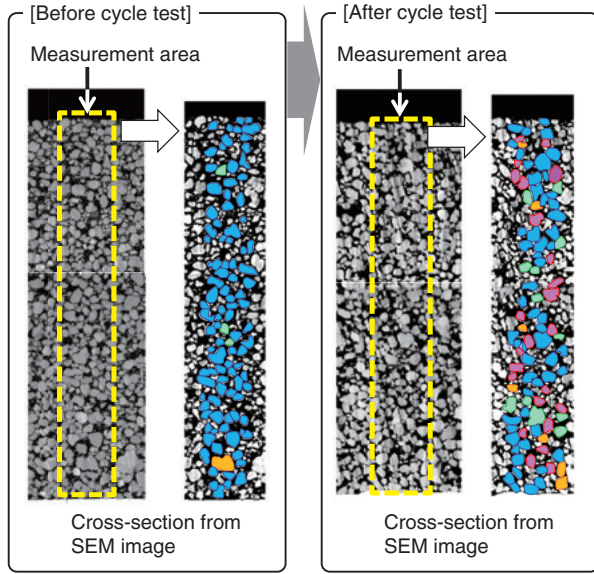
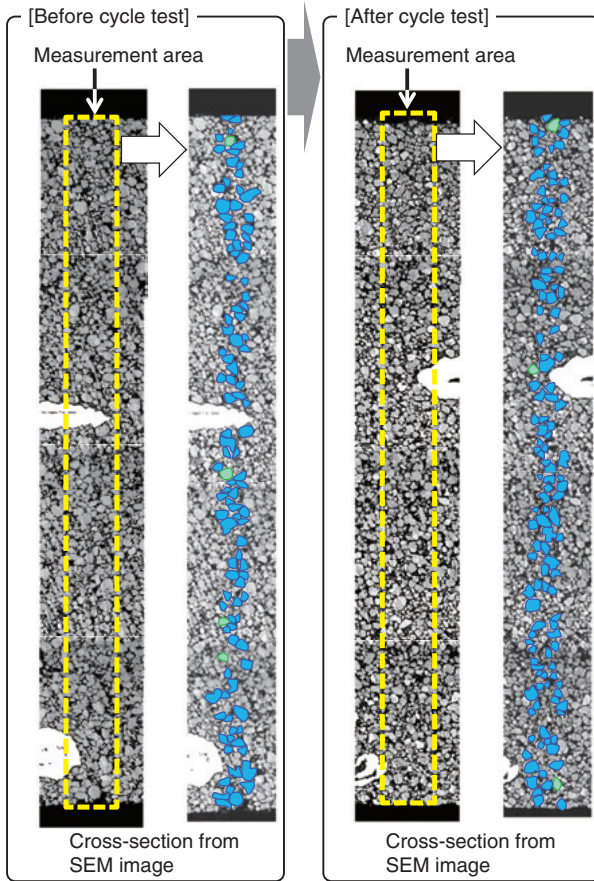


Fig. 12 Resistance performance of cathodes retention



(a) Foil coated cathode



(b) 3D cathode (C coating)

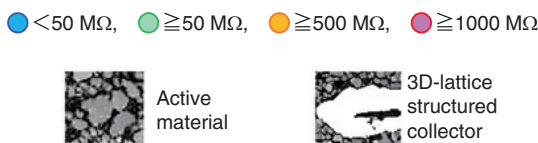


Fig. 13 Results of conductivity measurements by SPM

confirmed that there was no change in the conductivity to the active material before and after each cycle. In the 3D cathodes, the lattice-structure collectors have a constant ratio regardless of the direction of electrode thickness. Moreover, Fig. 15 confirms that the conductivity of the active materials near the collector is stable even after the durability test. In other words, even when the 3D electrodes are made thicker, the presence of the collector within the electrode suppressed structural change during each cycle. Furthermore, because there is no change in distance between the active material and the collector in the direction of thickness, it can be assumed that the interruption of electron conductive paths to the active material is suppressed. In particular, it is thought that this effect was further amplified in the 3D cathode (C coating), due to the enhanced contact between the active material and collector imparted by the carbon coating. This

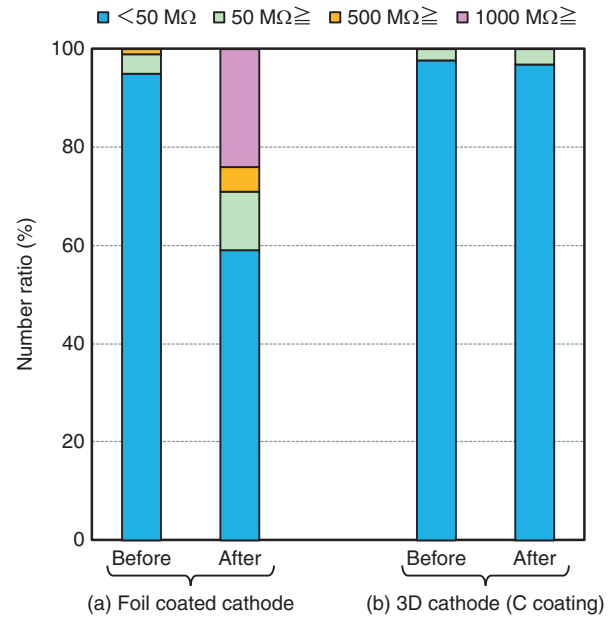


Fig. 14 Relationship between resistance and number of active materials retention

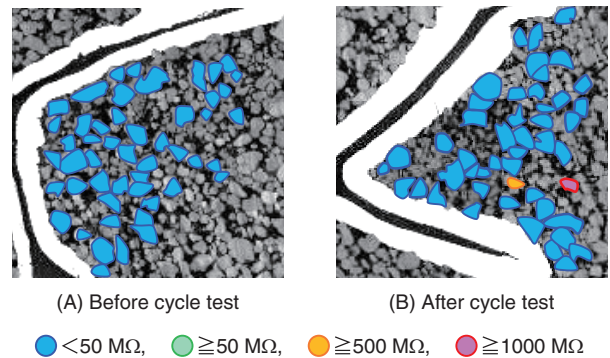


Fig. 15 Results of conductivity measurements of 3D cathode (C coating) by SPM

Table 6 Energy density of cell element

	Reference cell	3D cell
Cathode volume (mL)	4.64	4.56
Anode volume (mL)	4.38	4.52
Separator volume (mL)	1.38	0.81
Element volume (mL)	10.40	9.65
Capacity (Ah)	1.76	1.80
Cell Voltage (V)	3.62	3.61
Energy density (Wh/L)	614	674

is clearly established in Fig. 12 by the fact that the post-cycle rate of increase in Resistance A was kept to within 6%.

4.5. Laminated Cell Characteristics

Figure 16 shows the charge/discharge curve for the laminated cell rated discharge test. Table 6 shows the energy density results for each cell element calculated from this discharge capacity. The energy density per cell element for the reference cell and 3D lattice-structured electrode cell (3D cell) was 614 Wh/L and 674 Wh/L, respectively. Therefore, it is clear that using 3D collectors increases energy density by 9.8%. This shows that using 3D electrodes made it possible to increase electrode layer thickness, and decrease the number of electrode layers from 9 to 5. The result, as shown in Table 4, was a 41.7% reduction in the volume of separator used, and an increase in the ratio of active materials in the cell element, which increased energy density.

Figure 17 shows the 10-sec DCR results for each cell. The resistance was 85.1 mΩ for the 3D cell, compared with 100.5 mΩ for the reference cell, confirming a 15.4-mΩ reduction in resistance. A 24-mΩ decrease in Resistance A,

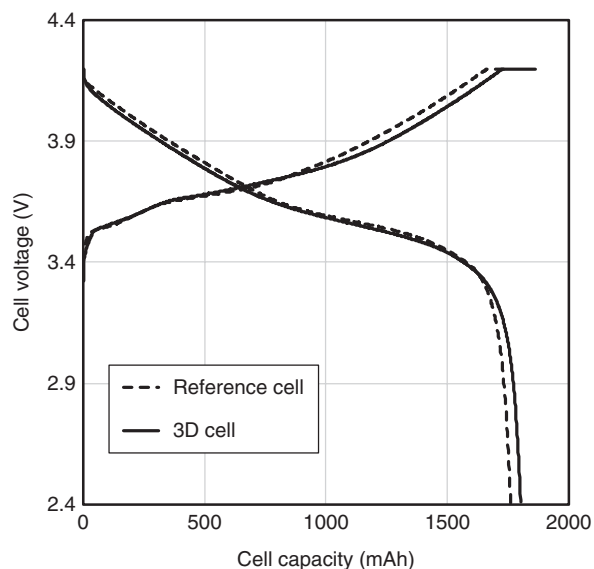


Fig. 16 Charge and discharge curves at 0.3 C

7.4-mΩ increase in Resistance B, and 1.3-mΩ increase in Resistance C were confirmed for the 3D cell with respect to the reference cell. Therefore, it was confirmed that reducing Resistance A caused a reduction in overall resistance. As was confirmed by evaluation of electrode characteristics in small cells, increasing electronic conductivity through the presence of a metal framework in the 3D electrode reduces Resistance A, whose primary component of resistance is electronic resistance. Conversely, as Fig. 8 shows, factors such as the uneven distribution of binder cause an increase in Resistance B, whose primary component of resistance is reaction resistance. In addition, because the coating thickness on one sheet of electrode is roughly double that of the reference cell, the distance ions travel is increased. This is thought to increase Resistance C, whose primary component of resistance is ionic diffusion resistance.

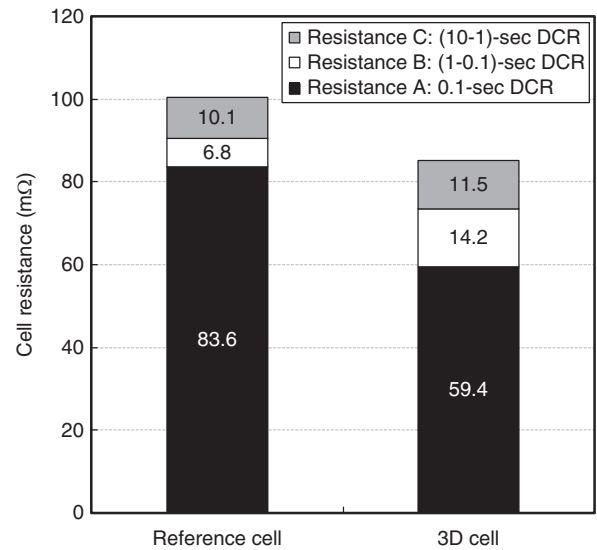


Fig. 17 Results of 10-sec DCR

5. Conclusion

Remedial measures were implemented in the application of 3D electrodes to lithium-ion batteries, and the following results were obtained.

- (1) It was confirmed that applying a conductive carbon layer to the surface of the aluminum framework allowed the active material to contact the collector evenly via the conductive carbon layer.
- (2) It was confirmed that the dispersion of each material was enhanced by applying a fine particle conductive agent dispersed within a solvent.
- (3) The results of the initial resistance measurement confirmed an inhibitory effect for each component of resistance.
- (4) The results of the durability test confirmed an effect

increasing capacity retention and suppressing increase in resistance.

- (5) Conductivity evaluations were carried out before and after the durability test, and it was confirmed that the interruption of conductive paths was suppressed in the 3D electrodes even following the durability test.
- (6) It was confirmed that the effective reduction in the number of electrode layers accompanying the enhanced loading in 3D electrodes resulted in a 9.8% increase in energy density of the cell element for a cell using 3D lattice-structured electrodes (674 Wh/L), compared with a cell using foil-coated electrodes (614 Wh/L).

The results above show that by applying 3D electrodes, it is possible to increase the energy density of lithium-ion batteries while reducing initial resistance and increasing durability.

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High Performance Si Negative Electrode Composed of Silicate Inorganic Binder

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ABSTRACT

Use of a silicate inorganic binder was investigated with the goal of suppressing volume expansion of Si negative electrodes associated with charge-discharge.

Use of a Si negative electrode with the electrode density lowered by conductive carbon and with inorganic binder permeated to the electrode interior enabled control of the amount of electrode expansion associated with charge-discharge and suppression of delamination from the current collector and conductive path breakdown within the active material layer. This realized a high-performance Si negative electrode with a large reversible charge-discharge capacity.

XPS analysis and STEM-EDX analysis were performed to elucidate these factors. The results showed that in electrodes coated with an inorganic binder, a network of siloxane bonds formed and strong bonds were obtained, and an interface phase in which the Si and inorganic binder are fused also formed.

1. Introduction

Development and popularization of electric vehicles (EV) and fuel cell vehicles (FCV) is one solution for helping realize a low-carbon society. Further increases in battery energy density are desired for automotive application of lithium-ion batteries^{(1), (2)}, and methods that use active materials with a large capacity are being investigated as one approach. Si has a high theoretical capacity of 4200 mAh/g, which makes it attractive as an active material for the negative electrodes of next-generation lithium secondary batteries, but volume changes associated with the charge-discharge reaction are large and lead to electrode disintegration. Therefore, it is important to achieve an electrode design that maintains the electrode structure⁽³⁾⁻⁽¹⁰⁾.

The binder types, conductive carbon type, electrode composition, and other factors are being investigated with the goal of maintaining the electrode structure of Si electrodes⁽³⁾⁻⁽⁵⁾. As shown in Fig. 1, binders can be broadly classified into “organic binders” and “inorganic binders”⁽⁶⁾⁻⁽⁸⁾. However, this research focused on a silicate inorganic binder

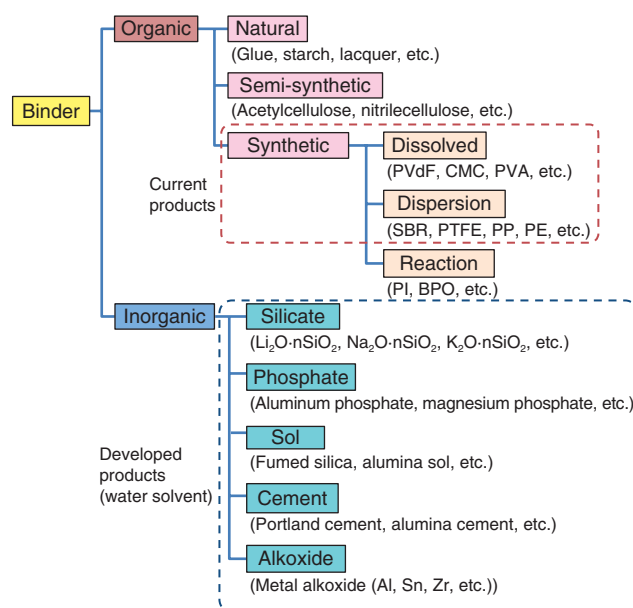


Fig. 1 Classification of binders

¹ Innovative Research Excellence

² Innovative Research Excellence Power Unit & Energy

³ ATTACCATO Limited Liability Company

(hereafter, inorganic binder), which has strong binding force for maintaining the electrode structure⁽¹¹⁾.

It has been demonstrated that when an inorganic binder $A_2O \cdot nSiO_2$ ("A" indicates an alkali metal) undergoes hydrolysis, a silanol (-Si-OH) group is generated and adsorbed to the inorganic material surface by hydrogen bonding, and when this is heated a dehydration condensation reaction occurs, enabling the formation of a strong siloxane (-Si-O-Si-) bond^{(12), (13)}.

It is anticipated that when Si is used as the active material, the active material surface is etched under the condition of an alkaline aqueous solution ($pH \leq 11$), and the -Si-OH group is formed on the Si surface by the reaction shown in Eq. (1)^{(14), (15)}.



When this Si surface etching reaction occurs, the Si of the inorganic binder and the Si of the active material integrate as shown in Fig. 2, and a powerful binding action can be expected, especially when Si active material is used. However, there are no known reports that describe the detailed interface structure.

This research attempted to use an inorganic binder to obtain a high-performance Si negative electrode with enhanced reversible charge-discharge capacity. At the same time, an attempt was also made to evaluate the binding force of the inorganic binder and to clarify the bonding scheme of the inorganic binder and the interface structure between the Si active material and the inorganic binder, which are factors enhancing the binding force.

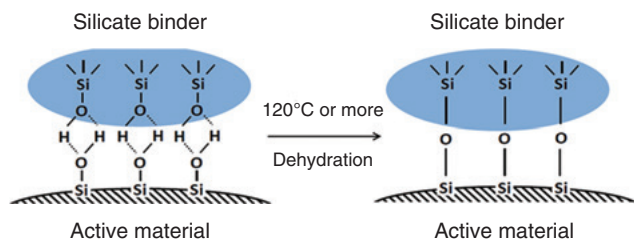


Fig. 2 Reaction mechanism of silicate inorganic binder

2. Experimental Method

2.1. Si Negative Electrode Sample Prototypes

As inorganic binders are higher density compared with conventional organic binders⁽⁸⁾, a higher mass ratio is needed to obtain sufficient binding force by the slurry coating method. Therefore, methods are being investigated for applying inorganic binder aqueous solution as a structure forming agent by permeating it into a conventional electrode and then heat-treating the electrode as shown in Fig. 3⁽⁶⁾⁻⁽¹⁰⁾. In this process, the electrode structure is the key to uniformly permeating the inorganic binder into the electrode, and porosity adjustment is needed to enable the

Table 1 List of electrode samples

No.	Conductive carbon		Silicate binder
1	AB1	5 wt%	None
2			$K_2O \cdot 3SiO_2$
3	AB2	20 wt%	$K_2O \cdot 3SiO_2$
4		20 wt%	$K_2O \cdot 3SiO_2$

inorganic binder to permeate.

Conductive carbon forms conductive paths and also plays a role to retain the electrolyte solution in the pores. For example, it has been demonstrated that the more developed the chain structure (structure) of acetylene black (AB), the higher the conductivity and fluid retentivity⁽¹⁶⁾. This research investigated AB conductive carbon with different structures in order to enhance the permeability and conductivity of the inorganic binder.

Electrodes of the levels shown in Table 1 were fabricated using the conductive carbons AB1 and AB2 with the physical properties shown in Fig. 4. Compared to AB1, AB2 has a smaller particle size and a more developed structure, and thus it is thought to better enhance the impregnating ability of the inorganic binder and create conductive paths⁽¹⁶⁾. In addition, increasing the conductive

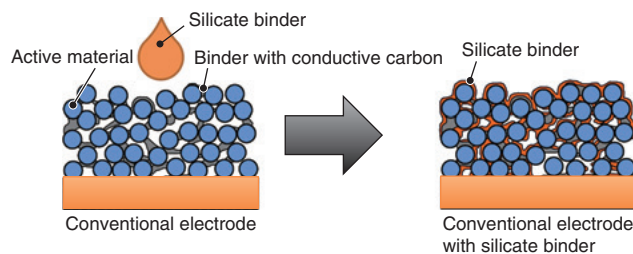


Fig. 3 Manufacturing process of Si electrode

Item	AB1	AB2
Particle size (nm)	37	23
Specific surface area (m ² /g)	58	133
Quantity of iodine adsorption (mg/g)	82	180
Packing density (g/ml)	0.08	0.05
Image of AB structure		

Fig. 4 Physical property values of conductive carbons

carbon quantity can also be expected to enhance the impregnating ability and conductive paths.

Each conductive carbon was used to prepare slurries containing 4 wt% styrene butadiene rubber (SBR) as a binder and 1 wt% sodium carboxymethyl cellulose (CMC) as a thickener. The prepared slurries were then applied to current collectors (copper foil) and allowed to dry to obtain precursors of each negative electrode. The precursor coating amount was adjusted to approximately 2.3 mg/cm². An inorganic binder aqueous solution (K₂O·3SiO₂ 10 wt%) was applied by the spray method to the obtained negative electrode precursors of samples No. 2 to No. 4, allowed to permeate, and then heat-treated using a 120°C drying furnace to cure the inorganic binder and obtain negative electrodes for use as test electrodes.

2.2. Evaluation of Samples

2.2.1. Measurement of electrode DC resistance

The composite layer DC resistance of the electrode sheet of each prepared negative electrode was measured using the Electrode Resistance Measurement System RM2610 (HIOKI E.E. Corporation).

2.2.2. Observation of electrode cross-section and distribution of inorganic binder

Cross-section magnified observation of negative electrode samples No. 2 to No. 4, which were coated with inorganic binder, was performed using a scanning electron microscope (SEM). In addition, an electronic probe micro analyzer (EPMA) was used to map the potassium (K) element, which is a component derived from the inorganic binder, and the distribution of inorganic binder permeation in the cross-section was examined. The observation samples were made by punching a ϕ 5-mm-size piece from each negative electrode, cutting to halve the electrode area, and then cross-section polishing the obtained cut surface by Ar ion milling.

2.2.3. Evaluation of binding force of binder

The shear strength was evaluated using the Surface and Interfacial Cutting Analysis System (SAICAS) in order to evaluate the electrode internal binding force of negative electrodes No. 1 and No. 2. The measurement conditions were a Borazon blade (blade width 1.0 mm), rake angle 20°, clearance angle 10°, horizontal speed 2 μ m/s, and vertical speed 0.2 μ m/s. The blade was moved horizontally at the three depth points of 5 μ m, 10 μ m, and 15 μ m, and the shear strength was obtained by Eq. (2).

$$\tau = \frac{F_h}{2wd \cot \phi} \quad (2)$$

τ : Shear strength

F_h : Horizontal load

w : Blade width

d : Shear thickness

ϕ : Shear angle

The deemed shear strength assumes $\phi = 45^\circ$.

2.2.4. Analysis of Si-O bonding in electrodes

The electrodes coated with inorganic binder were analyzed by X-ray photoelectron spectroscopy (XPS) to confirm whether Si-O bonds were newly formed due to the inorganic binder. XPS measurement was performed of negative electrodes No. 1 and No. 2, and the spectrum near Si 2p was compared. The Si-O bonding ratio was calculated from the spectral area ratio.

2.2.5. Analysis of interface between active material and inorganic binder

A scanning transmission electron microscope (STEM) was used to analyze the inorganic binder coating state and the composition of the interface between the active material and the inorganic binder of negative electrode No. 2, which was coated with inorganic binder. STEM observation was performed for an approximately 300-nm-square area, and the presence and thickness of the interface phase was investigated. In addition, element analysis was performed by energy dispersive X-ray spectroscopy (EDX), and the respective ratios of alkali metal atoms to all constituent atoms (at%) in the active material, interface phase and inorganic binder phase were estimated from the EDX spectral intensity. Element mapping measurement was also performed by EDX.

2.3. Evaluation of Cells

2.3.1. Coin cell prototypes

Coin cells (R2032) were fabricated using a negative electrode (ϕ 14 mm) as the test electrode, lithium metal foil (ϕ 16 mm) as the counter electrode, nonwoven glass fabric (Advantec GA100) as the separator, and an electrolyte consisting of lithium hexafluorophosphate (LiPF₆) dissolved in ethylene carbonate (EC), ethyl methyl carbonate (EMC), and diethyl carbonate (DEC) (1.1 M LiPF₆/EC:EMC:DEC = 3:4:3 vol.).

2.3.2. Evaluation of coin cells

The capacity of each negative electrode during the first charge-discharge cycle was confirmed with a test environment temperature of 25°C, current density of 0.025 C-rate, and cutoff potential varied from 0.01 V to 1.5 V (potential versus Li⁺/Li).

2.3.3. Observation of electrode cross-section after charge-discharge

The coin cells were disassembled after the first charge-discharge cycle, and cross-section SEM observation was performed of negative electrodes No. 1 and No. 2.

3. Results and Examination

3.1. Degree of Inorganic Binder Permeation due to Conductive Carbon

3.1.1. Electrode density and inorganic binder quantity

Table 2 shows the inorganic binder mass ratio, the

Table 2 Electrode density and silicate binder ratio

No.	Conductive carbon		Silicate binder ratio (wt%)	Electrode density (g/cm ³)	
				Precursor	With silicate binder
1	AB1	5 wt%	-	0.83	-
2			11		0.87
3		20 wt%	10.2	0.98	0.87
4	AB2	20 wt%	20	0.66	0.7

precursor electrode density, and the electrode density after coating with inorganic binder for each negative electrode sample. In the electrodes that used AB1, the electrode density before coating with inorganic binder increased together with the conductive carbon quantity. However, the conductive carbon quantity did not produce a large change in the inorganic binder ratio. In the electrode that used AB2, which has a small particle size and a developed chain structure, the electrode density dropped greatly at a conductive carbon quantity of 20 wt%, and the inorganic binder coating amount also increased compared to AB1. These results are thought to indicate that use of a large quantity of conductive carbon with a small particle size and a developed chain structure lowers the electrode density, which increases the porosity within the electrode, with the result that a sufficient quantity of inorganic binder aqueous solution can impregnate the electrode.

3.1.2. Composite layer DC resistance of samples

Figure 5 shows the DC resistance values of the electrode composite layer of each negative electrode. Comparison of No. 1 without inorganic binder and No. 2 with inorganic binder shows a slight increase in resistance due to coating with inorganic binder. Comparison of No. 2 (5 wt% conductive carbon quantity) and No. 3 (20 wt% conductive carbon quantity) shows that increasing the conductive carbon quantity lowered

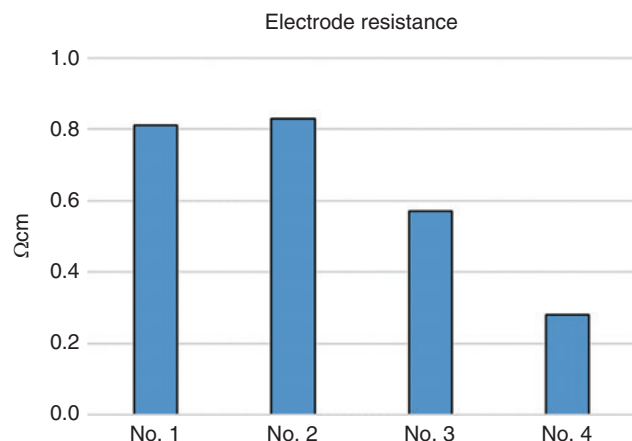


Fig. 5 Electrode DC resistance of samples

the resistance. It is thought that increasing the conductive carbon quantity enhanced the electron conductivity within the electrode. Comparison of No. 3 (AB1) and No. 4 (AB2), which use the same quantity of different conductive carbon types, shows that the resistance value dropped even further in No. 4 (AB2). This indicates that AB2, which has a small particle size and a developed structure, exhibits a greater conductive performance enhancement effect.

3.1.3. Observation of sample cross-section and distribution of inorganic binder

Figure 6 shows cross-section SEM images and EPMA mappings of K element, which is a component derived from the inorganic binder, for negative electrode samples No. 2 to No. 4. In samples No. 2 and No. 4, which had a low negative electrode precursor density, the K element derived from the inorganic binder was confirmed to sufficiently permeate to the current collector interface of the entire negative electrode layer. In contrast, the K element was unevenly distributed near the surface of the negative electrode layer in sample No. 3, which had a high negative electrode precursor density.

It is thought that the low electrode density of the negative electrode precursor enabled porosity to form inside the negative electrode precursor, so a sufficient quantity of inorganic binder aqueous solution could impregnate from the electrode interior to the current collector interface. In the high-density sample No. 3, however, it is thought that sufficient porosity was not obtained, and thus the inorganic binder could not permeate to the electrode interior.

3.2. Charge-discharge Performance Enhancement Effect of Inorganic Binder

3.2.1. Evaluation of coin cells

The capacity of coin cells using negative electrode samples No. 1 to No. 4 was measured. Figure 7 shows the respective first charge-discharge curves, and Table 3 shows the respective first charge-discharge capacities and efficiency.

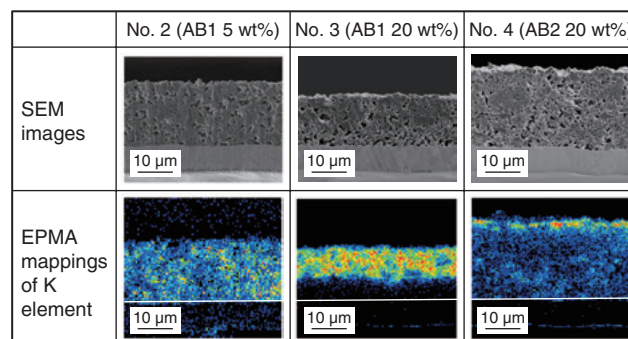


Fig. 6 Cross-section SEM images and EPMA mappings of K element

Table 3 First charge-discharge capacity and efficiency

No.	Capacity (mAh/g)		Efficiency (%)
	Charge	Discharge	
1	2346	397	16.3
2	3059	2550	83.4
3	3657	695	19.0
4	4164	3885	93.3

Coating with inorganic binder greatly increased the first reversible capacity from 397 mAh/g to 2550 mAh/g. Sample No. 4, which used large quantities of conductive carbon and inorganic binder and had the inorganic binder permeate to the electrode interior, exhibited a first charge capacity of 4164 mAh/g, which is close to the theoretical capacity of Si, and the high reversibility of a first charge-discharge efficiency of 93.3%. The enhanced discharge characteristics of sample No. 4 are thought to be the effect of the inorganic binder and also the enhancement of electron conductivity within the electrode. In contrast, sample No. 3 used a large quantity of conductive carbon, but the inorganic binder was unevenly distributed only near the surface, so although first charge could be adequately performed, the charge-discharge efficiency was just 19% and the inorganic binder had little effect. This showed that it is important for the inorganic

binder to permeate sufficiently to the electrode interior in order to manifest adequate effects.

3.2.2. SEM observation of cross-section after charge-discharge

Figure 8 shows cross-section SEM images of electrodes No. 1 and No. 2 after the first charge-discharge cycle in coin cell evaluation. Large volume expansion of the electrode composite layer and delamination around the current collector were confirmed in the electrode not coated with inorganic binder. It is thought that delamination occurred during first charge, with the result that conductive paths broke down and discharge was impaired. In the Si electrode coated with inorganic binder, some cracking occurred within the electrode, but volume expansion was

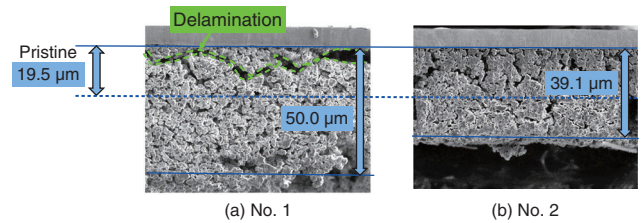


Fig. 8 Cross-section SEM images after first cycle

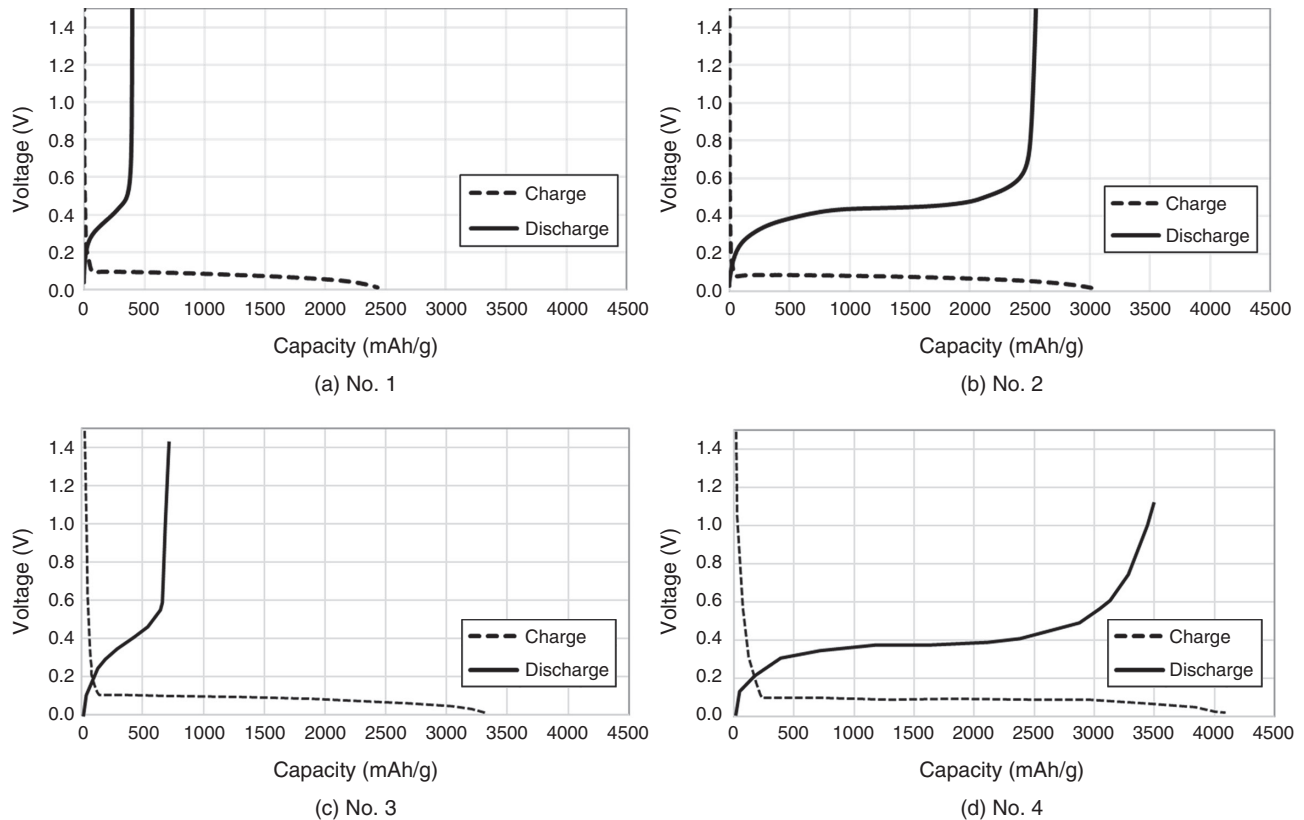


Fig. 7 First charge-discharge curves of Si/Li coin cells at 0.025 C

suppressed and delamination from the current collector was not confirmed. These results are thought to indicate that the bond between the active material and the inorganic binder increased the binding force of the electrode, which led to increased reversible capacity.

3.3. Analysis of Binding Action of Inorganic Binder

3.3.1. Evaluation of bonding force inside electrodes using SAICAS

Figure 9 shows SAICAS measurements of the shear strength τ inside electrodes No. 1 and No. 2. The inorganic binder coating increased the shear strength, which indicates the binding force inside the electrode, by around four times. This shows that coating with inorganic binder forms strong bonds inside the electrode composite. The strength tended to decrease as the depth increased, which is thought to be an impact of the SBR binder distribution prior to coating with inorganic binder. The slope of this tendency is roughly the same regardless of the presence of inorganic binder, which infers that the inorganic binder was uniformly distributed to the electrode interior and increased the strength.

3.3.2. XPS analysis of Si-O bonding

Figure 10 shows the Si 2p spectra of electrodes No. 1 and No. 2 obtained by XPS measurement. A peak around 99 eV that indicates Si-Si bonding and a peak around 103 eV that indicates Si-O bonding were confirmed in each sample. Table 4 shows the detected Si-O bonding ratio of all Si. Coating with inorganic binder was confirmed to increase the Si-O bonding ratio of all Si. This means that in addition to the SiO_2 originally present near the Si active material surface, silicate-derived Si-O bonding is also thought to increase in electrodes coated with inorganic binder.

Furthermore, the Si-O bonding peak shifted to the lower energy side in electrodes coated with inorganic binder. The

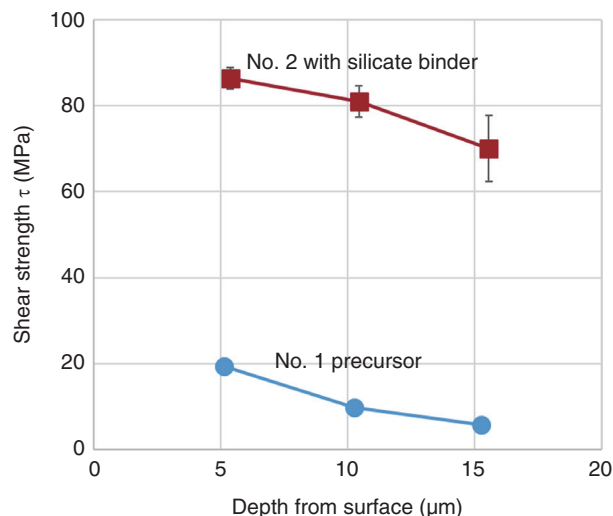


Fig. 9 Shear strength in electrode

Table 4 Si-O bonding ratio for all Si

Sample	Si-O bonding ratio (%)
No. 1 precursor	32
No. 2 with silicate binder	48

bonding energy of SiO_2 is 103.2 eV to 103.9 eV, but the bonding energy of silicate is 102 eV to 103 eV, and thus it can be inferred that this peak shift occurred due to the increase in Si-O bonds derived from the inorganic binder. These results suggest that a network of strong Si-O bonds deriving from the inorganic binder formed in the electrodes coated with inorganic binder.

3.3.3. Analysis of interface between active material and inorganic binder

Figure 11 shows the EDX mapping of an 18-μm-square area of sample No. 2. Here, O and K elements, which are inorganic binder components, were observed around the Si

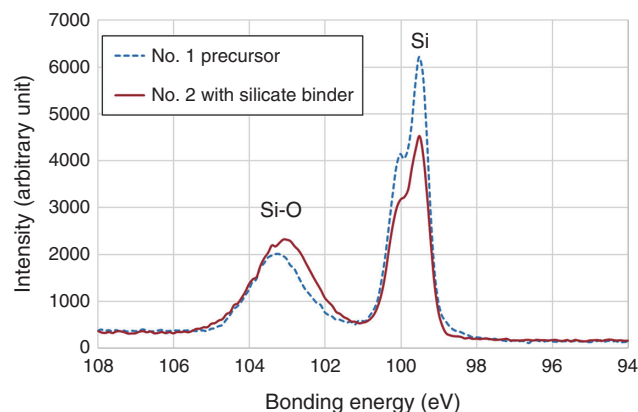


Fig. 10 XPS spectra of Si 2p peak of Si electrode

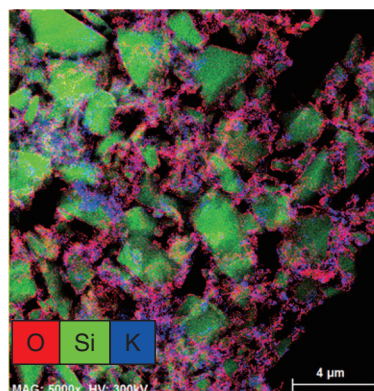


Fig. 11 EDX mapping (18 μm × 18 μm) of electrode No. 2

active material.

Figure 12(a) shows a STEM image of the Si active material surface. An inorganic binder phase with a thickness of approximately 40 nm was confirmed on the Si active material surface. Figure 12(c) shows the EDX line analysis results of the Si, O, and K elements in the interface domain between the Si active material and the inorganic binder in the direction of the arrow in Fig. 12(b). Table 5 shows the respective element ratio in each of active material phase A, interface phase B, and inorganic binder phase C, as shown in Fig. 12(c). Figure 13 shows an image drawing of the element distribution of the interface phase. Interface phase B was found to have a greater K element content compared with the inorganic binder phase C. The reason for this is thought to be that the Si of the active material and the inorganic binder reacted as per Eq. (1), and neutralization of the inorganic binder progressed simultaneously with etching of the Si surface, so a large quantity of alkali metal was precipitated to the interface phase (active material surface) as a salt. In other words, it can be inferred that when the Si surface of the active material is dissolved by etching, -Si-O-Si- bonds form that have strong bonding force and integrate with the inorganic binder, which forms an even stronger interface.

Table 5 Element ratio of interface domain

	Phase A Si grain	Phase B Interface	Phase C Silicate binder
Si (at%)	93.8	43.9	37.8
O (at%)	6	54.4	62.1
K (at%)	0.2	1.7	0.1

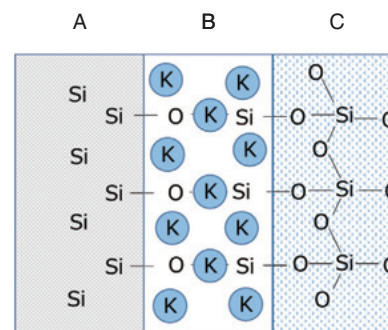


Fig. 13 Element distribution model of interface domain

4. Conclusion

A silicate inorganic binder was applied to Si negative electrodes adjusted by conductive carbon. Permeation of the inorganic binder to the electrode interior enabled control of the amount of volume expansion associated with charge-discharge and suppression of delamination from the current collector, which realized a high-performance Si negative electrode with a large reversible charge-discharge capacity. The factors for this were analyzed, and the following conclusions were reached.

Coating with inorganic binder increased the bonding force inside the electrode to around four times that of an uncoated electrode. XPS analysis showed that Si-O bonds formed inside the electrode due to the inorganic binder.

Composition analysis of the interface between the active material and the inorganic binder revealed the presence of an interface phase with large quantities of alkali metal elements. This interface phase supports the hypothesis that the Si surface is etched by the alkaline aqueous solution and the Si and inorganic binder integrate.

It was clarified that in addition to -Si-O-Si- bonding between inorganic binders, the formation of an interface phase in which the Si and inorganic binder are fused is key to realizing a high-performance Si negative electrode that can maintain an electrode framework capable of withstanding the expansion and contraction of Si.

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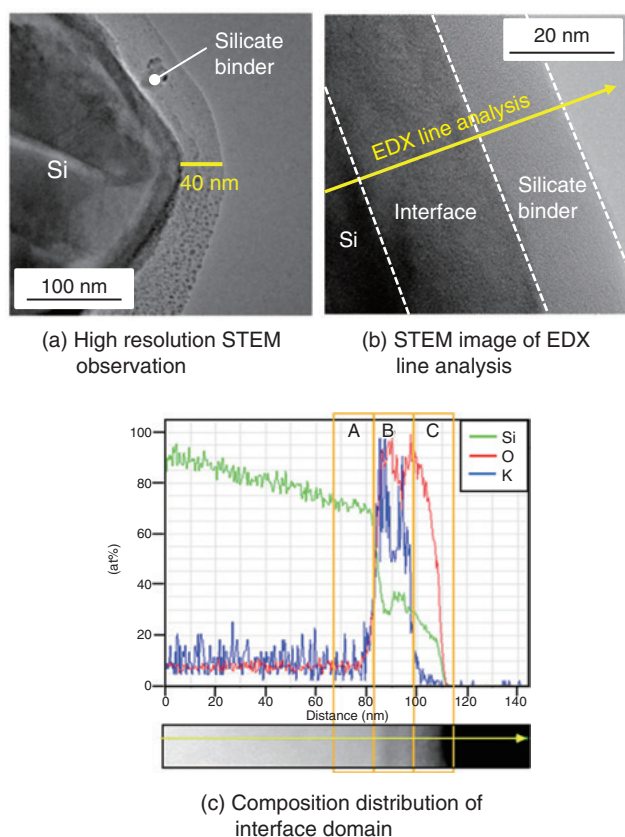


Fig. 12 STEM image and EDX line analysis of Si surface

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Oxidation Potential and Absolute Hardness Relationship in Lithium-ion Battery Electrolytes

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ABSTRACT

In this paper, we investigated the increase in oxidative stability of electrolytes in order to respond to the high-voltage operation of Li-ion rechargeable batteries. DFT geometry optimization calculations were performed for those molecular models of which side chain in the carbonate solvent substituted with a fluorinated alkyl group and the carbon in the main chain substituted with sulfur or oxygen. Linear correlation was found between the absolute hardness calculated from the frontier orbital energy following structural optimization and the oxidation potential determined by linear sweep voltammetry. Taking absolute hardness as an index, a mixed solvent of fluorinated alkyl ether and sulfolane, which was predicted to have better oxidative stability than carbonate solvent, was prepared as a prototype electrolyte. We then measured discharge capacity retention by a cyclic charge-discharge test using a battery with $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$, which is a well-known cathode material for high-potential operation. The result showed that the number of cycles taken to reach a discharge capacity retention index of 80% increased from 45 cycles, which is the figure when using carbonate electrolyte, to 80 cycles, which is the prototype.

1. Introduction

The Nobel Prize in Chemistry 2019 was awarded jointly to Whittingham, Goodenough, and Yoshino for the development of and distribution of lithium-ion rechargeable batteries (LiB)⁽¹⁾. In addition to intercalation reaction, LiCoO_2 cathode, and graphite anode they proposed, a non-aqueous organic electrolyte for which Harris proposed the basic concept⁽²⁾ is an important part that constitutes LiB. A non-aqueous organic electrolyte (hereafter referred to as electrolyte) is a liquid where Li salt is dissolved in an organic solvent with the water content reduced to a part per million (ppm) level. It conducts Li ions between a cathode and an anode in charge-discharge reactions. Suppression of electrolysis of water by reduced water content achieves a cell voltage of 3 V or higher, contributing to a smaller and lighter LiB with high input⁽³⁾.

The main property that is required for electrolytes is a wide potential window and a high ion conductivity, which have an impact on the operation voltage and input/output properties of batteries⁽⁴⁾. To choose organic solvents with wide potential window among many types of organic solvents, electrochemical measurement results were accumulated since the 1970s, and solvents were chosen⁽⁵⁾⁻⁽⁹⁾. The result led to carbonate solvents being the main component of present electrolytes.

Measures for the higher energy density of LiB include

an increase in high-voltage operation and a higher capacity. Figure 1 shows the discharge curve of major cathode-active materials. Because the discharge plateau of $\text{LiNi}_{0.5}\text{Mn}_{1.5}\text{O}_4$ (hereafter referred to as LNMO4) is near

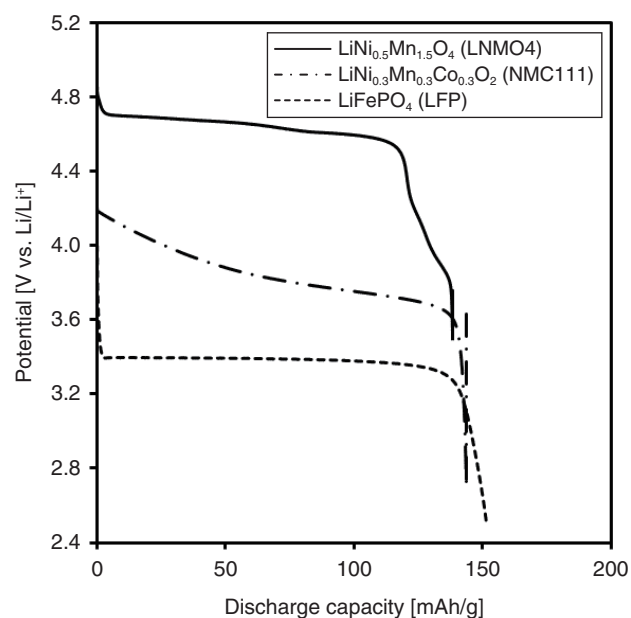


Fig. 1 Discharge curves for various cathodes

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4.7 V vs. Li/Li⁺, it has garnered attention as a cathode-active material that contributes to higher energy density. However, charge-discharge reactions that occur at a potential of about 1.0 V higher than the LiNi_{0.3}Mn_{0.3}Co_{0.3}O₂ cathodes that are in use today, oxidatively decompose electrolytes, leading to lower cycle performance⁽¹⁰⁾; thus, organic solvent with a higher oxidation potential than the carbonate solvent is desired.

2. Searching for Materials with Computational Science

Recent increase in accuracy and speed of material search methods in conjunction with computational science is phenomenal⁽¹¹⁾⁻⁽¹³⁾. If a calculation index that is correlated to material properties of interest is identified, target materials can be automatically screened. In terms of the oxidation potential of organic solvent, which is the main topic of the present study, a method exists that determines the oxidation-reduction potential by approximating the difference between total energy of the oxidized form and total energy of the reduced form to the standard chemical potential difference⁽¹⁴⁾. To screen numerous organic molecules, a method with less calculation burden is desired. Thus, the authors focused on the frontier orbit of organic solvent molecules and obtained the absolute hardness (η) as the material search index from the energy of the Highest Occupied Molecular Orbital (HOMO) and the Lowest Unoccupied Molecular Orbital (LUMO).

Pearson examined a formulation based on the frontier orbit theory in terms of the degree of resistance of reactive species to chemical reactions; that is, hardness and proposed η shown in Eq. (1)^{(15), (16)}.

$$\begin{aligned}\eta &= (I - A) / 2 \\ &= (E_{\text{LUMO}} - E_{\text{HOMO}}) / 2\end{aligned}\quad (1)$$

I and A are the first ionization energy and electron affinity of molecules, respectively. According to Koopmans' theorem⁽¹⁷⁾, I can be approximately replaced with the energy level of HOMO (E_{HOMO}) and A can be replaced with the energy level of LUMO (E_{LUMO}); thus, the median of the energy difference of the molecular frontier orbit (HOMO-LUMO Gap: ΔE) is η . Parr et al. verified that a larger η implies more thermal stability for molecules⁽¹⁸⁾. There are reports predicting color reaction for a photographic coupler that uses η as an index of chemical reaction⁽¹⁹⁾ and antioxidant performance of phenols⁽²⁰⁾. In the present study, we verified the correlation between η of organic solvent obtained from the electronic state calculation based on the density functional theory (hereafter referred to as DFT geometry optimization) and the actual oxidation potential, and prepared a prototype electrolyte with the organic solvent only, for which oxidative stability was predicted to enhance. The effectiveness of estimating oxidative stability by η was verified by the charge-discharge cycle performance of LNMO₄.

3. Calculation and Experimental Methods

3.1. Calculating the E_{HOMO} and E_{LUMO} Energy of Organic Solvents

Figure 2 shows the molecular structure of target organic solvents. Initial structures of ethylene carbonate [Fig. 2(a), R₁ to R₄ are hydrogen, noted as EC hereafter] and dimethyl carbonate [Fig. 2(b), R₁ and R₂ are methyl groups, noted as DMC hereafter]. We created a virtual molecular model where side chain extension (CH₃, C₂H₅, and C₃H₇) for R₁ to R₈, fluorinated alkyl group substitution (CH_xF_{3-x}, C₂H_yF_{5-y}, C₃H_zF_{7-z}, x = 1 to 3, y = 1 to 5, and z = 1 to 7), and O and S substitution of the main carbon chain were performed to these initial structures [Figs. 2(c-1) to (c-3)]. The objective of the fluorine substitution is to reduce the electron density of the carbonate by introducing a fluorinated alkyl group as a substitution with a strong electron acceptance rate. It creates an electronic state wherein it will be less likely for the cathode to accept electrons; that is, less likely to oxidize. To create a molecular model, we used the Pipeline Pilot by Accelrys. Virtual molecules were automatically created by combining the above substituents, which was followed by structural optimization and calculation of E_{HOMO} , E_{LUMO} , and η . For structural optimization, we used DFT geometry optimization package DMol^{3(21), (22)} by Accelrys. We used the Generalized Gradient Approximation (GGA) as the exchange-correlation function and Double numerical basis set with polarization function (DNP) as the basis-set. Comparison of BOP⁽²³⁾, PW91⁽²⁴⁾, and BLYP^{(25), (26)} for E_{HOMO} of ethylene carbonate found that their difference was about 0.2 eV; thus, we chose BLYP with many reports as the exchange interaction term. The calculation of the convergence condition was 10⁻⁶ Hartree.

3.2. Measurement of Oxidation Potential by Linear Sweep Voltammetry

Among the solvent molecules calculated in Section

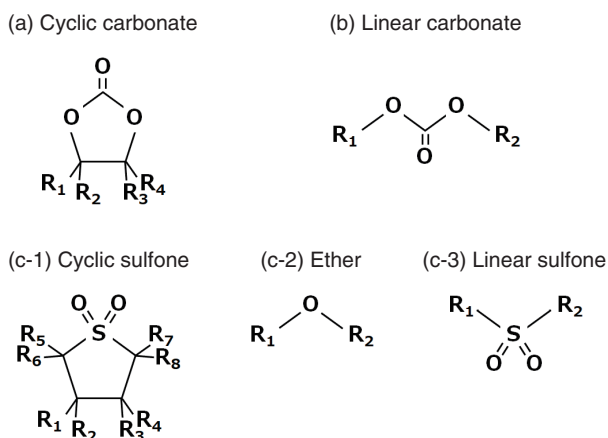


Fig. 2 Schematic illustration of organic solvent molecules

3.1., we performed linear sweep voltammetry (LSV) for solvents that could be synthesized or procured. We dissolved 0.1 mol/L of lithium hexafluorophosphate (LiPF_6) in the target organic solvent and added 2.0 mL into the electrochemical cell shown in Fig. 3. Linear carbonate [dimethyl carbonate (DMC), ethyl methyl carbonate (EMC), diethyl carbonate (DEC)], and fluorinated alkyl ether (FAE) did not fully dissolve LiPF_6 ; thus, we prepared a solvent with 10 vol% of propylene carbonate (PC) and fully dissolved LiPF_6 . The working electrode was a platinum plate (The Nilaco Corporation, purity of 99.98%, diameter of 10 mm, and thickness of 0.1 mm) polished with an emery-paper (3M, 3000 grit). For the counter electrode and reference electrode, we used metallic lithium (Honjo Metal Co., Ltd., purity of 99.9% and thickness of 0.1 mm). For the separator, a microporous polyolefin membrane (Celgard 2500) was used. The prepared electrochemical cell was placed in a constant temperature bath with a temperature of 25°C. Solartron Analytical potentiometer/galvanostat 1287/1255 was used in scanning, with the scanning speed of 0.5 mV/sec. from the open circuit potential (OCP) to 7.0 V vs. Li/Li^+ . The oxidation potential was defined as an intercept of the slope of oxidation current against the LSV scanning baseline.

3.3. Preparation of an LNMO4 Cathode Composite Sheet

LNMO4 was synthesized with the solid phase method under the existing manufacturing conditions⁽²⁷⁾. For the synthetic layer of the cathode, ink in a slurry state dispersed in the *n*-methylpyrrolidone (NMP) solvent with a weight ratio of LNMO4: conductive material: binder = 91: 4: 5 was painted on an aluminum foil to prepare a sheet. The conductive auxiliary agent was acetylene black of Denka Company Limited, and the binder was polyvinylidene fluoride of Kureha Corporation that was dissolved in an NMP solution. The cathode composite sheet was pressed so that the electrode density would be 3.0 g/mL and punched with a diameter of 14 mm.

3.4. Electrochemical Test that Uses LNMO4

The charge/discharge reversibility of LNMO4 cathode was confirmed by changing the working electrode of the LSV measurement configuration (Fig. 3) from the platinum plate to the cathode composite sheet, and then using cyclic

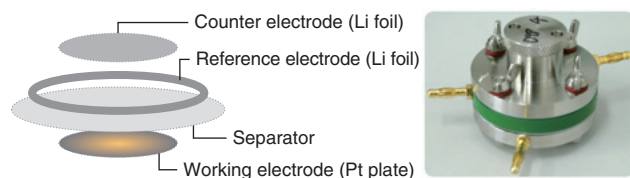


Fig. 3 Schematic illustration and cell appearance of three-electrode cell used for LSV

voltammetry (CV). The scanning rate was 0.5 mV/sec. and the potential range was 2.5 V to 5.4 V vs. Li/Li^+ . For charge-discharge cycle performance, we sealed a cathode composite sheet, separator, Li metal counter electrode, and electrolytes in a 2032-coin cell, and performed in a bath with a constant temperature of 25°C. The upper and the lower limits of the potential were 4.95 V to 2.6 V vs. Li/Li^+ , and the charge-discharge load was 0.1 C at a constant current.

As the electrolyte, 1.0 mol/L of LiPF_6 was dissolved in EC, EMC, and vinylene carbonate as a carbonate solvent at the volume ratio of 30:69:1 (hereafter referred to as carbonate electrolyte). We also created a prototype electrolyte comprising organic solvents for which enhancements of oxidative stability is anticipated.

4. Results and Discussions

4.1. The Relationship between η and Oxidation Potential

Calculation of E_{HOMO} and E_{LUMO} of organic solvents is shown in Fig. 4. Because η is calculated from E_{HOMO} and E_{LUMO} using Eq. (1), diagonal lines in Fig. 4 have the same value. The basic structure of carbonate solvent, EC and DMC, showed a tendency where the fluorinated alkyl group substitution of side chain R_1 to R_4 increased E_{HOMO} and decreased E_{LUMO} . However, there was no notable change from $\eta = 3.25$. This trend was consistent with the result of Yamaki et al.⁽²⁸⁾, where ΔE of the polar solvent was mostly

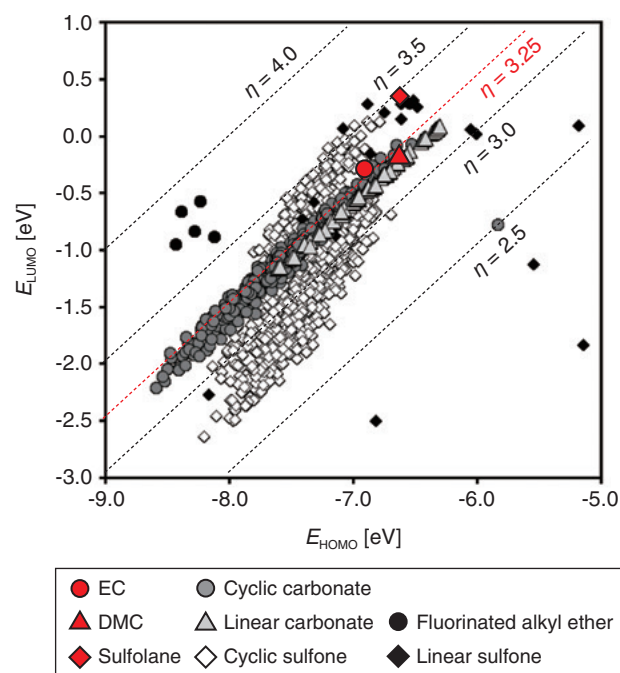


Fig. 4 HOMO and LUMO energy levels of various organic solvents

the same regardless of the type of solvent. Fluorinated alkyl ether and part of the cyclic sulfone and linear sulfone were the only basic structures where an increase of η was confirmed against carbonate solvents and their fluorinated alkyl group substitution. The molecular structure where the fluorinated alkyl group substitution of the side chain R_1 to R_8 was performed against the basic structure of cyclic sulfone, sulfolane, did not present a meaningful increase in η . In most substituted structures, η decreased.

Subsequently, among solvents that had DFT geometry optimization performed, we measured the oxidation potential with LSV in solvents that could be procured. Figure 5 shows the LSV measurement results. Oxidative current was confirmed from 4.8 V regardless of the molecular structure in the carbonate organic solvents [Fig. 5(a)]. The oxidative current of fluorinated alkyl ether (FAE1 to FAE3) was confirmed from around 5.5 V in the fluorine substitution solvents, indicating an enhancement of oxidative stability from the carbonate solvents by 0.7 V. The oxidative current of sulfolane was confirmed to be approximately 6 V in solvents that contain sulfur in the main chain [Fig. 5(c)], indicating an enhancement of oxidative stability from the carbonate solvents by 1.2 V. Figure 6 and Table 1 show the relationship between the oxidation potential and η of organic solvents estimated

from the above LSV measurement results. It indicated that the η and oxidation potential have a linear correlation. To enhance the oxidative stability of electrolytes, it would be

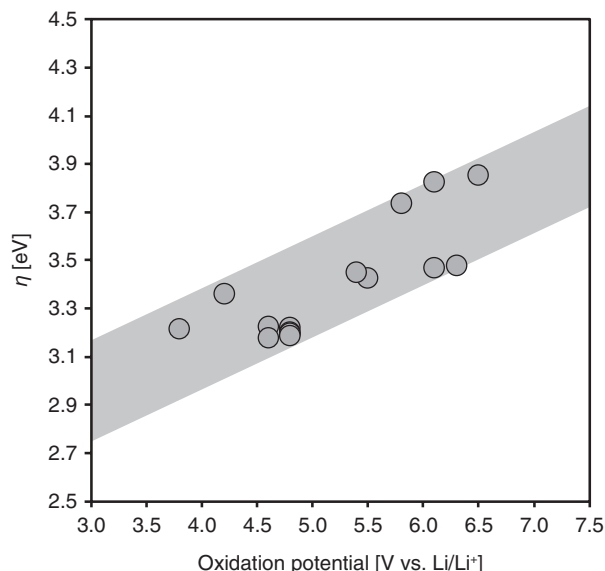


Fig. 6 Correlation between oxidation potential and η for several organic solvents

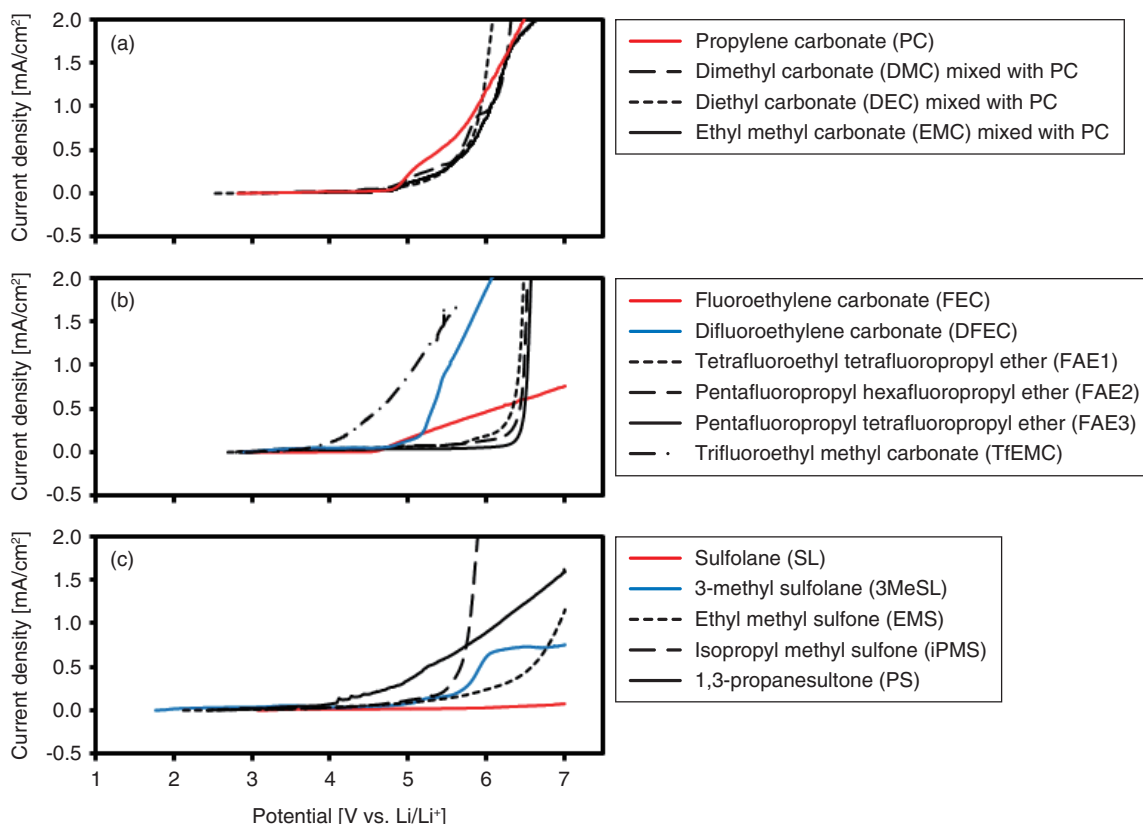


Fig. 5 LSV curves of (a) carbonate solvents, (b) fluorinate solvents, and (c) sulfonate solvents

Table 1 E_{HOMO} , E_{LUMO} , η , and oxidation potential of solvents

Solvent	E_{HOMO} [eV]	E_{LUMO} [eV]	η	Oxidation potential [V vs. Li/Li ⁺]
Propylene carbonate (PC)	-6.722	-0.279	3.222	4.8
Dimethyl carbonate (DMC)	-6.546	-0.143	3.201	4.8
Diethyl carbonate (DEC)	-6.367	0.010	3.189	4.8
Ethyl methyl carbonate (EMC)	-6.454	-0.063	3.196	4.8
Fluoroethylene carbonate (FEC)	-7.340	-0.885	3.228	4.6
Difluoroethylene carbonate (DFEC)	-7.747	-1.390	3.179	4.6
Tetrafluoroethyl tetrafluoropropyl ether (FAE1)	-8.233	-0.577	3.828	6.1
Pentafluoropropyl hexafluoropropyl ether (FAE2)	-8.426	-0.955	3.736	5.8
Pentafluoropropyl tetrafluoropropyl ether (FAE3)	-8.381	-0.672	3.855	6.5
Trifluoroethyl methyl carbonate (TFEMC)	-7.091	-0.655	3.218	3.8
Sulfolane (SL)	-6.603	0.333	3.468	6.1
3-methyl sulfolane (3MeSL)	-6.503	0.292	3.428	5.5
Ethyl methyl sulfone (EMS)	-6.750	0.210	3.480	6.3
Isopropyl methyl sulfone (iPMS)	-6.619	0.285	3.452	5.4
1,3-propanesultone (PS)	-6.867	-0.147	3.360	4.2

desirable to prepare electrolytes using solvent molecules with large η only.

4.2. Formulation of the Prototype Electrolyte and Confirmation of the Potential Window

Sulfolane (SL), a type of fluorinated alkyl ether, pentafluoropropyl tetrafluoropropyl ether (FAE3), and vinylene carbonate (VC) were mixed at the volume ratio of 30:69:1 respectively, as an organic solvent with enhanced oxidative stability. When LiPF₆ was dissolved in this mixed solvent, an insoluble component was confirmed at the concentration of 0.7 mol/L or more. Thus, we stirred and dissolved the LiPF₆ at 0.6 mol/L at room temperature as the prototype electrolyte. Given that SL and FAE3 had no known reports regarding reduction film formation on a Li metal anode, we used VC^{(29), (30)} as a general additive.

Figure 7 shows the LSV measurement result of the prototype electrolyte and cyclic voltammogram of the LNMO4 cathode. The result of oxidizing sweep showed that the oxidative current of the prototype electrolyte was confirmed from 6.0 V vs. Li/Li⁺. There was an enhancement of the oxidative stability of the carbonate solvents [Fig. 5(a)] by about 1.2 V vs. Li/Li⁺. Conversely, in the reducing sweep, there was a reducing current likely from the formation of a VC-reducing film near 1.0 V vs. Li/Li⁺ and because of Li metal precipitation at 0 V vs. Li/Li⁺. Consequently, the potential window of the prototype electrolyte was 0 V to 6.0 V vs. Li/Li⁺. Subsequently,

to confirm whether the oxidation/reduction reaction of LNMO4 can occur reversibly within the potential window of the prototype electrolyte, we performed a CV measurement. Figure 7 confirmed an oxidation peak of 4.9 V vs. Li/Li⁺, and a corresponding reduction peak of 4.5 V vs. Li/Li⁺. These oxidation and reduction peaks could be sufficiently covered by the potential window of the prototype electrolyte.

4.3. Confirmation of Enhancements of Oxidative Stability with a Cyclic Charge-discharge Test

Figure 8 shows the result of a cyclic charge-discharge test that used an LNMO4 cathode. The initial discharge capacity was 137 mAh/g for a cell that used the carbonate electrolytes (hereafter referred to as Cell_{conv}) and 134 mAh/g for a cell that used the prototype electrolyte (hereafter referred to as Cell_{proto}). These were 93% and 91% of the theoretical capacity of LNMO4 (147 mAh/g), respectively. When the number of cycles needed for the capacity to reach 80% relative to the initial discharge capacity was compared, it was found that the durability was increased to 45 cycles for the Cell_{conv} and 80 cycles for the Cell_{proto}. As for the Coulombic efficiency, it was about 99% for the Cell_{proto}, and decomposition reaction of the electrolyte was likely not to occur. However, a reduction in the Coulombic efficiency was confirmed in the Cell_{conv} after 32 cycles. After 54 cycles, the seal of the coin cell was opened, as shown in the Fig. 8, making it incapable of charging or discharging. In the LSV measurement result shown in Fig. 5(a), oxidation of the carbonate electrolytes was indicated from 4.8 V vs. Li/Li⁺, it is assumed that the gas emitted from oxidation of the carbonate electrolytes accumulated in the

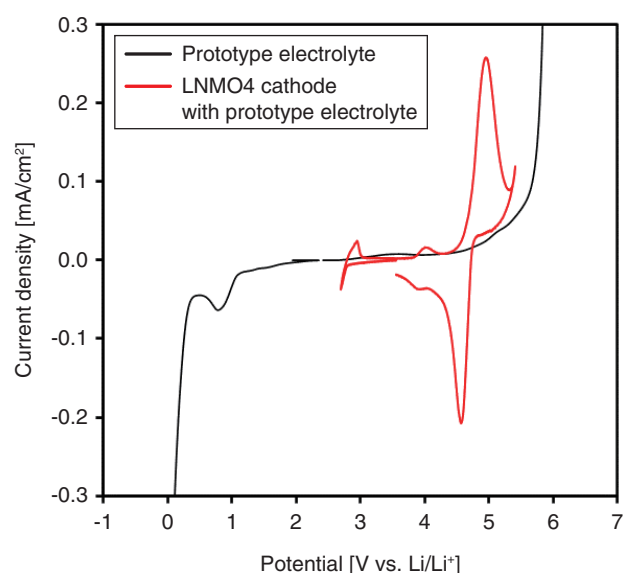


Fig. 7 LSV curve of prototype electrolyte and CV curve of LNMO4 cathode with prototype electrolyte

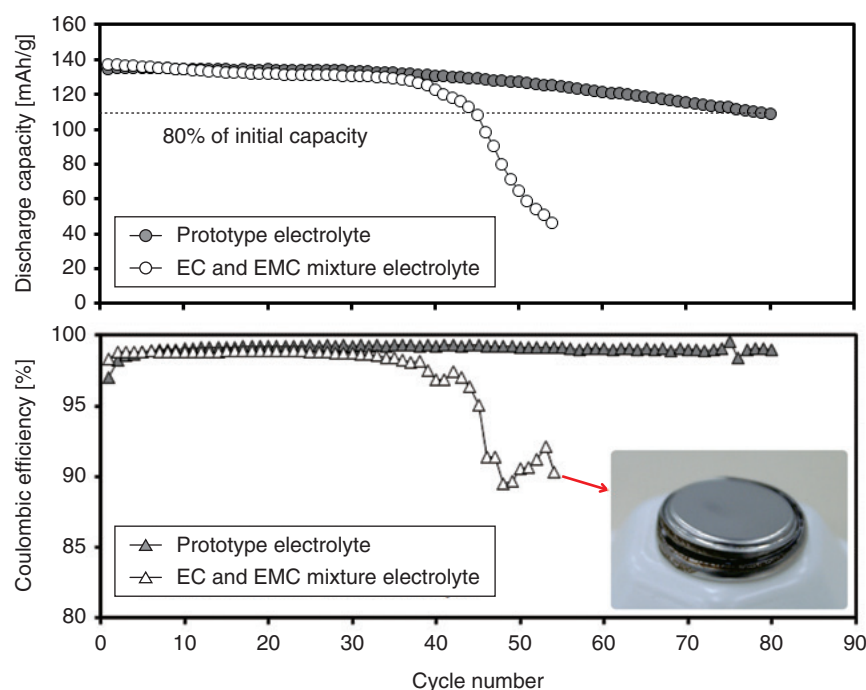


Fig. 8 Discharge capacity and coulombic efficiency vs. cycle number for LNMO4 - Li cell compared with different electrolyte composition

$\text{Cell}_{\text{conv}}$, and the increased pressure in the cell released the seal.

Consequently, enhancements in the oxidative stability of the prototype electrolyte, where the solvent was chosen by the relationship between η and the oxidation potential, were confirmed. We successfully extended the cycle life of LNMO4 by 1.7 times.

5. Conclusions

In response to high-voltage operation of lithium-ion rechargeable batteries, we examined enhancements of the oxidative stability of electrolytes. As an examination method, we applied a calculation index η that estimates the oxidation potential of organic solvents. We reached the following conclusions:

- (1) There was a linear correlation between the measured oxidation potential and η of organic solvents.
- (2) The prototype electrolyte that used sulfolane and fluorinated alkyl ether, for which an enhancement of oxidative stability has been achieved, presented the oxidative stability of 6.0 V vs. Li/Li^+ .
- (3) The use of the above prototype electrolyte extended the charge-discharge cycle life of LNMO4 by 1.7 times.

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Predictive Technique for Seat Belt Submarining Injury by Triaxial Iliac Load Cell

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ABSTRACT

Submarining is one of the confirmation items in the frontal crash test, and if signs of submarining can be grasped with a single crash test, it will contribute to increasing the development efficiency of crash safety performance. This study created a prototype of a triaxial iliac load cell for an anthropomorphic test device and devised a method for calculating the position change of the acting point of the seat belt restraint load applied to the front end of the ilium, as a sign of submarining. In frontal crash sled tests that intentionally generated submarining, the acting point of the load applied to the ilium was observed to move upward from the front end of the ilium in the time zone before submarining occurred. As a result, this enabled to detect the signs prior to the occurrence of submarining.

1. Introduction

In 1992 during a period known as the “second traffic war” in Japan, there were a total of 11,452 traffic accident fatalities, of which 4,783 were vehicle occupants⁽¹⁾. Since then, however, traffic accident fatalities have trended downward^{(2), (3)}, with a total of 3,215 traffic fatalities in 2019, of which 1,083 were vehicle occupants⁽³⁾. Especially for vehicle occupants, the rate of decline is remarkable, at 77%.

This can be attributed to various factors, such as stiffer penalties for driving under the influence of alcohol, development of traffic infrastructure, popularization of safety devices such as airbags and child seats, and body frame structures with enhanced safety performance⁽²⁾. In addition, higher seat belt usage rates due to mandatory seat belt usage^{(2), (4)} can also be considered as a contributing factor.

However, there are also scattered reports of trauma in which the seat belts that should protect occupants are considered as the source of injury⁽⁵⁾. These injuries are so-called “seat belt injuries⁽⁶⁾,” and occur mainly in the thoracoabdominal region⁽⁷⁾.

Furthermore, comparison of vehicle occupant fatality rates from 2018 traffic statistics⁽⁸⁾ by main injury site excluding factors such as overall injury, asphyxiation,

and drowning reveals that abdominal injuries have the highest fatal and serious injury rates, as shown in Fig. 1. For this reason, research and study continue related to the occurrence of abdominal injury due to load input from a seat belt, with the aim of further reducing traffic accident fatalities and injuries^{(9), (10)}.

Among the phenomena that are thought to result in seat belt injury, submarining refers to the phenomenon where the lap belt that restrains the pelvic region of the

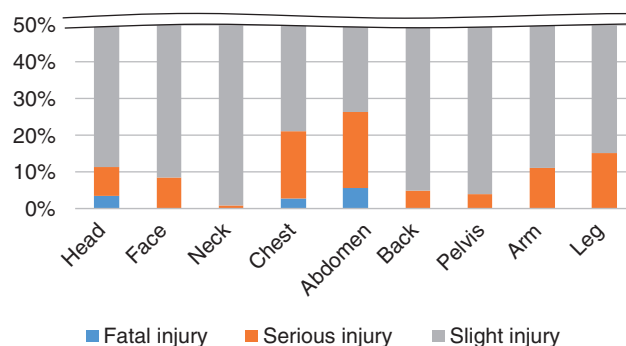


Fig. 1 Percentage of fatal, serious, and slight injuries of vehicle occupants by main injury site in Japan in 2018

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occupant moves from the intended restraint position of the recess below the anterior superior iliac spine (ASIS) to above the iliac crest, deviating from the ilium and directly compressing the occupant's abdomen, as shown in Fig. 2⁽¹¹⁾.

In the frontal crash test, an anthropomorphic test device (ATD) is used to confirm the absence of submarining. To perform this confirmation, the ATD's pelvic region has a structure that simulates the shape of the human body not only in the shape of the outer surface, but also the ilium inside. As an example of this structure, Fig. 3 shows the structure of the pelvic region of the Hybrid III 5th percentile female (H-III 5F) ATD⁽¹²⁾, which is the ATD for a small female physique. The illustration uses a finite element model made by Humanetics Innovative Solutions, Inc.⁽¹³⁾

In addition, the occurrence of submarining is detected using the time histories of iliac loads measured by the load cells built into the ATD's ilium. A total of two load cells are built into the left and right sides near the ASIS of the ilium, as shown in Fig. 3(a). During the period when the lap belt restrains the front of the ATD's ilium, a corresponding reaction force is generated as the load F_x and the moment M_y shown in Fig. 3(b). However, when submarining occurs, the lap belt no longer restrains the front of the ilium, and thus the magnitudes of F_x and M_y decrease sharply. This is used to detect the occurrence of submarining. A more detailed detection method is defined in Technical Bulletin TB-021⁽¹⁴⁾ of the Euro NCAP (European New Car Assessment Programme).

The occurrence of submarining and the instant of occurrence can be identified from these measured loads and detection method. In cases without submarining, however, it is a challenge to quantitatively detect signs preceding the occurrence, i.e., margins left before

occurrence, as physical quantities. Therefore, repeated crash tests are needed to help ensure with certainty that submarining will not occur. If a method can be devised for quantitatively detecting signs of submarining with a single crash test, it would enable increased development efficiency of crash safety performance.

Serra et al.⁽¹⁵⁾ proposed use of the value obtained by dividing the moment M_y by the load F_x (both measured by a biaxial iliac load cell) as an index for evaluating the risk of submarining occurrence. In this method, however, the calculated value is a physical quantity representing the length dimension, but there is insufficient mechanical explanation of what length it specifically indicates. Serra et al.⁽¹⁵⁾ also applied the created index to six cases of crash test results to confirm whether it matched the submarining occurrence results, but there is no indication whether there was any sign in cases with submarining. This calls for a method capable of quantitatively detecting these signs.

In the relative motion of the pelvic region and the lap belt immediately before submarining occurs, the lap belt moves to above the ASIS as described above. Accordingly, the hypothesis can be considered that the position of the acting point of the load applied by the lap belt to the pelvic region will also be observed to move to above the ASIS.

Existing ATDs are not equipped with a device that directly measures the position of this acting point, and thus a method was devised for alternatively calculating it using the iliac load cell measurements. The horizontal component F_x , vertical component F_z , and moment M_y of the lap belt restraint load received by the ASIS shown in Fig. 4 and described hereafter are needed for this calculation. However, the current iliac load cell is a biaxial load cell that measures the load F_x component and the moment M_y , as shown in Fig. 3(b), and is unable to measure the F_z component.

Therefore, this study prototyped a pair of triaxial iliac load cells that added measurement of the load F_z component to the conventional iliac load cell. In addition, frontal crash sled tests that intentionally generated

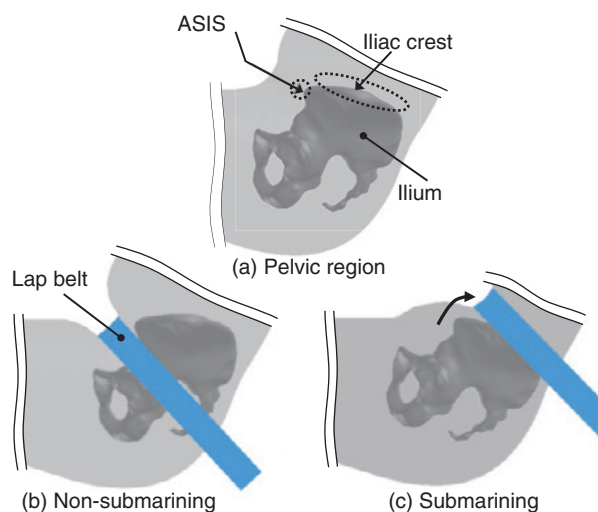


Fig. 2 Non-submarining and submarining

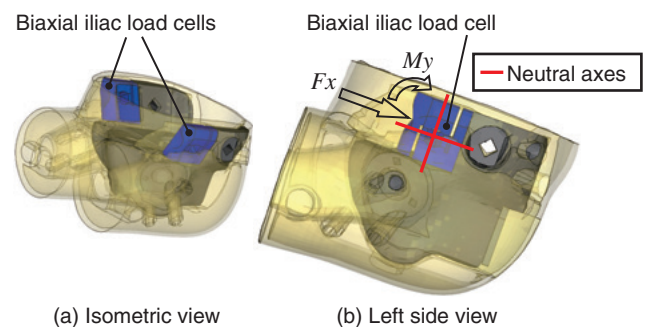


Fig. 3 Pelvis surface and pelvic bone of H-III 5F

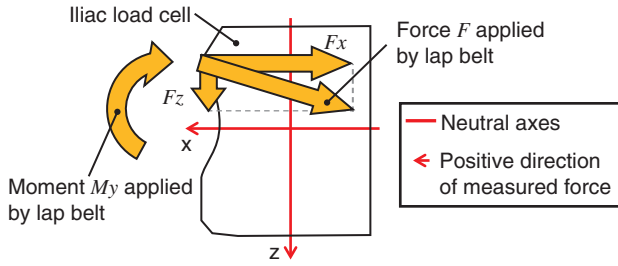


Fig. 4 Force and moment applied to iliac load cell by lap belt

submarining were conducted, the position change of the acting point of the lap belt restraint load applied to the ASIS was calculated, and it was verified whether signs of submarining could be quantitatively evaluated.

2. Principle of Measurement and Verification Method

2.1. Selection of ATD Type

This study selected the H-III 5F ATD, which simulates a small female. The reason is that it has been reported that submarining occurs more easily with the smaller 5F ATD⁽¹⁶⁾, and a smaller physique results in a lower ASIS height relative to the lap belt height, and thus submarining is thought to occur more easily.

2.2. Triaxial Iliac Load Cell

Creation of a prototype triaxial iliac load cell for the H-III 5F ATD was commissioned to Kistler Japan Co., Ltd. Figure 5 shows the front view and left side view of the triaxial iliac load cell for the right side. This load cell can be installed in place of the biaxial iliac load cell equipped as standard in the H-III 5F ATD. The red lines in the figure indicate the load measurement axes, and the

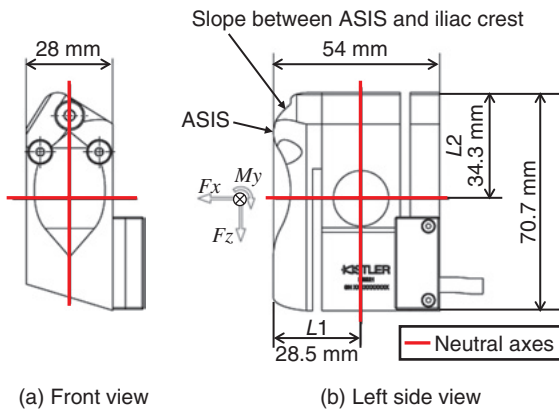


Fig. 5 Triaxial iliac load cell for right side

intersection of the red lines indicates the measurement point of load.

2.3. Principle of Calculating the Acting Point of the Lap Belt Restraint Load

Figure 6 shows a schematic drawing of the vector and the position of the acting point of the lap belt restraint load received by the triaxial iliac load cell. F_x and F_z are respectively the x -axis and z -axis components of the load measured by the load cell, and F is the total force of F_x and F_z . L_x and L_z are respectively the x -axis and z -axis components of the position of the acting point as viewed from the measurement point of load.

The premises when calculating the position of the acting point of the lap belt restraint load were that the load measured by the triaxial iliac load cell is entirely the restraining force of the lap belt, and the impact of inertial force due to motion of the load cell can be ignored. At this time, the components F_x and F_z and the moment M_y of the load measured by the triaxial iliac load cell have the relationship described by Eq. (1).

$$M_y = -L_z F_x + L_x F_z \quad (1)$$

The acting point of the lap belt restraint load is positioned on the front surface of the iliac load cell. When the acting point moves on this surface, there is little change in L_x , and thus it can be thought simply that the acting point is on the imaginary plane shown in Fig. 7. Thus, L_x is fixed to the dimension $L1$ in Fig. 5(b), and L_z , that is to say the height of the acting point of the seat belt restraint load, is obtained using Eq. (2).

$$L_z = \frac{L_x F_z - M_y}{F_x} = \frac{L1 F_z - M_y}{F_x} \quad (2)$$

The lap belt restrains the front surface of the iliac load cell, and thus the obtained acting point height L_z does not exceed the dimension $L2$ in Fig. 5(b). In addition, the lap belt restraint position is thought to move upward in cases with submarining. Therefore, it was assumed that

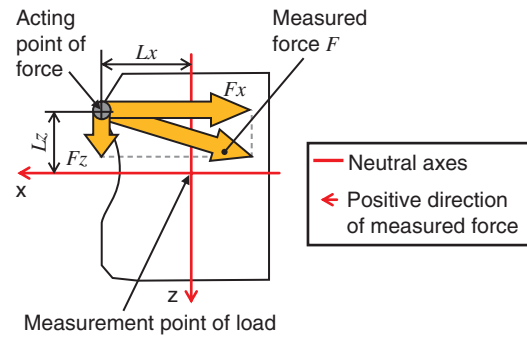


Fig. 6 Vector and acting point of measured force

submarining is more likely to occur as L_z approaches the value of L_2 . This study used this L_z as information for detecting signs of submarining.

2.4. Conditions of Frontal Crash Sled Test for Verification

Sled tests that simulate three cases of frontal crashes, including conditions that intentionally generated submarining, were conducted to verify the method for detecting signs of submarining. Figure 8 shows photos of the sled test condition before conducting the test.

All tests used the same settings that assumed an existing vehicle, and were conducted for the front

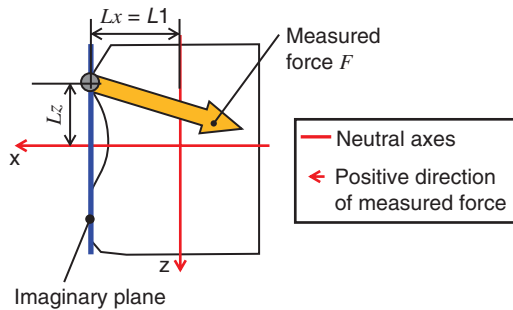


Fig. 7 Imaginary plane of acting point of load



(a) Left side (b) Right side

Fig. 8 Photos of sled test

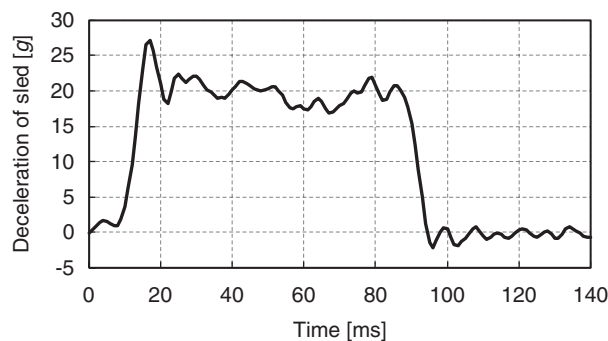


Fig. 9 Deceleration pulse of sled test

passenger seat of a right-hand drive car. An H-III 5F ATD that incorporates the prototype triaxial iliac load cells was used. Figure 9 shows a graph of the vehicle deceleration used in the tests. The initial speed was set to 50 km/h to reduce the damage to the ATD when submarining occurred. The shape of the deceleration pulse was adjusted to enable reproduction by the test apparatus, with deceleration exceeding 20 g by 15 ms, which was the initial stage of the crash, to facilitate the occurrence of submarining. Instrument panel parts that had the potential to contact the ATD's knees were removed to facilitate the occurrence of submarining. A three-point seat belt and a seat belt retractor with a pre-tensioner and a load limiter were used. A SRS (supplemental restraint system) airbag for front passenger, with the same specifications as that of the assumed vehicle, was also used.

In this study, test conditions with different lap belt anchor heights were set for the abovementioned three cases. The reason is that at a higher lap belt anchor height, the center line of the lap belt passes closer to the iliac crest, as shown in Fig. 10, and thus it is thought that submarining in which the lap belt moves to above the iliac crest occurs more easily.

Figure 11 shows the positions of the outside anchors of the lap belt with respect to the hip point (H.P.) of the ATD. An increasing lap belt outside anchor height was

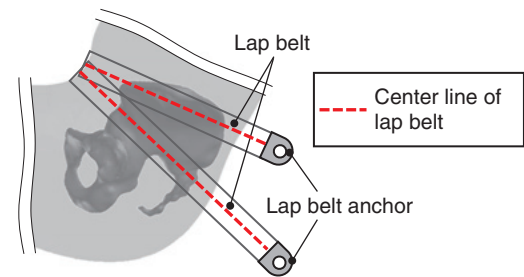


Fig. 10 Difference in lap belt position with respect to height of lap belt anchor

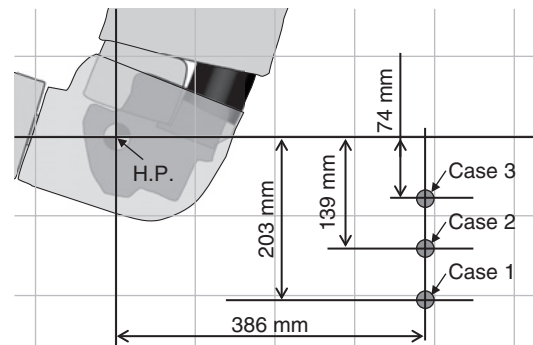


Fig. 11 Positions of lap belt anchor with respect to H.P. of ATD

set in order from Case 1 to Case 3. The intention was for submarining not to occur in Case 1, and to occur in Case 3. Case 2 used an intermediate lap belt outside anchor height with the intention of making submarining more likely to occur compared with Case 1.

2.5. Verification Procedure

In this study, the difference in conditions impacting the occurrence of submarining was the height of the lap belt anchor on the left side of the seated ATD. Therefore, verification focused on the iliac load and moment on the left side.

First, the occurrence of submarining was examined, and the time histories of the measured iliac load and moment in each of the cases were compared.

Next, the height L_z of the acting point of the lap belt restraint load was calculated using Eq. (2), and the relationship with the occurrence of submarining was investigated.

Lastly, in order to simultaneously understand the magnitude, orientation, and position of the acting point of the measured load, the vectors measured by the iliac load cell were drawn on a diagram showing the side outline of the ATD's pelvic bone, and were compared to each other.

3. Verification Results

3.1. Time History of Measured Triaxial Iliac Load and Submarining Occurrence

Figures 12 to 14 show time histories of the left iliac load (F_x , F_z) and moment (M_y) in the three sled test cases. The time history polarity is the same as the polarity drawn in Fig. 5 (b), with F_x pushing backward as negative, the F_z downward load as positive, and M_y rotating the iliac load cell backward as positive. Table 1 lists whether submarining occurred in the three sled tests cases.

Submarining occurred only in Case 3. In addition, the magnitudes of F_x , F_z , and M_y in Case 3 could be seen from Figs. 12 to 14 to decrease sharply after 52 ms.

3.2. Calculation Results of Acting Point of Lap Belt Restraint Load

Figure 15 shows the time history of the height L_z of the acting point of the lap belt restraint load calculated by the left iliac load cell.

In Case 3 with submarining, L_z was 33 mm at 52 ms, which was the timing immediately before submarining occurred. This was roughly the same value as dimension L_2 in Fig. 5(b). The value of L_z fluctuated wildly in the time zone after 52 ms, but Figs. 12 to 14 show that the iliac load in this same time zone decreased to almost zero. Therefore, L_z is considered meaningless in the time period during which the lap belt does not restrain the ilium.

Table 1 Occurrence of submarining in each test

Test No.	Occurrence of submarining
Case 1	No
Case 2	No
Case 3	Yes

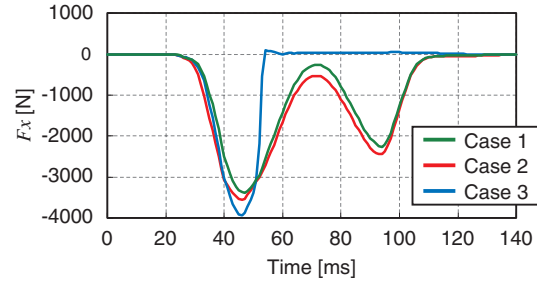


Fig. 12 Time history of longitudinal force F_x of left iliac load cell in each test

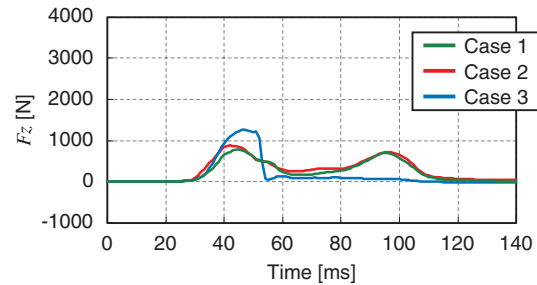


Fig. 13 Time history of vertical force F_z of left iliac load cell in each test

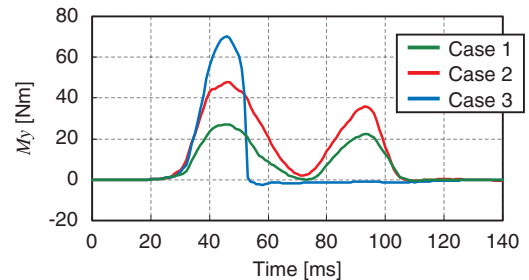


Fig. 14 Time history of moment M_y of left iliac load cell in each test

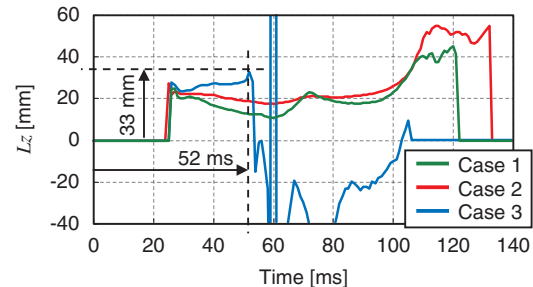


Fig. 15 Time history of height of load acting point L_z of left iliac load cell in each test

The same phenomena are observed when lap belt restraint of the occupant ends after approximately 100 ms in Cases 1 and 2 without submarining.

3.3. Results of Visualization of Lap Belt Restraint Load Vector

Figures 16 to 18 show the lap belt restraint load vectors obtained by the left iliac load cell at 40 ms, 44 ms, 48 ms, 52 ms, and 54 ms in the three sled test cases. The load vectors are drawn overlapping on the left side view of the outline of the ATD's pelvic bone.

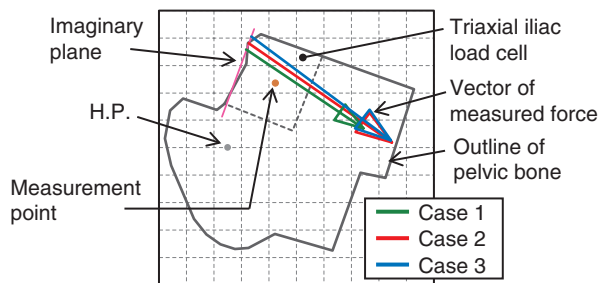


Fig. 16 Vector of restraint force acting on left iliac load cell at 40 ms

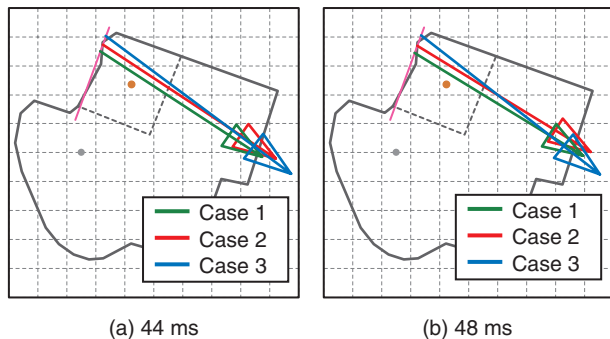


Fig. 17 Vector of restraint force acting on left iliac load cell at 44 and 48 ms

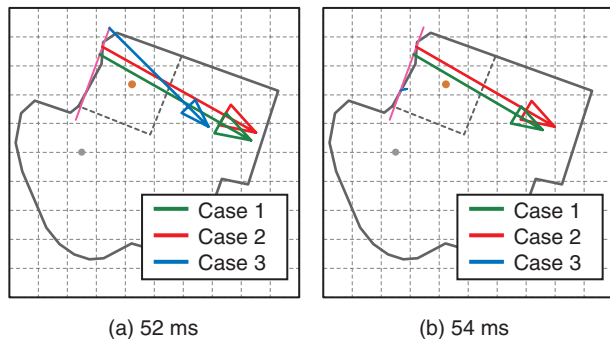


Fig. 18 Vector of restraint force acting on left iliac load cell at 52 and 54 ms

The position of the measurement point of load and the direction of the load vector were adjusted relative to the outline of the pelvic bone to reproduce the actual iliac load cell mounting position and orientation. The drawing scale was 20 mm per grid, the load vectors were drawn at 500 N per grid, and the angle of the pelvic bone outline diagram was fixed to the initial angle prior to crash.

The results for Case 3 with submarining show that the acting point of the lap belt restraint load rises as the time approaches 52 ms, which is immediately before submarining occurs, and the load vector almost disappears when 52 ms is passed. Furthermore, the restraint load vector was observed to become oriented downward during the time period from 48 to 52 ms, near the occurrence of submarining.

The results for Cases 1 and 2 without submarining show that the acting point of the lap belt restraint load did not exceed the upper end of the slope between the ASIS and the iliac crest, and remained around the recess below the ASIS.

These findings demonstrate that signs of submarining can be detected by observing the rise of the acting point of the lap belt restraint load.

4. Discussion

In Case 3 with submarining, the lap belt restraint load vector became oriented downward as described above. This looks contrary to the general thought that the direction of the restraint load of Case 3, because of its highest lap belt anchor location among the three cases as shown in Fig. 11, was expected to become closest to the horizontal line. The reason for this is considered below.

Figures 16 to 18 show that in Case 3 with submarining, the position of the acting point of the lap belt restraint load rose to near the upper end of the iliac load cell in the time period immediately before submarining occurred. Comparison of the height L_z of the acting point at this time with the shape of the load cell shown in Fig. 5 shows that the acting point was positioned on the slope between the ASIS and the iliac crest. Here, focusing on the changes in F_x and F_z from 48 to 52 ms shows there was little change in F_z , whereas F_x decreased. This infers that the restraint load in the F_x direction decreased as the lap belt slipped along the slope between the ASIS and the iliac crest in this time period resulting in the lap belt restraint load vector becoming oriented downward.

In addition to the height L_z of the acting point of the lap belt restraint load, the iliac moment M_y was also given as a candidate for a physical quantity that could be a sign of submarining. The usefulness of each when considered as a sign is examined below.

The time history shown in Fig. 14 shows that the peak value of the iliac moment M_y near 46 ms increased in order from Case 1 to Case 3, and exhibited a large

value especially for Case 3 with submarining. Therefore, it appears at first glance that M_y can be used to measure signs of submarining. In Case 3, however, the peak value of M_y was generated earlier than 52 ms, the timing at which submarining occurred, and the value of M_y at the timing when submarining occurred was close to that of Case 2 without submarining. This means that it is not easy to establish a boundary for the occurrence of submarining with respect to the time history of iliac moment M_y .

In contrast, the height L_z of the acting point of the lap belt restraint load rose to the slope between the ASIS and the iliac crest in Case 3 with submarining, as described above. From this it can be inferred that the lap belt slipped upward along this slope and then off the ilium.

Next, Figs. 16 to 18 show that L_z was positioned in the recess below the ASIS in Cases 1 and 2 without submarining. This infers that submarining did not occur because the lap belt restrained the ilium by getting caught in this recess. In Case 2, L_z is positioned near the ASIS at the upper end of this recess, and if the acting point rises further for some reason such as variance, it is expected that the lap belt will slip upward along the slope between the ASIS and the iliac crest and then off the ilium in the same manner as Case 3. Therefore, the upper limit of L_z at which submarining does not occur is expected to be around the same position as the height of the ASIS.

The above findings demonstrate that the signs of submarining before it occurs could be detected in a more quantitative manner by continuous observation of the height L_z of the acting point of the lap belt restraint load relative to the geometric shape of the ASIS to which the lap belt restraint load is applied over time. Furthermore, it is expected that the boundary for submarining occurrence in L_z can be established by way of contrasting with the ilium shape around the ASIS.

However, as only a limited number of tests were conducted in this study, setting a specific upper limit L_z at which submarining does not occur remains a future issue. Going forward, it is hoped that a number of the tests will be performed under other conditions in order to increase the reliability and repeatability of the method used in this study.

5. Conclusion

This study performed the following with the goal of developing a method for detecting the signs preceding the occurrence of submarining in an ATD.

- (1) A pair of triaxial iliac load cells was prototyped and a method was devised for calculating the height L_z of the acting point of the lap belt restraint load applied to the ASIS for use as information to detect signs of submarining.
- (2) Three cases of frontal crash sled tests were

conducted, including conditions that intentionally generated submarining, the change in L_z was compared with the ASIS shape, and various examinations were performed.

As a result, the following knowledge was obtained.

- (1) In the case with submarining, L_z rose to the slope between the ASIS and the iliac crest in the time period immediately before submarining occurred. In addition, the lap belt was inferred to have slipped off along this slope.
- (2) In the cases without submarining, L_z remained in the recess below the ASIS. In addition, it was inferred that submarining did not occur because the lap belt restrained the ilium by getting caught in this recess.

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Correction of errors

No.	Vol. No.	pdf No.	Title of the paper	Page	Corrected part	Details
1	Vol.26 No.1	26-1e_05	Development of 7-speed Dual Clutch Transmission for SPORT HYBRID i-DCD	p. 30	Fig.3 EV Drive Mode (Low)	EV Drive Mode (Low) Blue: Odd Red: Even
						EV Drive Mode (Low) Blue: Odd Red: Even

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Editorial Afterword

The day before yesterday, as I was writing this, it was exactly one year since the novel coronavirus arrived in Japan. A state of emergency has also been declared again, and the world truly seems to have entered a new normal state in which it is normal to hold academic conferences online while some other events are simply forced to cancel. As this was going on, I had the opportunity to receive an online lecture by the molecular biologist Professor Shin-Ichi Fukuoka in an event for Honda employees.

For bioorganisms to go against the universal law of entropy enhancement and survive as individuals, they use nourishment from outside themselves to foster new cells as ongoing replacements. This is the concept of dynamic equilibrium that Professor Fukuoka spoke about. Citing a professional baseball team that retains the same team name even when its players are replaced as another example, he conveyed a view of life that is dynamic beyond imagining in language that even an engineer in a different field could understand. I was truly fascinated.

What appealed to me even more so was Professor Fukuoka's way of living his life straight ahead. This quality came through in his reminiscences of a long-ago boyhood fascination with insects and his talk about "learning because you want to know" and "translating what you want to do into action." It is not just in order to continue enduring as a life-form that maintains the same external appearance that we go on ingesting and metabolizing our food day after day. That is what he told us.

We take in numerous swarms of printed text, interpreting them through our intelligence, sensitivity and understanding. On top of that, we layer our own experiences and ideas, and put them together to turn out new bits of printed text. I would like to believe that we individual engineers and researchers bring together such dynamically equilibrated activity to overlap and accumulate, and in doing so, we as people grow and evolve together with our knowledge and understanding. And this is so even under the coronavirus crisis.

I want to take this occasion to express my gratitude to everyone who submitted their contributions to this issue, and to everyone who put their efforts into editing and publishing it. It is my hope that all the bits of printed text in this journal will serve as nourishment for our readers, as well.

Sei WATANABE

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