1. Test technologies that support the competitiveness of electric vehicles

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1. Introduction

The role of the Test Department in Nissan Motor Company's R&D division is to set performance targets for vehicles and systems that meet customer expectations and market requirements worldwide. It involves evaluating the achievement of performance targets through physical assessment after the design and prototyping phase. The engineers in the Test Department determine the type of tests necessary to fulfill this role. They are responsible for introducing the required equipment and measuring instruments for conducting tests, as well as developing evaluation and measurement technologies.

In this feature, we will introduce Nissan Motor Company's test technology, particularly the test technologies contributing to the electrification of vehicles as one of the responses to the current issue of global warming.

Fig 1 represents a simplified and conceptualized depiction of the automotive development process. It illustrates the vehicle hierarchy from the top (vehicle level) to the bottom (parts level). The development of a new car starts from the top-left and progresses towards the top-right, development completion and start of sales.

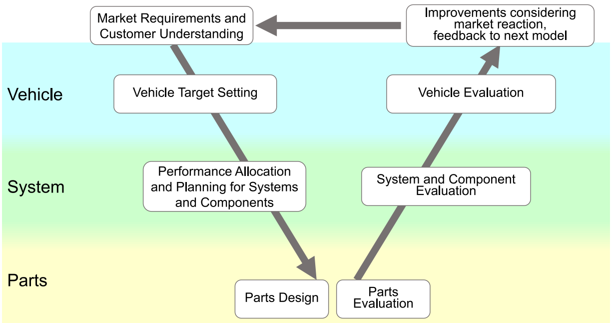

Fig. 1 Schematic of the development process of automobiles (V-process)

The role of the Test Department starts from the upper left section of the V-Model, from "Market Requirements and Customer Understanding" to "Vehicle Target Setting". Depending on the performance domain, the Test Department may also be involved in activities such as "Performance Allocation and Planning for Systems and Components". Afterward, the responsibilities shift to the design department and parts suppliers for "Parts Design" and "Parts Evaluation", followed by the Test Department's involvement in "System and Component Evaluation" and "Vehicle Evaluation" once again.

2. Various test technologies

2.1 Test technologies to understand market requirements and customers

To establish performance targets, it is necessary to understand how customers worldwide use and drive their cars, their expectations at that time, and the usage environment. Each country or region may have unique usage patterns, and customer expectations vary from person to person. The usage environment encompasses not only road conditions and traffic environments but also various climate conditions such as temperature, humidity, solar radiation, as well as altitude (air density), radio wave environment, and more, which form a vast combination.

To set targets for individual performance, components, and systems among these infinite combinations, it is essential to create a market model and extract scenes that represent the real world. Market research is a classic method used to understand real-world market requirements. This involves observing and interviewing customers, measuring data related to vehicles and the surrounding environment, analyzing the collected data. It requires specific technical expertise and know-how. In recent years, the analysis of big data using statistical methods has also become possible, enabling the understanding of market requirements through the collection and analysis of large amounts of data. These technologies are also essential test technologies.

2.2 Vehicle test technologies

To establish performance targets through vehicle-based tests and evaluate the achievement of vehicle performance, it is necessary to compare and evaluate the

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current models and competing vehicles, measuring surrogate characteristics that indicate the quality of each performance aspect. While it is sometimes evaluated through comparative test drives on public roads, ensuring reproducibility in real-world conditions is challenging due to the uncontrollable traffic environment. Therefore, closed test courses called "Proving Grounds (PG)" are constructed to run the vehicles. When establishing an in-house PG, the Test Department's engineers are involved in considering and planning the concept of the PG, working collaboratively with specialized design and construction companies to create the PG. This is an integral part of the responsibilities of the Test Department's engineers.

To efficiently and effectively evaluate and measure various performance aspects, it is necessary to design courses that encompass a wide range of combinations of flatness, elevation, and road surfaces. Often, real-world roads and surfaces are replicated. These may include famous roads with poor ride quality, roads that challenge road noise and “squeak & rattles”, and roads that allow assessment of handling performance, among others. Determining which types of roads should be replicated in the Proving Ground (PG) is also part of test expertise.

For example, Nissan Motor Hokkaido Rikubetsu Proving Ground in Japan is designed to replicate German autobahns and country roads. During winter, it becomes the coldest test facility in Japan, where surfaces such as compacted snow and ice are reproduced for test purposes.

Fig. 2 PG of Nissan’s Rikubetsu Proving Ground (Hokkaido)

2.3 Bench test technologies of systems/ components

By testing in PG, we can freely control and replicate the driving conditions. However, it is not so straightforward when it comes to climate and weather conditions. Furthermore, it is difficult to isolate and accurately measure various phenomena occurring in a moving vehicle and analyze them in detail. Therefore, it is necessary to establish bench test technologies that replace or supplement on-road tests, tailored to the performance, functionality, and system being evaluated. On the left side of the V-process, the phenomenon mechanisms are analyzed for each performance, and performance allocation to each component is conducted. On the right side of the V-process, evaluation and achievement confirmation are carried out for the system and performance. An important aspect here is determining what and to what extent should be replicated, depending on the objective, which showcases the skill of the bench test engineers.

For example, to evaluate the durability of the vehicle body and chassis, a road simulator is used to replicate inputs from road surfaces during driving and inputs from driving and braking forces. It reproduces forces acting on the four wheels in the front, rear, left, right, up, and down directions, as well as rotational moments around the X, Y, and Z axes. Rather than replicating the input waveforms exactly as they occur during actual driving, the waveforms are manipulated to accelerate the tests, allowing for durability evaluations in a shorter time frame. The fatigue damage is reproduced to be equivalent to the market model. However, the replication of temperature and lighting conditions is excluded since the evaluation mainly targets the fatigue strength of structures made of metallic materials.

Fig. 3 Photograph of the road simulator (as an example of bench test equipment)

In addition to on-road tests using actual vehicles or bench tests using the entire vehicle body, it is possible to extract specific components or systems and subject them to loads equivalent to those experienced in actual vehicles. This enables the elucidation of phenomena mechanisms that are difficult to observe and measure in vehicle conditions. Moreover, due to the smaller scale of tests, it becomes easier to compare and evaluate a larger number of specifications and increase the sample size for assessing variations. When constructing such bench tests for system-level evaluations, it is essential to determine how to replicate the vehicle conditions.

By breaking down the performance requirements from the vehicle level to the system level and further to the parts level, it becomes possible to align vehicle performance targets with the required specifications of parts. In the confirmation stage of target achievement, the evaluation is conducted in the following order: first, evaluating whether individual parts meet the specifications (usually done by parts suppliers), then system-level evaluation, and finally, vehicle-level evaluation. This allows for easy identification of causes and implementation of countermeasures in case the target is not achieved, ensuring the progress of development reliably.

2.4 Test technologies for the digital phase

In the V-process diagram described above, it is depicted that progress should proceed smoothly along the V-shape without any backtracking. However, in actual development, if the evaluation results on the right side of the V-shape do not achieve the intended targets, iterations and backtracking occur. This means going through a feedback cycle of design -> prototype -> evaluation -> redesign -> prototype iteration -> evaluation iteration, which requires a corresponding amount of time and cost. Consequently, there is a need to perform preliminary assessments of the achievement level before creating actual physical prototypes. The phase before arranging the formal prototype vehicles is referred to as the digital phase, while the phase after the arrangement is called the physical phase. It is important during the digital phase to determine how to assess the performance achievement level of the prototype vehicles, as this helps reduce the need for design, prototyping, and evaluation iterations during the physical phase. So, how do we evaluate the performance when we don't have actual physical prototypes? This can be done by utilizing computer simulations or creating mock-ups that replicate certain parts of the vehicle. The technical challenge in the digital phase lies in deciding what and how to replicate based on the performance or system being evaluated.

For instance, a traditional method for evaluating aerodynamic performance involves creating clay models that accurately replicate the vehicle's shape, allowing convenient shape modifications and trial and error evaluations. In recent years, there has been a trend towards faithfully reproducing structures within the engine compartment and under floor. However, these models only replicate the shape and do not have functioning engines or the ability to drive. The decision on what and to what extent to replicate is made by the test engineer.

Lately, there has been an increase in partial prototyping using 3D printers. This is particularly useful for pre-evaluating components with new structures or features that lack prior performance records. Although these prototypes may have lower strength, durability, or different surface finishes compared to actual parts, they provide the advantage of being physically evaluated for usability and other factors. Furthermore, there is a growing trend of combining virtual evaluation environments and test pieces created through computer simulations with realistic mock-ups or advanced prototypes.

Fig 4 illustrates an example of Hardware in the Loop Simulation (HILS) previously introduced in Nissan Technical Bulletin (No. 71, 2012). In this example, the entire brake hydraulic circuit, from the brake master cylinder to the VDC unit (ECU and actuator integrated), brake tubes/hoses, and brake unit, is reproduced in the real domain (actual device), while the remaining vehicle model is reproduced virtually (CAE) and combined.

Determining what to replicate virtually and what to replicate in the real domain and how to combine them for evaluation is a crucial consideration.

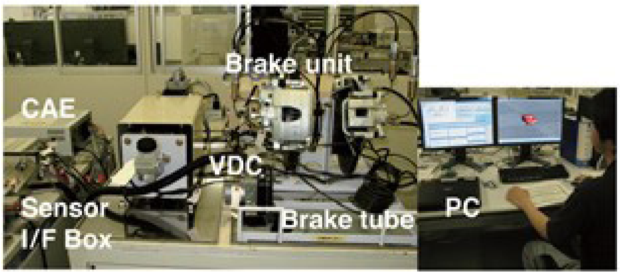

Fig. 4 VDC HILS (Source: NISSAN TECHNICAL REVIEW No. 71)

2.5 Measuring technologies

In discussing test technologies, another important element is measurement technology. To objectively and quantitatively capture vehicle performance, measurement is essential. Whether it is to reproduce and maintain the PG road surface, replicate the market environment on test benches, or recreate prototype vehicles based on design data, accurate measurement is necessary. To understand the mechanisms of phenomena and measure what needs to be known, the development of new measurement technologies is required. Additionally, in order to ensure the accuracy of test results, measurement accuracy assurance technology is crucial. This includes the establishment, implementation, and maintenance of facilities such as the Measurement Standard Center and the calibration equipment used within it. These responsibilities are also undertaken by engineers in the test department.

3. New Test Technologies Contributing to Electric Vehicle Development

In recent years, electric vehicle development has been progressing as a response to environmental issues such as global warming.

When it comes to developing new vehicles using matured technological areas, development can proceed relatively smoothly along the V-process using standardized know-how. However, when adopting new technologies, it is necessary to perform hypothesis verification through testing during the target setting and performance planning phases on the left side of the V-process. This allows for maximizing the value of the new technology and assessing the feasibility of its performance at an early stage to minimize backtrackings. This enables the development of high-value and competitive products for customers.

The first and most significant change in vehicle electrification is the replacement of the power source from an Internal Combustion Engine (ICE) to an electric motor. Electric motors generally offer superior responsiveness and finer control compared to ICE, thereby enhancing vehicle performance.

In Battery Electric Vehicles (BEVs), the vehicle is powered by rotating the driving motor using the stored electrical energy in the battery.

In Nissan's unique electric technology, e-POWER, a dedicated ICE drives the power generation motor to generate electricity, which in turn rotates the driving motor to move the vehicle.

Both in BEVs and e-POWER, the range of performance control through electronic control is expanded, providing greater flexibility. With increased flexibility, there is a need to test with a greater variety of specifications in order to find optimal solutions. Attempting to accomplish this solely through physical tests using prototype vehicles would require significant time, effort, and cost for vehicle prototyping, modification (specification changes), and test evaluations. Therefore, applying virtual test technologies, as mentioned earlier, becomes essential.

The following chapters will introduce driving simulator test technologies and e-POWER powertrain bench test technologies, which have been developed against this backdrop.

Fig. 5 Driving simulator

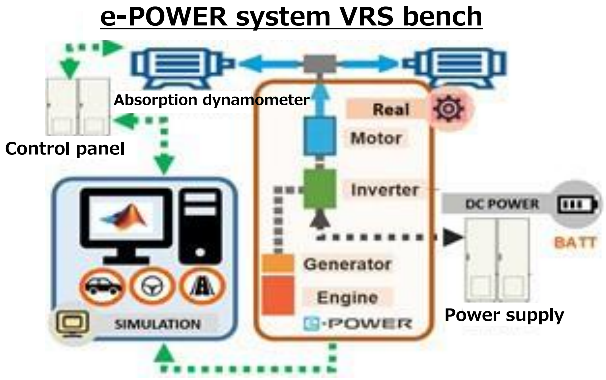

Fig. 6 e-POWER powertrain bench test technology

Compared to Internal Combustion Engine (ICE) vehicles, customers place a higher emphasis on the driving range when it comes to Battery Electric Vehicles (BEVs). The driving range of a BEV is determined by battery capacity and energy efficiency. Among the factors affecting energy efficiency, aerodynamic resistance has the most significant impact. As a means of reducing aerodynamic resistance, the adoption of electrically retractable door handles is becoming more prevalent. Even with the movement of such electric components, setting appropriate targets allows us to provide customers with emotional values such as a sense of luxury and advancement. In this regard, utilizing virtual technology is more efficient and effective than repeating trial and error with various prototype specifications. This is exemplified in Chapter 4, which introduces virtual reality test technologies.

With electrification, new challenges arise regarding heat balance. BEVs have high efficiency as they lack the waste heat energy generated by ICE, but this also means that interior heating utilizing waste heat is no longer possible. Furthermore, cooling is required during high-load driving and quick charging to maintain the battery and motor at optimal temperatures, and this cooling system is shared with the interior air conditioning system. Achieving an efficient thermal management system necessitates a vast number of test evaluations based on different combinations of driving, charging scenarios, and ambient temperatures, given the increasing complexity of the system.

To address this, Chapter 5 presents the thermal management system test technologies that have been developed.

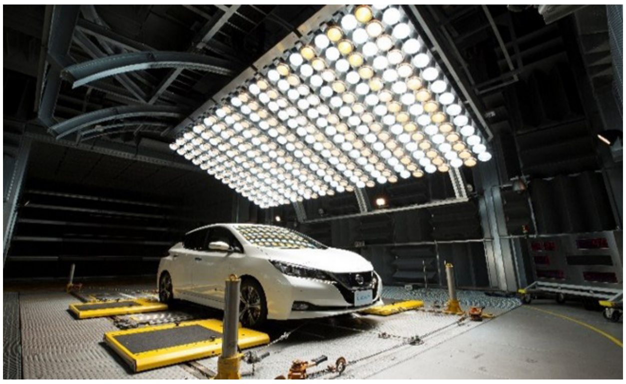

Fig. 7 Heat management system test

The last technology to be introduced is X-ray CT non-destructive measurement technology. The demand for non-destructive measurement is increasing in areas such as the development of electric vehicle-specific components and systems like batteries and motors, as well as the adoption of new materials and methods for vehicle lightweighting. By having this technology in-house, Nissan is able to respond quickly to these needs.

What all these technologies have in common is that they are not simply purchasing off-the-shelf products and using them as is. Instead, they are developed internally. Of course, in addition to in-house development, there are also cases where commercially available products are purchased or equipment and measurement instrument manufacturers are contracted to create specific items. However, it is the engineers in the test department who are responsible for determining what type of equipment to introduce, what specifications of measurement instruments are needed, and how to combine and operate them. As the individuals conducting vehicle evaluations, they have the ability to discern what is necessary.

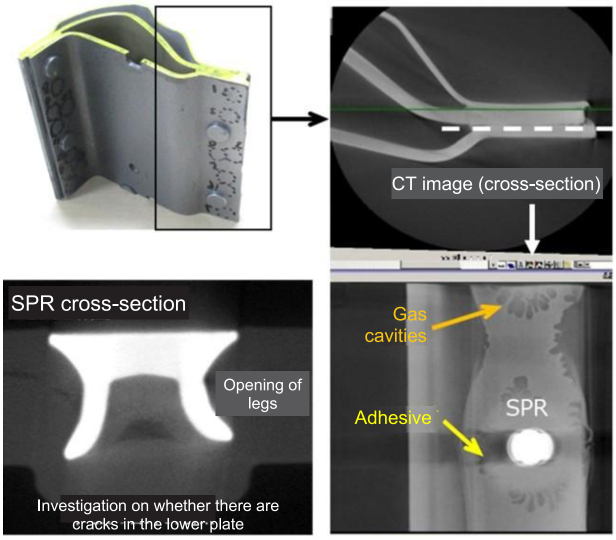

Fig. 8 Example of an X-ray CT

4. Summary

No matter how innovative a technology may be, without proper performance target setting and analysis of phenomena mechanisms backed by testing, it cannot be leveraged to create new value.

Through new test technologies, performance can be improved, development efficiency can be enhanced, and development timelines can be shortened, enabling the delivery of attractive new vehicles to customers.

Unlike technologies incorporated into vehicles, test technologies themselves are not directly delivered to customers. However, the performance and quality generated by test technologies deliver value to customers. Furthermore, while technologies incorporated into vehicles can be relatively easily known to competing companies through reverse engineering, it is difficult to obtain knowledge of test technology know-how from the outside.

Nissan will continue to refine its unique test technologies and contribute to the creation of highly competitive and appealing vehicles.

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2. Driving Simulator Test Technologies for Establishing Unique Performances of Electric Vehicles

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1. Introduction

Considering the increasing electrification of vehicles, a novel driving experience can be induced by finely controlling the highly responsive driving force. The flexibility of compliance can also be enhanced by increasing the number of control parameters and range of adjustment, which requires considerable effort and a longer compliance period when using an actual vehicle.

Nissan Motors started the full-scale implementation of a driving simulator (DS, see Fig. 1) in 2019 and has since then employed it to test the safety of ProPILOT 2.0 (in the overriding mode) and the steering performance depending on the tire characteristics and vehicle specifications (e.g., height of the center of gravity and weight distribution). DS can evaluate the driving operation of general as well as highly skilled drivers, and therefore, it has recently been used to set new targets for driving experiences and complying with achievement levels based on the way people feel.

To this end, reproducing the driving feeling more accurately is essential, and therefore, the DS motion system is being improved, and cueing control and other technologies are being developed to pursue more accurate reproductions. The details of the development of the DS technology and examples of applications that utilize its results are presented in this article.

Fig. 1 View of DS

2. New DS technology development

2.1 Motion system improvements

Nissan Motors' DS includes long and short parallel rails, a hexapod, and a turntable to simulate real-time vehicle motion with one-to-one correspondence with a real vehicle (Fig. 2).

The Y-parallel rails can generate a maximum acceleration of 12 m/s^2 with an effective stroke of only ± 11 m before they are upgraded to ensure a safe stop at the maximum acceleration. However, in some cases, the DS system halted suddenly because of a shortage of effective strokes when performing various evaluations, such as acceleration sensation and control by electrification. In these cases, the feeling of acceleration was reduced by decreasing the gain in motion cueing or reducing the sensory time by using a filter. Some evaluation drivers commented that they felt a delay in motion in the DS evaluation compared to when using an actual vehicle, which implies that the system did not provide sufficient performance.

As a measure of improvement, the control method of the Y-parallel rails was revised to increase the effective stroke from ± 11 m to ± 14 m, which extends the effective distance by 6 m; further, the servo characteristics were changed to improve the response of the XY-parallel unit, hexapod, and turn table. These revisions improve the response by up to 344% compared with the conventional time constant for the Y-parallel rails.

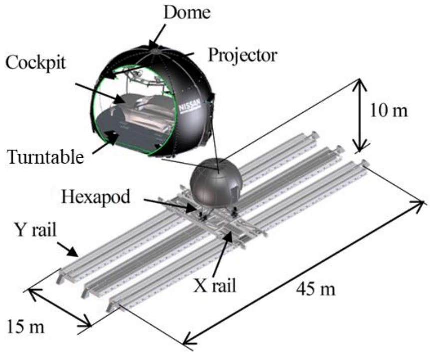

Fig. 2 DS system configuration

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The pure delay, time constant, and frequency characteristics of each step response are measured following the change in motion system control. The configuration of the DS control system is illustrated in Fig. 3. Signals are transmitted to the motion system within 1 ms using a real-time simulator. The characteristics are measured after the signals are sent from the PC in the real-time simulator until the acceleration is transmitted to the cockpit floor in the hexapod.

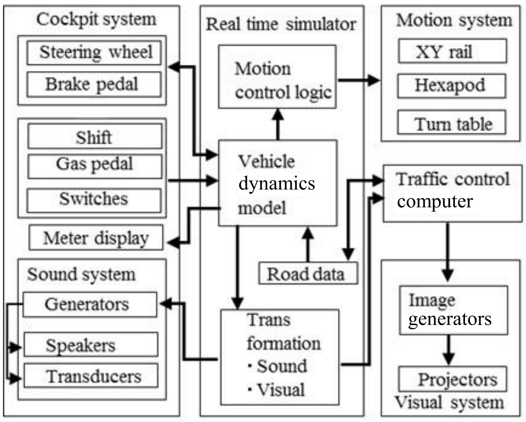


Fig. 3 Control system configuration

The pure delay from the start of the motion system until it is transmitted to the cockpit floor is listed in Table 1. The largest pure delay is for the turntable, which is a delay of 22 ms more than that for the parallel rails. Each transmission characteristic at 0.3 Hz is listed in Table 2. The transmission characteristics of the hexapods are worse than those of the others because the dome is structurally supported by six cylinders, which makes the inertial load less advantageous. These results, which indicate that only roll and pitch are delayed when signals are input simultaneously, suggest that parameters to match the area to be evaluated on the motion system cueing side must be set.

Table 1: Pure delay

		Pure delay [ms]
Rail	X	33
	Y	33
Hexapod	Z	37
	Roll	45
	Pitch	48
Turntable	Yaw	55

Table 2 Transmission characteristics

0.3 Hz		Gain [db]	Phase [deg]
Rail	X	-0.1	-4.1
	Y	0.2	-4.5
Hexapod	Z	0.1	-4.5
	Roll	0.3	-12.5
	Pitch	0.7	-12.9
Turntable	Yaw	-0.1	-3

2.2 Motion cueing development

Significant discomfort can be caused by a small change in the DS when driving experience is prioritized. Motion cueing is developed using the measured results of the transmission characteristics of the system to improve the sensory motion experienced by people. Developments in two aspects—the acceleration characteristics in the fine steering range and the roll motion of the upper structure—observed in the comments of evaluation drivers are discussed below.

The response in the DS vehicle motion simulation may be better than when driving an actual vehicle because of the absence of vehicle stiffness or mechanical delay caused by backlash, which can lead to discomfort in some cases. In an actual vehicle, the steering angle is derived from the operating force of the steering wheel based on the action and reaction forces. However, in the DS, the steering angle is used for the simulation instead of the operating force. The response delay is expected to be small because the steering angle is forcibly generated regardless of the balance of forces. Although a solution can be provided by an analysis that simulates the relationship between the steering force and steering angle, it is difficult to calculate it in real time with the current technology. Thus, a pseudo-rising delay is added to motion cueing to improve sensory motion. An example of such a control is presented in Fig. 4. The rise is moderately delayed with respect to the input, and the output is constant when the change is constant. Given this approach, control is changed for each signal sent to each of the devices and complied with such that the timing of the acceleration felt by people is consistent.

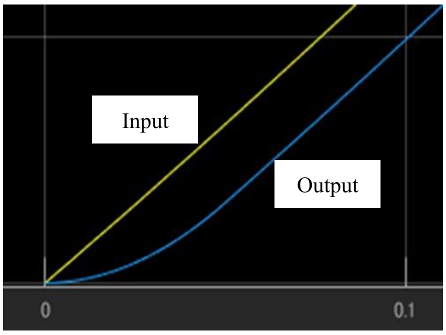


Fig. 4 Signal control

The center of rotation of the vehicle and that of the yaw are different in this system because the seat position of the driver is centered between the hexapod and yaw table in the DS (Fig. 5). Thus, the coordinates of the feeling of acceleration are transformed by the amount based on the difference between the positions of the center of rotation and center of gravity of the vehicle. DSs, which are referred to as racing simulators, often have a system where the seat of the driver is tilted or the center of rotation is set near the abdominal area. In this DS, the roll and pitch are controlled with the rotation center positioned near the abdomen of the driver.

However, the feeling is different from the actual sensation for motion of the upper structure because this method makes it difficult to feel the diagonal roll pitch sensation and vertical motion. Thus, the upper structure is designed to move along the roll axis for comparison. The center of rotation of the hexapod is transformed using a three-dimensional rotation matrix.

$$Roll' = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos(Roll) & -\sin(Roll) \\ 0 & \sin(Roll) & \cos(Roll) \end{pmatrix}$$

$$Pitch' = \begin{pmatrix} \cos(Pitch) & 0 & \sin(Pitch) \\ 0 & 1 & 0 \\ -\sin(Pitch) & 0 & \cos(Pitch) \end{pmatrix}$$

$$Yaw\_hex = \begin{pmatrix} \cos 0 & -\sin 0 & 0 \\ \sin 0 & \cos 0 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$Yaw\_Tbl = \begin{pmatrix} \cos(Yaw) & -\sin(Yaw) & 0 \\ \sin(Yaw) & \cos(Yaw) & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$S = \begin{pmatrix} X \\ Y \\ Z \end{pmatrix}$$

S: Seat position and rotation center vector

$$A = S \times Yaw\_Tbl$$

$$Ar = Roll' \times Pitch' \times Yaw\_Hex$$

$$S' = \begin{pmatrix} Surge \\ Sway \\ Heave \end{pmatrix} = A - Ar$$

S': Correction amount for the center of rotation for the hexapod

The center of rotation is changed based on the above to conduct a comparative evaluation. Some evaluators commented that they could feel the roll better than before, but not to the level of being able to fully reproduce the diagonal motion. This can be attributed to the motion in the pitch direction. The center of rotation of the pitch is expected to change dynamically depending on the situation; however, there is room for improvement in this regard.

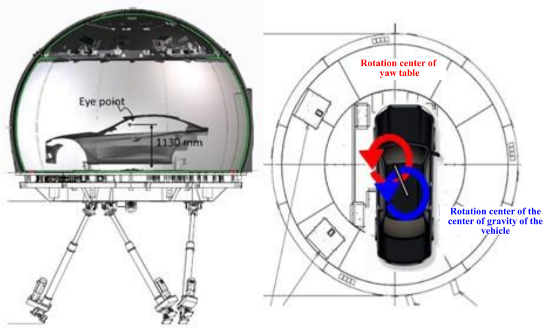


Fig. 5 Driver seating position

2.3 Evaluation results of the effectiveness of new DS technology development

The motion system improvements and developed motion cueing discussed in this chapter are incorporated and evaluated in comparison with previous specifications. This evaluation is performed by setting up the items necessary for vehicle motion evaluation and assigning a score on a scale of one to five to evaluate the drivers. A score of three is the minimum level at which an evaluation can be made in the DS.

Fig. 6 presents the evaluation results, which demonstrate that the overall evaluation is improved because of the DS technology developed in this study, which enabled the system to reproduce motions that are more consistent with those of an actual vehicle. By developing technologies to utilize DS, the evaluation area will be further expanded to include driving environments with disturbances such as uneven road surfaces and crosswinds, as well as special conditions such as snowy roads and race circuits.

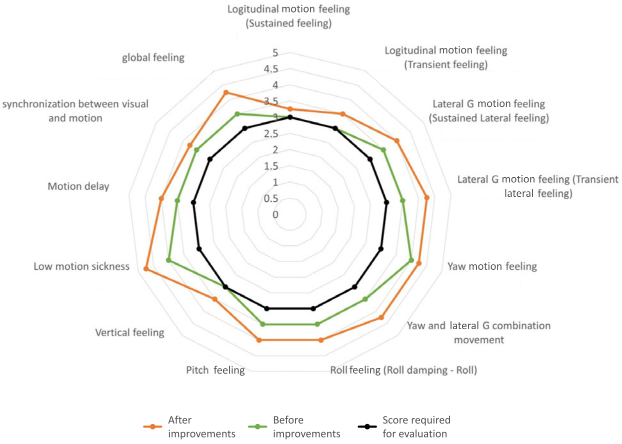


Fig. 6 DS evaluation results

3. Examples of development applications

3.1 Reproduction of growing acceleration feeling of AURA NISMO

AURA NISMO fine-tunes the sensation of acceleration. The driving force changes in response to the accelerator operation to provide the expected NISMO acceleration feeling. Currently, control parameters comply with each model in the development of NISMO, and the number of test patterns to evaluate various modes has increased in recent years. This has made it difficult to comprehensively find an optimal solution. Therefore, the DS is employed to achieve the feeling of acceleration emphasized by AURA NISMO by focusing on the human senses and analyzing each element of the feeling of acceleration.

Parameter studies were performed on the driving force and feeling of acceleration in response to the accelerator stroke with respect to three elements, “height,” “response,” and “growth” (Fig. 7), of the front and rear G in the DS. The actual vehicle evaluation using these results indicates that the feeling of acceleration was improved, which demonstrates that a parameter study evaluation with the DS is also possible. The "growth" of each element is explained in this section.

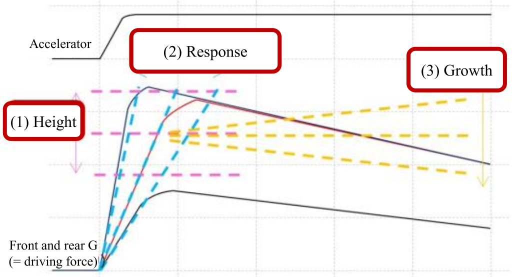


Fig. 7 Elements of acceleration

The decrease in acceleration after peak acceleration in relation to the accelerator opening was investigated to create a feeling of acceleration growth (Fig. 8). The smaller the drop in acceleration after the peak acceleration, the stronger the feeling of acceleration with more growth. However, peak acceleration was difficult to maintain because of the upper limit on the output.

We attempted to reproduce the feeling of acceleration growth by controlling the drop in acceleration. The Y-parallel rails of the DS were used in the test to evaluate front/rear acceleration, which enabled an approximately 3-second evaluation for an acceleration of 0.3 G. The change could be sufficiently felt, although the evaluation was only conducted for a brief time because the actual setup also included a deceleration section. As presented in Fig. 8, the acceleration dropped after the peak acceleration was varied to score the performance in the test. The scores for different drops in acceleration varied at speeds near the start and at medium speed. Acceleration with a feeling of growth could be felt at an acceleration reduction rate of 0.04 G/s or lower for low speeds and at 0.025 G/s or lower for a medium speed range (Fig. 9).

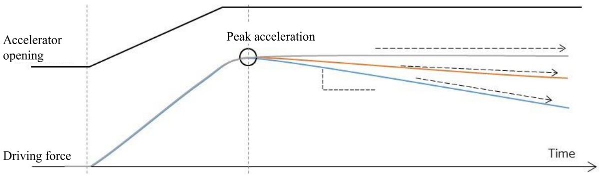


Fig. 8 Method of evaluating feeling of growth

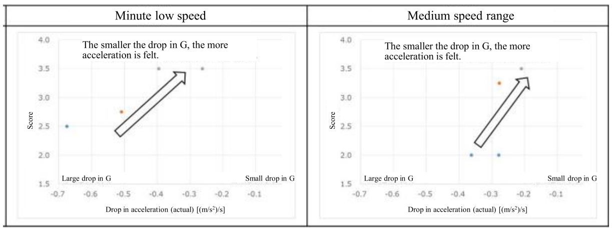


Fig. 9 Sensory evaluation results

AURA NISMO was specially tuned based on these results to provide the "NISMO" mode, which allows drivers to enjoy the feeling of powerful acceleration with growth that is unique to NISMO.

Approximately 130 specifications were evaluated in the three-day test using the DS. This is equivalent to a six-week test for an actual vehicle. The results indicate that analyzing the data in a short time would have been impossible without using the DS, which can perform stable evaluations.

Fig. 10 AURA NISMO

3.2 e-4ORCE acceleration and deceleration control development (1)

The design methodology includes the passenger sensation required for Nissan's automobile development in addition to quantitative performance evaluation. Many laboratories have reported on the prediction of vehicle and system behavior using CAE simulation; however, reports on performance prediction and design that include human subjective evaluation remain limited. The prediction of human senses is required for subjective human evaluations, which leaves a large part of its modeling unknown. Although performance design can be evaluated based on past data and experience, completely new behavior and performance can only be evaluated by testing an actual vehicle. However, building a large number of prototype vehicles is difficult.

Human subjective evaluation is added to predict not only the design and performance in CAE simulations, but also the sensory experience of passengers, which is difficult to include in the development of e-4ORCE control. Comprehensive tests, which include sensory tests, were efficiently developed using a DS without prototype vehicles. A performance design methodology incorporating subjective human evaluation and the influence of passengers is presented.

The performance design methodology using a DS, human body simulation, and vehicle motion simulation is presented in Fig. 11. Using the DS, the vehicle state quantities that can be changed by this new electric AWD were studied to perform a subjective sensitivity analysis for each state quantity. The parameters that most affect human senses were determined based on subjective sensitivity analysis results for clarifying the mechanism and incorporating them into quantitative index values using a human body simulation. The control logic and vehicle parameters for achieving the performance targets were examined using a vehicle simulation based on the incorporated target quantitative values. The validation prior to an actual vehicle test was conducted on a driving simulator using the final vehicle specifications and control logic, followed by a final checking process in an actual vehicle test.

The prediction of performance, which includes subjective human evaluation, is made possible by following the above procedure, which enables efficient development in actual vehicles.

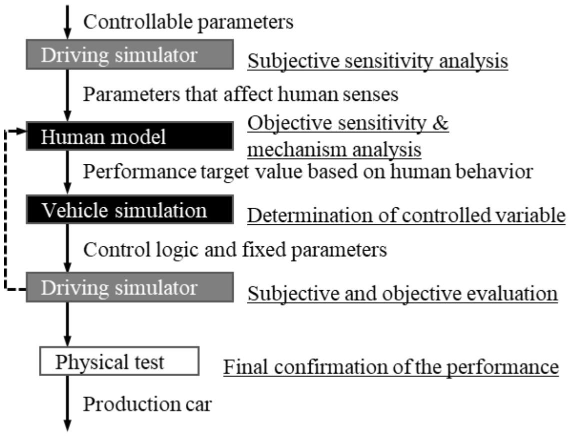


Fig. 11 Performance design process

The details of how a DS is utilized are described in this paper. Fig. 12 presents the steady-state front/rear acceleration magnitudes and front/rear jerk magnitudes, which are derivatives of the front/rear accelerations, for the front/rear motion obtained from the vehicle motion simulation. It also depicts the pitch angle and its derivative, the pitch rate, simulated as arbitrary values and input to the driving simulator to analyze the sensitivity to each influencing factor in the DS.

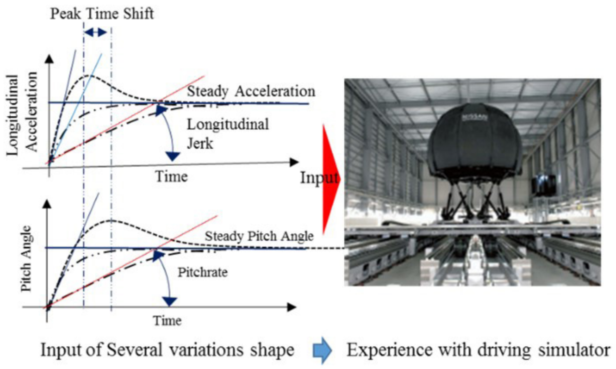
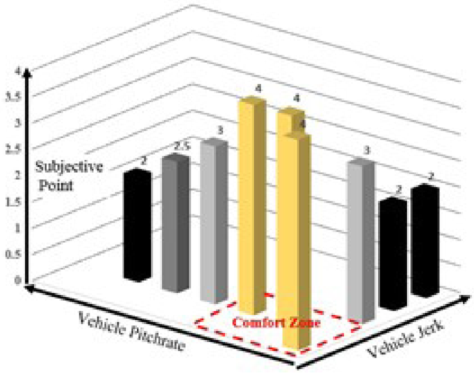
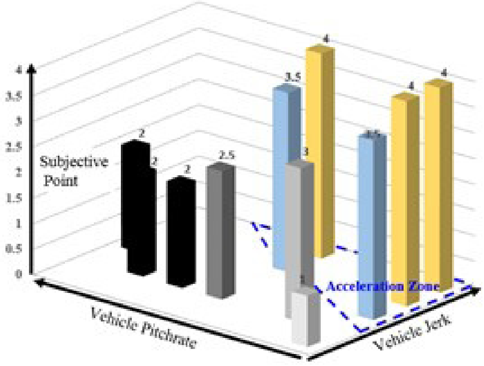


Fig. 12 Sensitivity analysis using the driving simulator

The results of the sensitivity analysis are presented in Fig. 13. With the upper direction of the graph indicating a better subjective score, which is differently colored for each score. The scores for feelings of comfort and acceleration are illustrated in Figs. 13a and 13b, respectively. The lower the pitch rate and front/rear jerk, the higher the passenger comfort level, as indicated in Fig. 13a. By contrast, the greater the front/rear jerk, the higher the score for acceleration; lower scores are observed when the pitch rate is too high. Consequently, both the feeling of acceleration and comfort can be increased by lowering the pitch rate, and a high subjective evaluation can be obtained in the acceleration/deceleration motion by setting the front/rear jerk to a value appropriate for the driver's situation.



(a) Feeling of comfort

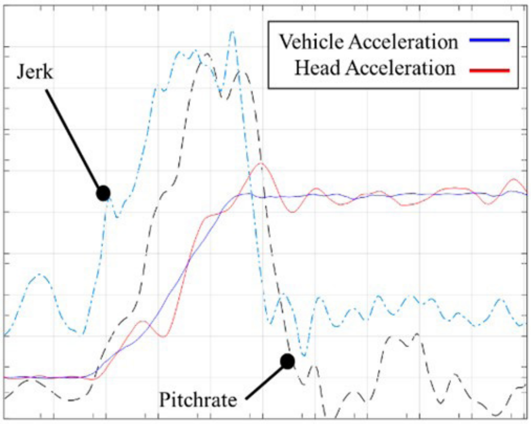


(b) Feeling of acceleration

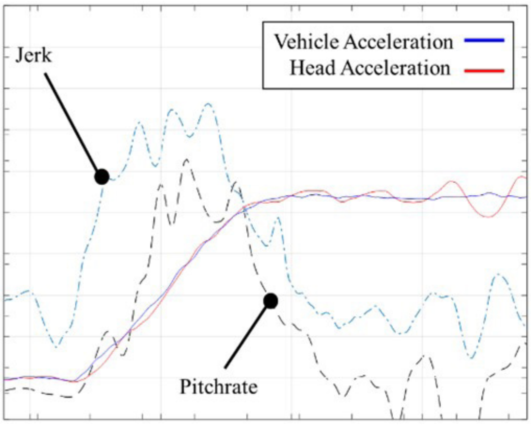
Fig. 13 Subjective evaluation of driving simulator

Based on the results of the above tests on the driving simulator and the simulation results of the passenger behavior prediction model, performance targets for the front/rear jerk and pitch rate are established to improve passenger comfort.

The effectiveness is verified on an actual prototype vehicle using the aforementioned target settings. Figs. 14a and 14b reveal the results for cases without reducing the load on passengers and with control to reduce the load on passengers when the vehicle accelerates at the same rate from a standstill to a specific vehicle speed, respectively. The front and rear jerks and pitch rates are presented on the second axis. The difference between the acceleration on the human head and that on the vehicle decreases by lowering the front/rear jerk and pitch rate. This implies that the shaking of the passenger's head could be reduced. Similarly, the passenger's feeling of comfort improved in the subjective evaluation. The results suggest that a smooth feeling of acceleration can be effectively realized using the target values determined by the driving simulator



(a) Control OFF



(b) Control ON

Fig. 14 Acceleration and pitch rate by driving force control

4. Summary

Targets for new values associated with electrification and better compliance with achievement levels were made possible through the development of the DS technology, which can reproduce the way people feel with high precision. The development of vehicles with new driving experiences and improved safety, along with electrification and intelligence, will be promoted by continually improving the reproducibility of the driving experience and meeting environmental requirements, such as various road surface unevenness and wind effects worldwide.

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3. Virtual Reality Test Technologies for Evaluating Quality of New Mechanical Parts Without Prototyping

Osamu Maruse* Yasunori Nakazono* Noriharu Kubo* Erina Ueno*

1. Introduction

In recent years, the competition to ensure greater cruising distances has intensified, and it has become one of the most important areas in the development of electric vehicles. A retractable door handle, which can retract while the vehicle is in motion, is being studied as a measure for improving cruising distance by reducing aerodynamic drag. Retractable door handles are expected to provide not only improved aerodynamic drag but also added emotional value, such as a sleek appearance when retracted and a sense of hospitality as they automatically unfold when boarding a vehicle. Based on the examples of mass-produced vehicles, door handles protrude in different styles (such as parallel and cantilevered types; Fig. 1). Creating an impression of the automatic door handle movement of protruding and retracting can provide emotional value.

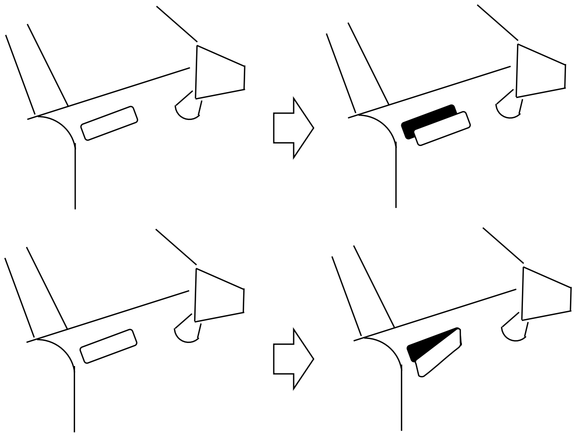

Fig. 1 Examples of retractable door handles

To develop emotional value, how people feel about using a target function must be evaluated, specifically the impression that people receive from the function. Virtual reality (VR) technology is used to reproduce the experience of using a function and to subjectively evaluate the impressions, in line with the idea of the proof of concept at Nissan Motors.

This paper presents the VR evaluation environment developed in-house for evaluating the impression of the experience when using a function. The application of this evaluation method to a feasibility study of a retractable door handle during the development of automobile functions is presented to demonstrate its effectiveness in the providing emotional value.

2. Evaluation methods for emotional value

The impression received from using the target function of a vehicle is used to evaluate the emotional value of the function. A method that measures subjective impressions (psychological scale construction) is often used in product development at Nissan Motors, regardless of the corresponding physical quantity, because the method corresponding to the measurement of the psychological aspect of how people feel must be selected for evaluating the impressions. The reproduction accuracy of the experience of using the target function has a significant effect on the evaluation results as it is based on the direct observation of subjective impressions. Until now, reproducing experience in automobile development has frequently involved the use of physical mockups that replicate the body and interior of a vehicle in its actual size. However, evaluating functions that accompany the movement of parts (which have gradually increased in number in recent years) is difficult within the given development timeline because reproducing the movement with a physical mockup takes time. Thus, a VR evaluation environment that provides a short experience of use is developed by reproducing the body and interior of a vehicle with CAD data and the movement of functions with a program in a virtual space.

3. VR evaluation environment construction

An example of the application of a retractable door handle in a feasibility study is presented in this section. The general functions assumed for retractable door handles are as follows: the door handle automatically protrudes when the door is unlocked with a remote key before the vehicle is boarded; it automatically retracts after the vehicle starts moving; and it automatically

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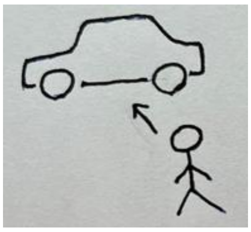
*Customer and Vehicle Performance Engineering Division Customer Performance and Vehicle Test Engineering Department No.2

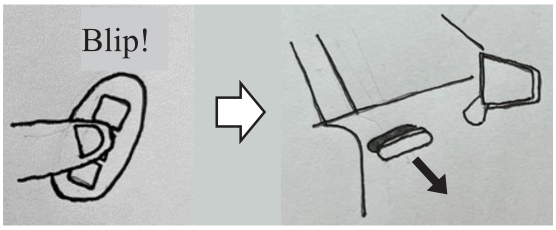
protrudes after the door is opened while exiting. The door handle then automatically retracts when the door is closed and locked (Fig. 2).

The user approaches the door of the driver's seat.



⬇

The door handle automatically protrudes from its retracted position when the door is unlocked by the user using a remote key.



⬇

The user grasps the protruding door handle, opens the door, and enters the driver's seat.

⬇

The door handle automatically retracts from its protruding position when the user starts driving.

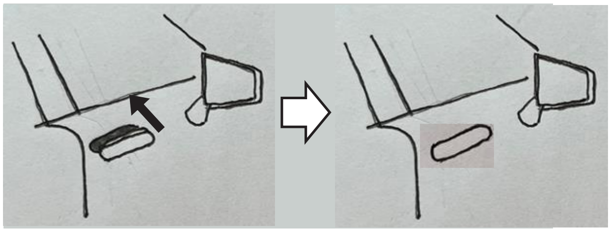
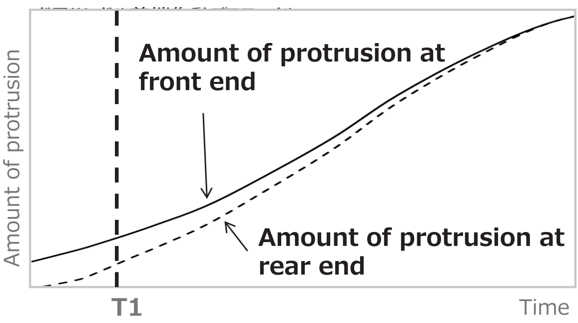


Fig. 2 Functions assumed for a retractable door handle (example)

The impression people receive from the automatic movement of a door handle is examined to determine whether it can provide customers with emotional values such as a sense of hospitality and quality. The following example illustrates how variations in the automatic movement of a door handle can affect the sense of quality.

The timing of automatic protrusion or retraction may be inconsistent between the front and rear ends because actual parts have certain structural design tolerances. The time-series change in the amount of protrusion during automatic protrusion and retraction varies depending on the design tolerance of the parts, as indicated in Fig. 3. The extent to which the variation in the time series changes during protrusion is considered to avoid losing the impression of high quality from the deviation.

Deviation of time-series change in the amount of protrusion during automatic protrusion and retraction: front and rear ends of a door handle.



State at T1

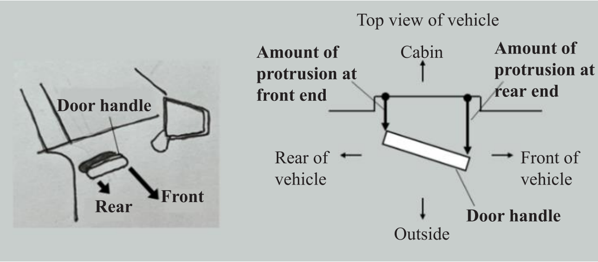


Fig. 3 Variation in the automatic movement of a door handle (example)

The impression received from the movement of the door handle is evaluated for several specifications with different amounts of variation in its automatic movement to determine the relationship between the variation in its automatic movement (Fig. 3) and the impression of high quality.

The environment for evaluating impressions from variations in the automatic movement of a door handle requires (1) the reproduction of slight variations in its automatic movement; and (2) the reproduction of the timing and appearance (viewpoint, field of view, and size of the object to be viewed) when viewing its movement during use.

(1) A mechanism dedicated to the evaluation is required when evaluating multiple specifications that reproduce combinations of deviations in the door handle protrusion timing (combinations of the amount of deviation between the front and rear ends of the door handle). Such a mechanism is required when using a physical mockup because of the design tolerances presented in Fig. 3. This makes completing the evaluation within the development timeline difficult. By contrast, the difference in the movement of different design parameters can be displayed in three-dimensional images in a short time with a VR evaluation environment that reproduces a virtual space.

(2) The impression of the movement of parts, as in the real world, cannot be evaluated without reproducing

the field of view from the viewpoint that matches the posture and physique of the evaluator, changes in the appearance of the object to be viewed synchronously with the behavior of the evaluator, and size of the object during use.

A VR evaluation environment with the potential to satisfy these requirements is selected from a variety of evaluation environments (Fig. 4).

	Evaluation environment		
	Movie	Mockup	VR
(1) Reproduction of slight variations in the automatic movement of a door handle	Poor Slight movements cannot be reproduced in actual size	Poor Long prototyping time make evaluations within the development timeline difficult	Good A virtual model of the door handle movement is required
(2) Changes in the appearance of a door handle synchronized with the behavior of the evaluator during use	Poor Movements of the evaluator are not synchronized with the viewpoints and fields of view	Good	Fair - Good Accurate reproduction of the movement of the viewpoint in response to a behavior is required

Fig. 4 Evaluation environment for the impression of automatic door handle movement

The VR evaluation environment, which reproduces the experience of use in a virtual space, includes three elements: an input section that receives the behavior of the evaluator; an environment reproduction section that reproduces changes in the surrounding environment resulting from the behavior; and an information presentation section that reproduces sensations (visual and audio) based on changes in the surrounding environment (Fig. 5).

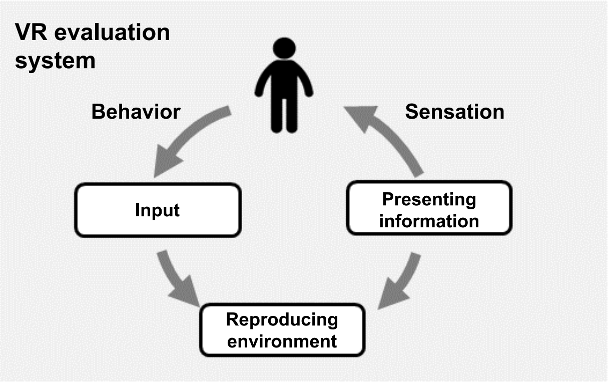


Fig. 5 Elements constituting a VR evaluation environment

The process of establishing a VR evaluation environment for retractable door handles is as follows:

(1) Use cases describing the experience of using retractable door handles in chronological order, as well as the perceptions and behaviors of the user for each use case, are summarized (Fig. 6).

Use case	Perceptions and behaviors of the user
The user approaches the door of the driver’s seat.	The user views the vehicle from outside, while focusing on the driver’s seat. The user walks up to the driver’s seat of the vehicle.
The door handle automatically protrudes from its retracted position when the door is unlocked by the user with a remote key.	The user unlocks the door with a remote key. The user watches the process of the door handle protruding from the retracted position.
The user grabs the protruding door handle and opens the door.	The user sees the door handle. The user grabs the door handle and opens the door

Fig. 6 Use cases and perceptions and behaviors of the user (example)

(2) The reproduction elements necessary to allow users to experience perceptions and behaviors linked to use cases in a virtual space are determined (Fig. 7).

Perceptions and behaviors of user	Reproduction elements
The user views the vehicle from outside, while focusing on the driver's seat.	Omitted
The user walks up to the driver's seat of the vehicle.	Omitted
The user unlocks the door with a remote key.	Omitted
The user watches the process of the door handle protruding from the retracted position.	[Input] • Detection of the actual eye positions and visual line of the evaluator. [Reproduction of environment] • Calculation of the field of view in response to the actual eye positions and visual line of the evaluator. • Calculation of the movement of the door handle protruding from the retracted position. [Presentation of information] • Presentation of the field of view of the evaluator, as well as the movement of the vehicle body and door handle within the field of view. • Reproduction of changes in the field of view in response to changes in the eye positions and visual line of the evaluator.
The user sees the door handle.	Omitted
The user grabs the door handle and opens the door.	Omitted

Fig. 7 Reproduction elements of a virtual space (example)

The determined reproduction elements are structured in a virtual space using a head-mounted display. The software to construct the "field of view in response to the actual eye positions and visual line of the evaluator" among the reproduction elements presented in Fig. 7 in a virtual space was developed in-house. This software allows matching the behavior of the evaluator and the approach to viewing the object with that of reality, and it thus helps realize an accurate evaluation of the impression of the automatic movement of the retractable door handles. Further, a software for the reproduction element "movement of the door handle protruding from the retracted position" was developed in-house. This software allows the direct input of design values for the time-series change in the variation, considering the amount of protrusion presented in Fig. 3. This allows for easy switching between different variation characteristics in the virtual space. Thus, the threshold value for impairing the sense of quality can be evaluated while changing the variation in the amount of protrusion (Fig. 8).

A general-purpose VR system cannot realize a virtual space suitable for evaluating impressions, and therefore, a VR evaluation environment was developed in-house by the test engineering division for automobile development. The developed VR evaluation environment considers the key points of evaluation.

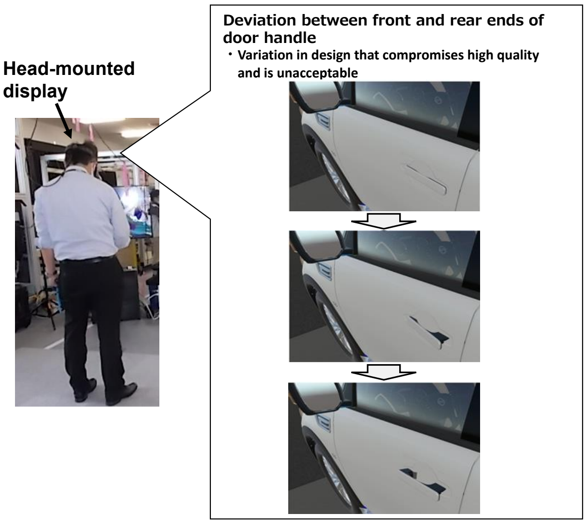


Fig. 8 Evaluation of the sense of quality using VR evaluation environment (example)

4. Technological features

The reproduction of the "field of view" in response to the actual eye positions and visual line of the evaluator contributes to evaluating the impression of appearance in the virtual space. The eye position, visual line, and field of view change in response to the behavior of the driver in real time in actual scenes when using a vehicle. In other words, the appearance of the object when viewed by the user and how it affects the impression are determined by the behaviors of the driver, such as while riding a car. Therefore, it is important to reproduce the field of view in response to the actual eye positions and visual line of the evaluator and to any changes in response to the evaluator's behavior. The position of a viewpoint in a general-purpose VR system is determined by defining a specific position in the virtual space. This implies that it does not reflect the absolute position of the viewpoint in real space relative to a specific reference point. The distance from the contact point between the evaluator's feet and the ground to the head-mounted display is calculated using the general-purpose VR function for detecting the relative position of the reference point and head-mounted display. This distance is used to correct the deviation between the sensor position of the head-mounted display and positions of the eyes to reproduce the position of the viewpoint in the VR evaluation environment.

5. Summary

To evaluate the impression received from the visual sense an in-house VR evaluation environment was developed that includes a digital mockup in which the field of view linked to the evaluator's behaviors and the movement of an object due to design tolerances can be reproduced and viewed in actual size. As a result, it was made possible to set goals for emotional value. The reproduction elements of the VR evaluation environment will be expanded to deal with emotional values of various functions in the future, contributing to maximizing the value of ever-increasing electrified and intelligent parts.

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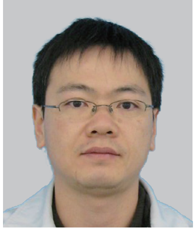
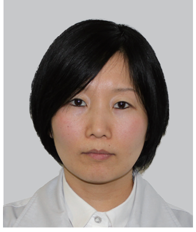


Noriharu Kubo



Erina Ueno

4. Virtual–Real, Simulator–Test Technology for Optimizing Electric Powertrain Performance Without Using an Actual Vehicle

Hidenobu Nakamoto*　Koji Hiraya*　Hiroyuki Taniai**

1. Introduction

There is a need to reduce carbon dioxide emissions from automobiles to respond to global environmental issues and prevent global warming. To this end, automobile companies have been rushing to develop and commercialize electrified power sources. These developments include hybrid vehicles that combine a conventional engine and a motor for driving and battery electric vehicles (BEV) that run with only a motor for driving. Unlike conventional vehicles that operate with only an engine, the development of vehicles with electrified powertrains is still in the nascent stage. Therefore, there is room to improve the efficiency of different processes and evaluation items. One such example is development of electric powertrains using prototype vehicles in a downstream process; the evaluation can be performed in an upstream process using a test bench equipped with a powertrain system. An upstream test can allow short-period feedback to contribute significantly to shortening the development period.

Nissan has developed a unique electrified powertrain system called the e-POWER system. In the upstream process, the tests are conducted on a test bench, wherein a real powertrain system and virtual vehicle system are combined to comply with various performance calibrations. In this section, we introduce the test technology, which is referred to as the powertrain virtual real simulator (VRS) system; this system reproduces the driving-vehicle conditions. We describe how front-loading powertrain development improves the quality and shortens the development period.

2. Development process and test system

2.1 Development process

Vehicle development involves many steps that can be expressed by a V-shaped diagram. Fig. 1 shows a schematic of the powertrain development process. In the upper-left bank, vehicle targets are initially set based on market requirements. Subsequently, the performance of the systems and components is defined, and the components are designed and evaluated. Finally, as shown in the right side of the V-shaped diagram, the systems and components are evaluated, followed by the vehicle. If a defect occurs during vehicle evaluation (a downstream development process), the entire development process is considerably delayed. During powertrain development, the entire vehicle development process becomes more efficient as it can help prevent defects during the vehicle evaluation process. Thus, it is important to conduct test bench with a powertrain system for simulating a vehicle driving.

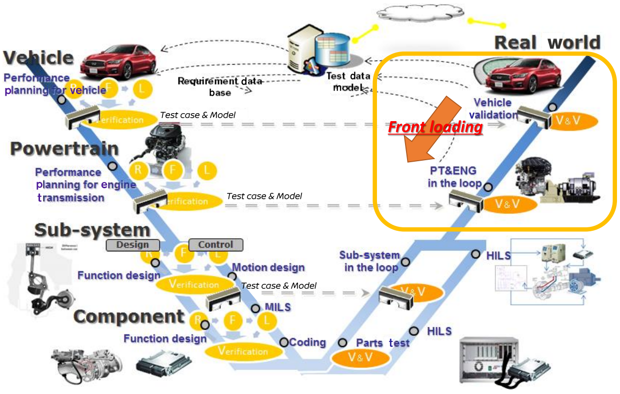


Fig. 1: Schematic of powertrain development process (V-shaped process)

2.2 Overview of VRS test system

Fig. 2 shows the schematic of the VRS test system. The e-POWER system includes an engine and motor for power generation, a motor for driving, an inverter, and a battery. The real powertrain system, which excludes the battery, is installed on a test bench in the laboratory; the power output from the running motor is absorbed by a dynamometer. A model simulating a vehicle is used in the dynamometer control system. The system follows a defined driving mode and simulates the driver, vehicle's travel resistance, and the load that the vehicle receives from the road. Upon receiving the instructions, the powertrain controller controls the running motor to match the required load. In the battery model, the engine is instructed to generate power when the battery capacity

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*Powertrain Test Engineering Department　**Powertrain and EV Advanced Engineering Department falls below a certain predetermined value, and the motor for power generation starts the engine. Conversely, the engine is instructed to stop when the battery capacity exceeds a predetermined value, and the motor for power generation stops the engine.

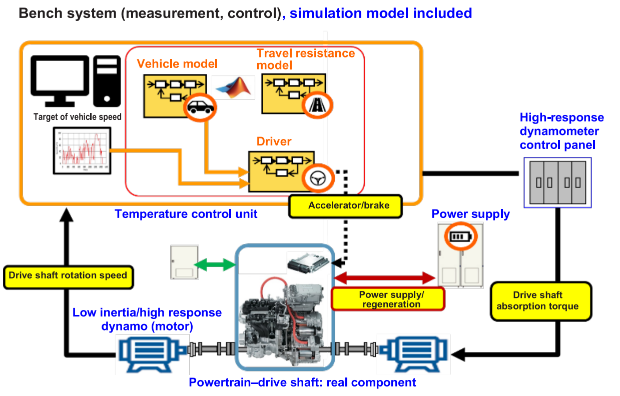
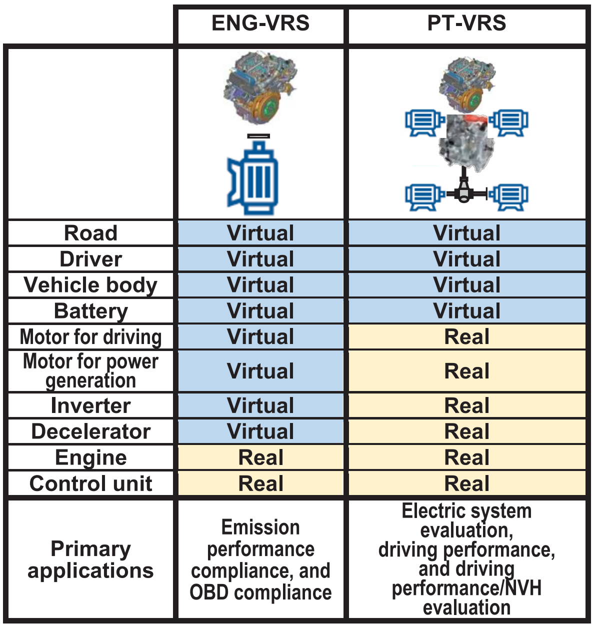


Fig. 2: Overview of VRS test system

Fig. 3 shows a comparison between the PT-VRS test system, in which an entire powertrain (PT) system is mounted on a test bench, and the ENG-VRS test system, in which only an engine (ENG) is mounted. In the PT-VRS used for the evaluation of the e-POWER system, the engine and motor for power generation, motor for driving, inverter, and decelerator are installed on the test bench. In the ENG-VRS system, the engine for power generation is installed on the test bench, but the motor for power generation, motor for driving, and inverter are replaced by a model.



	ENG-VRS	PT-VRS
Road	Virtual	Virtual
Driver	Virtual	Virtual
Vehicle body	Virtual	Virtual
Battery	Virtual	Virtual
Motor for driving	Virtual	Real
Motor for power generation	Virtual	Real
Inverter	Virtual	Real
Decelerator	Virtual	Real
Engine	Real	Real
Control unit	Real	Real
Primary applications	Emission performance compliance, and OBD compliance	Electric system evaluation, driving performance, and driving performance/NVH evaluation

Fig. 3 Comparison between PT-VRS and ENG-VRS systems

2.3 Overview of thermal management test

In the VRS tests, it is very important to reproduce the temperature condition of the powertrain for simulating the vehicle driving conditions. Fig 4 shows a system that reproduces the temperature around the exhaust treatment catalyst of a vehicle running on the ENG-VRS test bench. A fan with a variable flow rate is installed to change the airflow rate, which is adjusted to the vehicle speed during the vehicle driving simulation test. This causes the ambient flow volume around the exhaust aftertreatment catalyst to be equivalent to that of the actual vehicle. Consequently, the temperature distribution around the exhaust aftertreatment catalyst becomes equivalent to that of the actual vehicle.

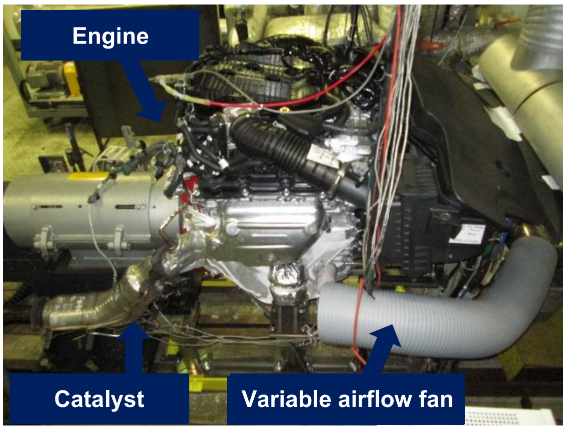


Fig. 4 Exhaust catalyst temperature distribution control system

A test system was constructed to actively control the oil and water temperatures of the engine in the bench test system such that the temperature condition in the test system approached that of the actual vehicle. Fig. 5 shows the test thermal management system. The system includes a controller (2) that controls the oil and water temperatures and model analysis systems (3) and (4) that reproduce the oil and water temperatures of a running vehicle.

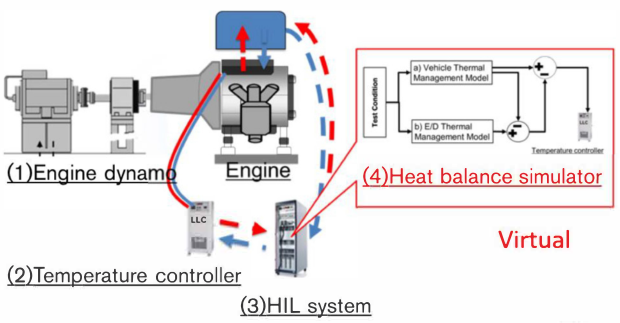
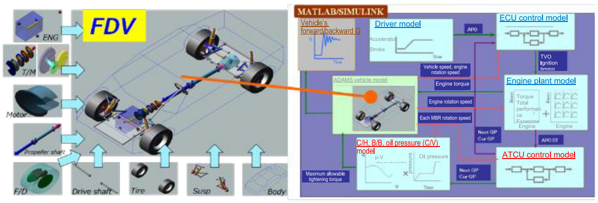


Fig. 5 Overview of thermal management test system

2.4 Overview of NVH evaluation test using FDV-R

Noise, vibration, and harshness (NVH) were evaluated in addition to the driving performance using the PT-VRS test system for the powertrain. The test system was linked to FDV-R, which runs a vehicle model called a functional digital vehicle (FDV) in real time. Fig. 6 illustrates the concept of the FDV. The FDV is a full-vehicle behavior analysis model that comprises all mechanical elements of an actual vehicle to reproduce its characteristics. Coupled plant and control models predict the behavior of the vehicle running in transient and steady states. However, the FDV is not suitable for use with actual components on the bench because the FDV simulation consumes more time than the real one. Therefore, we developed an FDV-R that performs computations in real time. With FDV-R, we evaluated the driving performance and NVH on the PT-VRS test system.



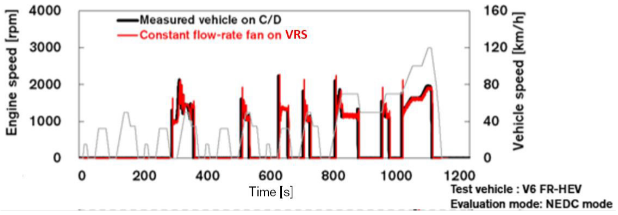
Vehicle mechanism model (FDV) **Full virtual model (plant model and coupling analysis)**

Fig. 6 Concept of FDV

3. Results of vehicle driving simulation test

3.1 Results of real-time test using models

The vehicle simulation model must be computed in real time in a VRS test system. Fig. 7 shows the results of a chassis dynamometer (C/D) test run in NEDC mode driving and a VRS test simulating the NEDC mode. The VRS test demonstrated the feasibility of the test model. The system shown in Section 2.1 shows the same vehicle and engine speeds as those of the actual vehicle running with C/D.



Test vehicle : V6 FR-HEV
Evaluation mode: NEDC mode

Fig. 7 Result of the real-time accuracy validation of the model

3.2 Results of temperature distribution obtained by vehicle driving simulation

The measurements in the test with C/D must be reproduced in the VRS test to develop powertrains with engine exhaust emissions below the regulatory limits. The test system shown in Section 2.3 is used to compare the internal engine and ambient temperatures with those obtained in the test with C/D. Fig. 8 shows a comparison of the exhaust after-treatment catalyst temperature. In the initial VRS test, the measurements were performed with a constant-rate wind blowing around the aftertreatment catalyst (red line). In this method, the temperature of the aftertreatment catalyst did not reproduce that obtained by the test with C/D, which resulted in a discrepancy in the amount of hydrocarbons (HC) emitted. The temperature of the aftertreatment catalyst became close to that obtained in the test with C/D when a fan with variable air volume was used to match the airflow around the aftertreatment catalyst with that used in the test with C/D (blue line). Therefore, the HC emissions matched well with those observed in the C/D test.

The ENG-VRS test system shown in Figs. 2 and 3 is used along with the techniques used in the tests, as shown in Fig. 8; the amount of modal emissions is measured using a test bench. Fig. 9 shows the unburned HC emissions obtained for the entire test mode. In Fig. 8, the colored lines represent the results obtained by these tests Similar to the behavior of HC emissions shown in Fig. 8, the unburned HC emissions observed over the entire mode reproduced the behavior observed in the test with C/D. The VRS benchtop test system enabled emission compliance tests.

Fig. 10 shows the effect of work-hour reduction in the compliance evaluation of the control constants related to exhaust emissions, and it compares the results obtained by the VRS and vehicle bench-top tests. The VRS test saves 65% workhours by reducing the time required to prepare vehicles and conduct tests.

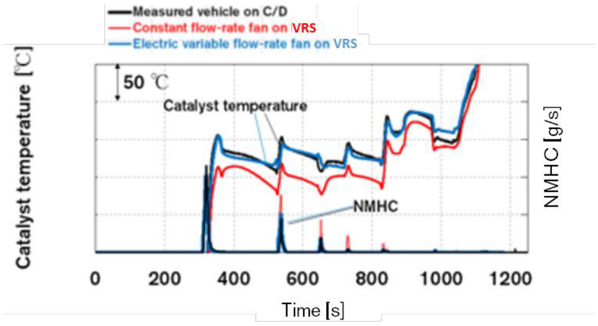


Fig. 8 Temperature comparison between actual vehicle and VRS

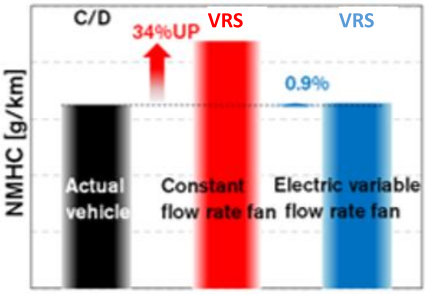


Fig. 9 HC comparison between actual vehicle and VRS

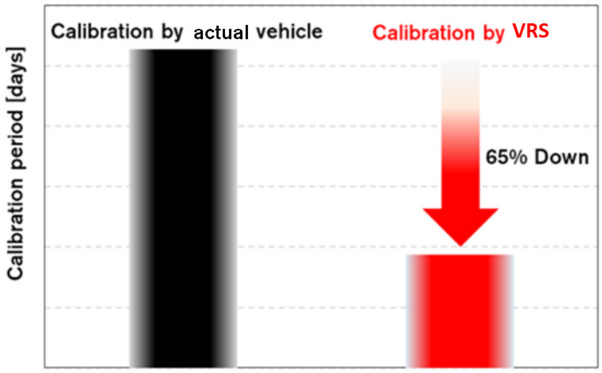


Fig. 10 Effect of workhour reduction achieved by VRS test for emission compliance

3.3 Overview of NVH evaluation test using FDV

A model of the e-POWER system in the PT-VRS test system was used to verify whether the FDV could reproduce the vibrations observed in an actual vehicle. Fig. 11 shows the vertical vibration measured at the engine mount on the rear side of the engine near the center of gravity of the PT system. The figure shows a comparison between the measurement results obtained by the driving vehicle test and the results reproduced by the FDV using the VRS test system. The solid lines represent the results log-fitted to the measurement data, as shown by the dashed line; the difference between the solid lines is less than 3 dB. In the same type of test, the same level of accuracy was obtained at other measurement points and in other vibration directions. These tests demonstrate that the vehicle vibration measured in the test with C/D can be reproduced by the PT-VRS bench-top test. The PT vibration of new vehicles can now be analyzed and evaluated before the prototype vehicle is constructed.

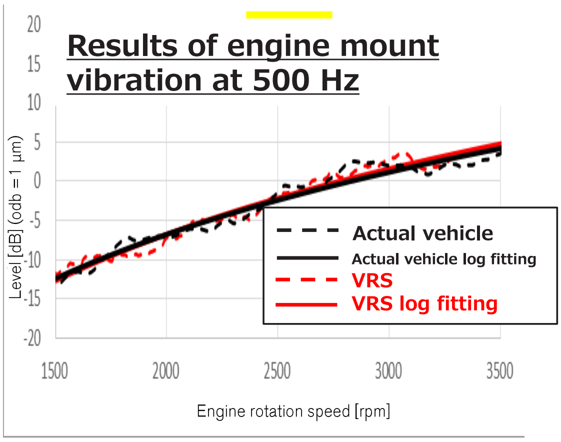


Fig. 11 Result of tests using FDV for validating the reproduced actual vehicle states

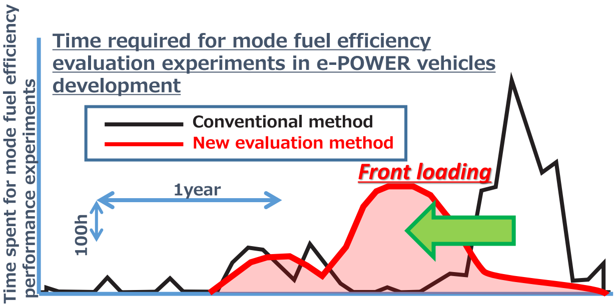


Fig. 12 Development front-loading achieved by applying new method

4. Summary

A VRS test system was developed for powertrain development. The temperature environment was set close to that of the actual vehicle to simulate the driving conditions of an actual vehicle with good real-time performance and model accuracy. With this system, the exhaust emissions and driving performance were evaluated using test bench. This development has made it possible to satisfy the increasingly stricter fuel consumption and exhaust emissions regulations. In addition, the development period was not lengthened, and rework caused by defects occurring in later processes was reduced, even as the electrification of vehicles made the systems more complex. Fig 12 shows the effects of the proposed method.

The conventional development method requires a large number of workhours during the later stages of development. In contrast, the application of the new method realizes not only the front-loading of development but also the prevention of rework. We will continue to develop this method and promote its use as a standard to further streamline the development process.

Authors

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5. Test Technology for Thermal Management System Achieving Both Low Electricity Cost and High Comfort

Masayoshi Tajiri*

1. Introduction

Electrification is achieved by a powertrain comprising a motor, inverter, and high-energy battery, which do not exist in conventional vehicles running with internal combustion engines (ICEs) (Figs. 1 and 2, respectively).

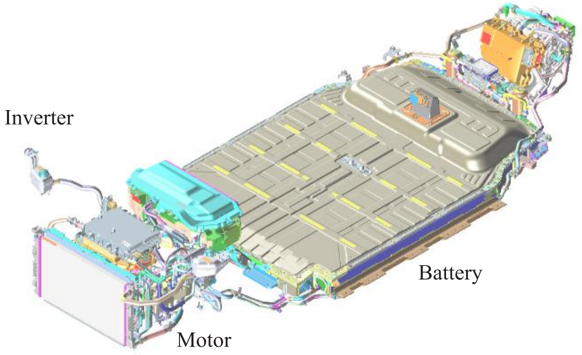

Fig. 1 Components targeted in EV thermal management

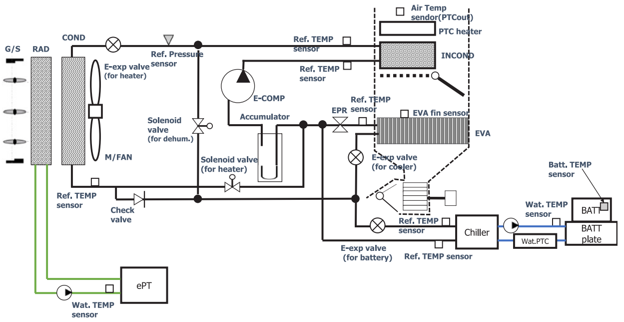

Fig. 2 Schematic of cooling system

EVs have reduced heat emission compared to that of ICEs. However, the temperature of these components must be properly controlled to ensure their efficiency and reliability, and thus, thermal management is important.

In ICEs, the amount of exhaust heat emitted from the engine is so large that it is used as the primary heat source to warm the room. In contrast, electric vehicles must use battery power to produce heat. Therefore, the inefficient use of power can lead to less power being available for driving. Furthermore, the battery generates heat originating from internal resistance, and its performance and life can be reduced depending on the thermal environment. Therefore, the battery temperature must be controlled properly. The thermal environments of the battery and e-PT must be controlled to achieve a good balance between electricity cost and interior comfort.

2. Challenges in tests for EV thermal management

2.1 Increase in test conditions

In ICE tests, operating conditions such as the on/off state of the air conditioner and the amount of heat emitted from the heat-generating engine can be evaluated independently. However, EVs use the cooling energy provided by the air conditioner to regulate the temperatures of the motor, battery, and inverter. Therefore, the electric compressor used by the air conditioner operates not only to switch the air conditioner on and off, but also to respond to the cooling demands of the battery. Furthermore, only the compressor battery cooling operation must be stopped to maintain the battery temperature environment. The combination of these conditions increase the number of driving modes. Further, it is necessary to process a large amount of time-series data obtained from the test because the driving modes change transiently.

2.2 Additional requirements for EV cooling system

Unlike an ICE vehicle, an EV cannot use the waste heat for interior heating, and therefore, battery power is used to produce heat. This increases the battery power consumption, which affects the cruising distance. Heat pump systems that use heat from outdoor air have become the norm for indoor heating in EVs to minimize this negative effect. The compressor must be operated at a high rotation speed to sustain cooling by removing heat from outside, not only when high-temperature outside air is present but also when low-temperature outside air is present. An electric compressor can be operated at any desired rotational speed; however, the noise of the compressor and other cooling components must be maintained at a low value to ensure a low-noise

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environment, which is an attractive feature of EVs.

The EV cooling system operates not only while driving, but also during charging, which is essential for EVs. The battery temperature varies with the charge output and driving conditions applied prior to charging, and this can affect battery performance. Therefore, it is necessary to reproduce not only the outside air temperature and driving conditions but also the temperature environment of the systems associated with the battery.

3. Solutions

3.1 Development of data processing system

The refrigerant used as cooling energy transforms into gas, liquid, and gas–liquid mixtures. The temperature and pressure are measured at multiple points to determine the physical properties of the refrigerant in the corresponding state to monitor whether the refrigerant is in the proper condition. The coupled temperature and flow rate of the cooling water are acquired at multiple points to determine whether the desired cooling is achieved.

Based on the data obtained from these measurement points, further data are obtained through tests in which the number of conditions is defined as the number of temperature levels multiplied by the number of driving modes. A large amount of data processing is required, and such data cannot be analyzed using conventional post-test processing. Therefore, we developed a real-time processing system that can perform these time-consuming evaluations.

Real-time measurements of temperature and pressure are not sufficient for determining the state of the refrigerant that provides cooling energy. The presence of an appropriate gas or liquid state must be confirmed by referring to the physical properties of the refrigerant that corresponds to temperature and pressure. Therefore, it is necessary to draw a pressure–enthalpy (p–h) diagram (see Fig. 3).

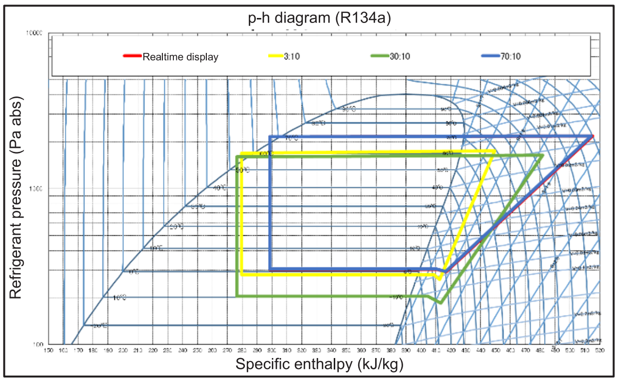


Fig. 3 p–h diagram

Thus, we developed a system to calculate the physical properties in real time based on the data measured in a time series. In this system, the measurement data are captured in real time and listed as time-series data. p–h diagrams were also drawn in real time to visually grasp the state of the refrigerant. This system reduces the data-processing time, as indicated in Fig. 4.

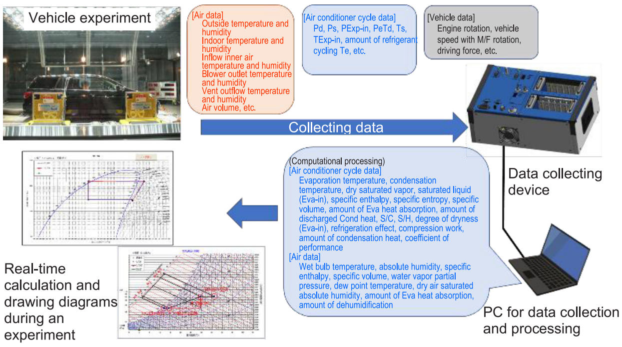


Fig. 4 Real-time data processing system

3.2 Test facilities reproducing temperature environment

The test facilities used to investigate the cooling circuits and interior comfort are equipped with an air-conditioner cycle bench tester and an actual vehicle, which are measured with a chassis dynamometer placed in an all-weather environment. The environment reproduces weather conditions ranging from low and high temperatures to rainfall and snowfall.

The air-conditioner cycle bench test equipment is used to evaluate the system performance prior to building a prototype vehicle. The equipment evaluates the characteristics of the components related to the cooling circuit, from air-conditioner-related components to cooling components (Fig. 5).

Fig. 5 Air-conditioner cycle bench test equipment

The test equipment reproduces the expected temperature environment in an actual vehicle from low to high temperature. It is possible to verify whether the heat balance with the HVAC, compressor, and other cooling circuits is on target. Tests can be performed by modifying the component characteristics and control conditions as required.

An all-weather environmental chassis dynamometer is used in the tests with actual vehicles (Figs. 6 and 7). The temperature environment of the vehicle is determined by external factors, such as ambient air temperature, humidity, and solar radiation, as well as internal factors derived from driving self-heating sources, such as the powertrain and the battery. These temperature environments affect one another. For example, the self-heating of a vehicle increases the outside air temperature; this change makes it impossible to conduct tests in a constant-temperature environment. Therefore, an test facility that is not affected by the self-heating of the vehicle is required. An additional facility is required to evaluate the noise from the operating HVAC and cooling components.

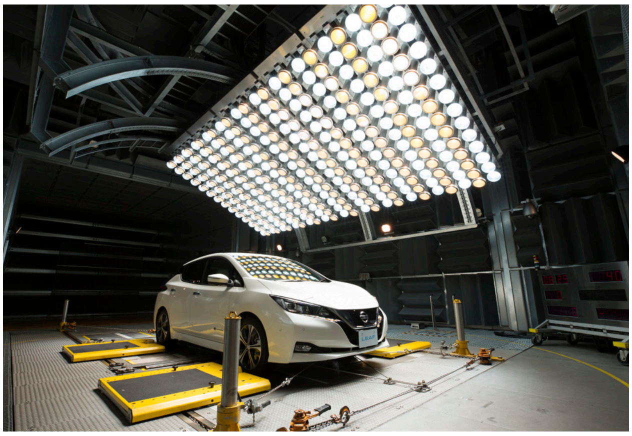


Fig. 6 Low-temperature solar radiation test room with all-weather environmental chassis dynamometer

Fig. 7 Rainfall and snowfall test room with all-weather environmental chassis dynamometer

An all-weather environmental chassis dynamometer responds to four-wheeled vehicles. This system can reproduce not only cold-to-hot temperature environments, humidity, and solar radiation, but also rainfall and snowfall environments. These facilities have sufficient refrigeration capacity to absorb the effects of heat from the vehicles, such as ICE vehicles. Furthermore, the noise from the chassis dynamometer and wind tunnel equipment is reduced to enable noise evaluation (Fig. 8).

Fig. 8 Rainfall and snowfall test room with all-weather environmental chassis dynamometer

The environmental test room is equipped with a rapid charger. With this charger, it is possible to measure the charging behavior immediately after driving in cold and hot environments, the accompanying effects on interior comfort, and even electricity costs.

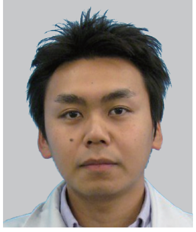
The environmental chassis dynamometer can accurately reproduce a temperature environment. EV-specific thermal management tests with complex transitions over driving modes are conducted at both low and high temperatures to investigate the performance limit.

4. Summary

EVs are spreading rapidly and expanding their markets. However, the thermal environment of EVs can significantly affect their performance, reliability, and battery life. Therefore, thermal management technology and its supporting test technologies were created to optimize the thermal environments using electrical energy without wasting it.

The comfortable and reliable EVs produced are expected to contribute to improved product appeal and market expansion.

Authors



Masayoshi Tajiri

Test Technologies Contributing to Electrification

6. X-ray CT Nondestructive Measurement Technology Supporting Vehicle Body Weight Reduction Technology

Yasuhiro Kanda*　Yoshitaka Usui*

1.Introduction

Considering the accelerating global competition to develop electric vehicles, product competitiveness is enhanced by increasing the cruising distance. Motor efficiency and battery power density are also increased, and the vehicle weight is reduced to further improve the performance of the electric powertrains, which requires streamlining part structures. Nondestructive measurement technology using X-ray computed tomography (CT) can be used in the research and development phase to analyze fine internal structures whose performances and conditions can change from those of the original when disassembled as three-dimensional profile data. The findings of this analysis can contribute significantly toward improving the performance of electric vehicles.

This study focuses on the use of X-ray CT for vehicle body weight reduction, which is gaining popularity given the advancements in electrification. Structural design technology that optimally combines materials with different physical properties is necessary to realize vehicle body weight reduction. The multi-materialization of vehicle body parts has evolved from using conventional steel sheets to using high-tensile steel sheets, aluminum alloy sheets, resins, carbon fiber-reinforced plastics (CFRP), and other materials, as presented in Fig. 1, in addition to structural streamlining.(1)

In this chapter, materials indispensable for multi-materialization and examples of applications to enhance the technological development of bonding dissimilar materials are presented, followed by the prospects for this measurement technology.

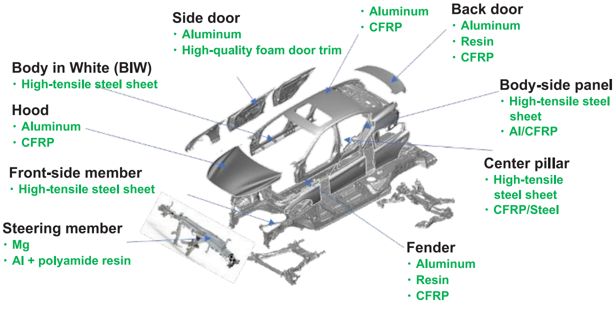


Fig. 1 Examples of lightweight material applications

2. Challenges in vehicle body weight reduction

2.1 Background

The supply chain for materials and parts in the automotive industry has become globalized, and this has prompted the expansion of local development and manufacturing bases. When developing lightweight vehicle bodies that combine individual part materials to achieve the performance goals by combining various materials, facility requirements of a manufacturing base must be considered. For example, the internal structure of joints for dissimilar material bonding and fiber orientation inside the material responsible for ensuring the strength and stiffness of carbon fiber-reinforced plastics (CFRP) must be evaluated. The design optimization of material processing based on the evaluation of several prototypes is necessary to achieve these performance goals.

2.2 Efficiency improvement of materials processing development

Bonding technologies for dissimilar materials (mechanical, solid phase, and adhesive bonding) depend on the application and material characteristics. For example, self-piercing riveting (SPR), used in mechanical bonding technology, is a joining method wherein the leg of a rivet piercing the upper plate is spread without piercing the lower plate.

Recently, the application of CFRP has expanded from the aerospace to automotive fields owing to improvements in material technology. Resin injection molding, press molding, injection molding, and other methods have been used based on application requirements. Resin injection molding is a process where carbon fiber is formed into a part shape in a mold and injected with resin to impregnate itself with the resin and harden it.

Performance indicators that indicate processing results such as strength, stiffness, and durability, and the internal structure, which represents factors associated with the processing parameters, are analyzed during the development of the material processing processes. The internal structure of prototyped parts

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*CP and Test Engineering Methodology Innovation Department must be analyzed and evaluated under different conditions to understand the mechanism of the phenomena and identify factors that affect the processing results. However, conventional analysis and evaluation techniques for internal structures rely on the observation of fractured cross-sections obtained after mechanical processing. Moreover, acquiring information about a specific cross-section is time-consuming.

Fatigue strength under repeated loading must be considered when designing vehicle body parts. Identifying internal structural changes over time using the same sample is an effective approach to understanding the fatigue mechanism. Therefore, a technology to efficiently analyze the internal structure in a nondestructive manner is expected to help realize competitive advantages in the development of vehicle body weight reduction technology. A technology for imaging three-dimensional internal structures developed in-house using X-ray CT is described in this special feature.

3. Internal structure visualization technology using X-ray CT

3.1 Overview of X-ray CT

X-rays can be generated using the following procedure: An electric current is passed through a filament inside the source, which heats the filament to generate thermal electrons. Thermal electrons are then accelerated using a high voltage. These collide with the target to generate X-rays, which are irradiated from all directions (360°) onto an object, and the X-ray transmission intensity is recorded as a transmission image by a detector located on the opposite side. The data from each direction are called projection data, and the three-dimensional image created by reconstructing all projection data from all directions (360°) is called a CT image. The sequence of this process is illustrated in Fig. 2.

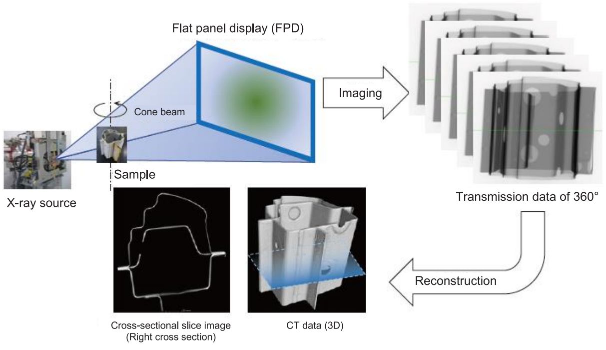


Fig. 2 Reconstruction process of X-ray CT

3.2 Challenges to implementing X-ray CT for vehicle body weight reduction

The energy of X-rays irradiated from commercially available industrial X-ray CT systems indicates a continuous distribution, with a peak on the low-energy side and a gradual decrease toward the high-energy side. X-rays are easily absorbed by parts made of dense iron, and a higher absorption is observed on the low-energy side, which allows only the high-energy X-rays to be transmitted. This is called "hardening" (beam hardening) because the apparent energy distribution shifts to the higher side. The illustrations of X-ray energy transmission and hardening are presented in Figs. 3-1 and 3-2, respectively.

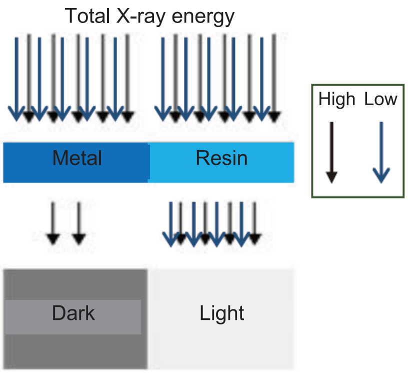


Fig. 3-1 Illustration of X-ray energy transmission

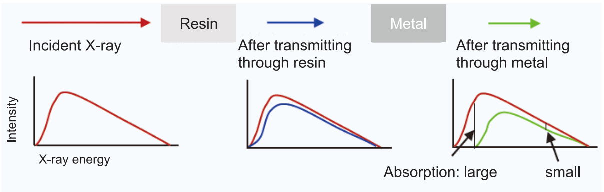


Fig. 3-2 Illustration of hardening

Hardening causes the relationship between the transmission length and transmission rate (irradiation intensity/transmission intensity) to deviate from the Lambert–Beer law, as indicated in Fig. 4. This deviation creates noise (metal artifacts) in the CT image that is not actually present as a structure during the reconstruction process.

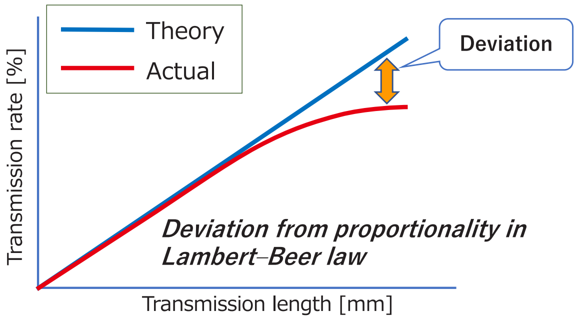


Fig. 4 Deviation of transmission rate as a function of transmission length

In general, metallic filters can be used to suppress hardening. Noise can be reduced by placing a metal plate as a filter in the X-ray irradiation section. The following steps are required to obtain CT images with reduced noise: the installation of a metal filter, trial imaging, and verification of the noise reduction effect. This process relies on the expertise and intuition of the operator, and therefore, it requires a long time to determine the imaging conditions each time the measurement target is changed. Metal artifact noise is more likely to be generated in X-ray CT imaging of multimaterial parts made of steel or resin-based materials such as CFRP. The challenge is establishing an engineering technique that can efficiently determine the specifications of the metal filter for obtaining accurate information on the internal structure.(2)

3.3 Noise reduction effect using metal filters

An example of the noise-reduction effect achieved by applying a metal filter is illustrated in Fig. 5, which depicts that the metal artifact noise from iron is reduced.

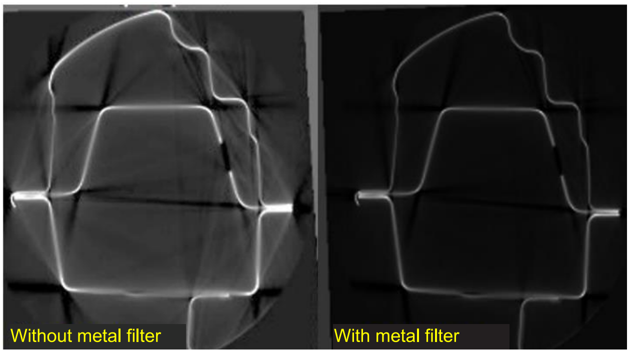


Fig. 5 X-ray CT image (cross section) of the side sill of an iron vehicle body

Fig. 5 illustrates that metal artifact noise is generated in a complex manner in response to the part profile. The noise reduction effect of the metal filter for a simple iron bolt, as indicated in Fig. 6, is evaluated to reduce the noise effect caused by the part profile.

One-mm-thick copper and aluminum plates were prepared as metal filters. A general filtered back projection (FBP) algorithm was used for reconstructing the CT images, and the brightness was corrected to visually emphasize the metal artifact noise, as presented in Fig. 6.

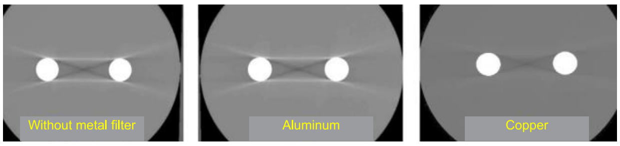


Fig. 6 Metal artifacts at the cylindrical section of iron bolts

The metal artifact noise is generated as white line-shaped false images arising from tangent lines between the two bolts in the CT images of the bolts (Fig. 6). The noise reduction effect increases in the order of copper filter > aluminum filter > no filter.(4)

The relative artifact index (AIr)(3), which is used in the medical field, was selected as the index for the quantitative evaluation of the noise reduction effect. The closer AIr is to 1, the better the noise reduction. The results of the calculation of AIr(*) in the area near the bolts presented in Fig. 6 are listed in Table 1. The AIr is 2.3, 2.0, and 1.3 for no filter, aluminum filter, and copper filter, respectively. These results indicate that the noise reduction effect depends on the metal filter material; the noise reduction effect of the copper filter is greater than that of the aluminum filter.

Table 1 Noise reduction effect by metal filter materials

Material/Thickness	None	1.0 mm
Aluminum	2.3	2.0
Copper		1.3

$$* \quad \mathrm{AIr} = \frac{\sqrt{(\sigma^2_A - \sigma^2_B)}}{\sigma_B}$$

σ_A : Standard deviation in areas with noise
σ_B : Standard deviation in background area

3.4 Discussion and hypothesis formulation on noise reduction

Fig. 5 illustrates that a noise reduction effect was observed when using a metal filter, and this suggests that hardening was weakened. The energy distribution on the low-energy side of the incident X-rays can be changed using a metal filter, which is assumed to weaken the hardening.

The principle that absorption increases significantly at the energy where transitions occur between electron orbitals, called absorption edges (unique to a material), is applied to the X-ray absorption fine structure (XAFS) for analyzing the absorption spectrum obtained by irradiating X-rays with a material. The K-shell electron orbitals, where transitions occur, are called K-absorption edges. These were studied to evaluate the effect of metal filters.

The attenuation coefficient of X-rays, which is a physical quantity affecting absorption, is theoretically estimated to determine the change in X-ray absorption from high to low energies; the results are presented in Fig. 7.

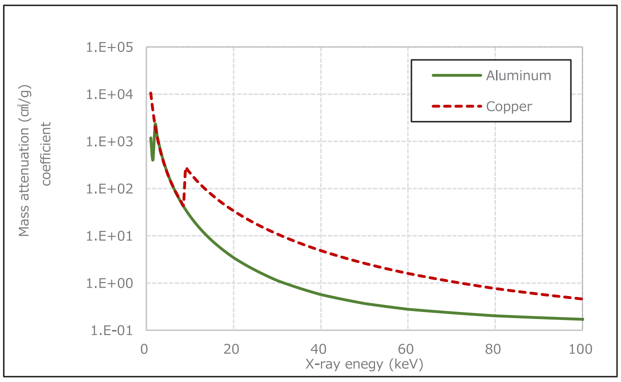


Fig. 7 Mass attenuation coefficient

The larger the attenuation coefficient, the greater the attenuation of the X-rays. Fig. 7 indicates that the attenuation coefficient changes with X-ray energy and becomes larger at lower energies. Moreover, the attenuation coefficient of copper increases sharply at the K-absorption edge of 8 keV, and it is approximately eight times higher than that of aluminum. The results lead to the hypothesis that the change in the energy distribution of the incident X-rays is significantly different at lower energies and affects hardening reduction.

3.5 Verification of the hypothesis

The X-ray spectra obtained to testly verify the above hypothesis for the aluminum and copper filters are presented in Fig. 8. The thickness of each filter is 1 mm.

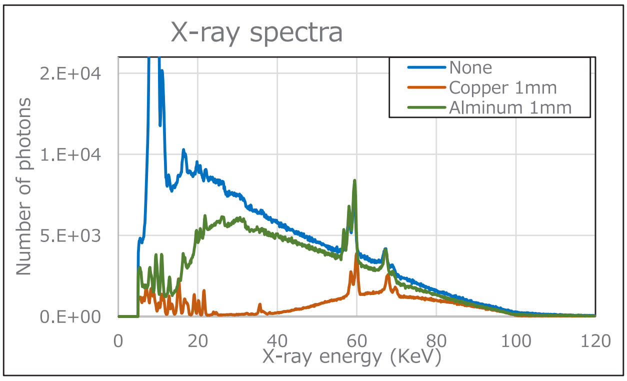


Fig. 8 X-ray spectra

In Fig. 8, The number of X-ray photons was qualitatively reduced on the low-energy side for both copper and aluminum filters. A comparison of the X-ray spectra for both filters indicates that the number of photons for the copper filter was significantly lower than that for the aluminum filter in the 20–40 keV energy band. The reduced number of photons calculated from the partial over-all (POA) in the 20–40 keV and 80–100 keV energy bands is illustrated in Fig. 9 and is used to quantitatively evaluate the difference in the X-ray spectra.

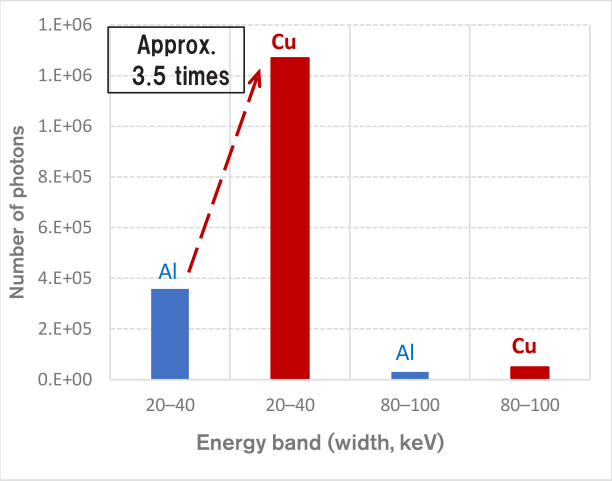


Fig. 9 Value of POA

The reduced number of photons for the copper filter in the 20–40 keV energy band is approximately 3.5 times higher than that for the aluminum filter. By contrast, the number of photons for both filters in the 80–100 keV energy band is 0.1 times less than that for the aluminum filter in the 20–40 keV energy band; this indicates a significant difference in attenuation between copper and aluminum in the 20–40 keV energy band. This result verifies the hypothesis that a change in the energy distribution of incident X-rays in the low-energy band caused by metal filters affects hardening reduction.

4. Results of application to weight-reduced parts

The relationship between the X-ray energy distribution and CT imaging results was determined to develop a method for selecting an optimal metallic filter. Reliable imaging was realized through an engineering approach that does not rely on the expertise and intuition of the operator. High effectiveness was achieved with new materials that had not been used in the past. Examples of clear visualization of internal structures that were previously difficult to visualize because of image noise are listed and illustrated below.

Example 1: The appearance and imaging results of a test piece consisting of aluminum plates bonded with an iron SPR and adhesive are illustrated in Fig. 10. The state (shape) of the adhesive application and the SPR bonding requirements, i.e., the piercing of the upper plate by a rivet, spreading of the rivet leg within the lower plate, and absence of cracks in the lower plate, were evaluated in the three-dimensional structure.

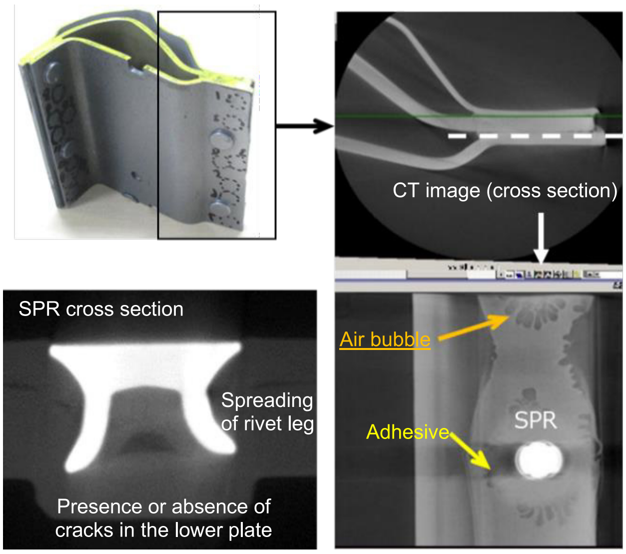
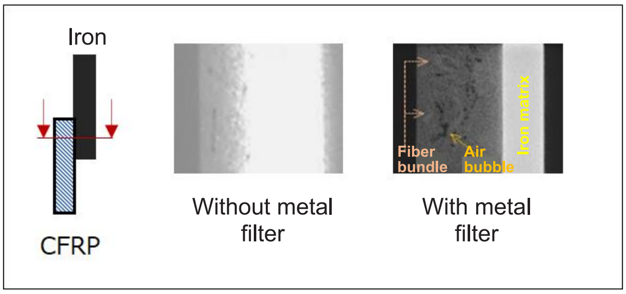


Fig. 10 CT images of a test piece of aluminum plates bonded together

Example 2: The imaging results of the multimaterial composite of iron and CFRP are illustrated in Fig. 11. The fiber orientation of the CFRP was observed in iron-mixed materials even when a metal filter was inserted.

Thus, a correlation with the tensile strength was obtained, which provides feedback on the molding conditions.



Without metal filter

With metal filter

Fig. 11 CT images of a test piece of iron and CFRP bonded together

5. Summary

There is an urgent need to understand the mechanisms linking performance and structure to efficiently realize new structures in this era of innovation in vehicle manufacturing. The effect of using metal filters to reduce metal artifact noise in X-ray CT is not limited to vehicle body weight reduction. High effectiveness was also demonstrated in the visualization of complex structures such as motors and batteries consisting of a variety of materials.

As a powerful measurement technology in electric vehicle development, this technique is expected to help solve the trade-off between high quality and low cost and to contribute toward the development of attractive products.

6. Prospects of measurement technology using X-ray CT

Industrial X-ray CT is utilized globally and is expected to develop into a measurement technology that guarantees the uncertainty of the profile and dimensions. This technique is expected to enhance manufacturing competitiveness, which will play a significant role in the metrological traceability system through digital twin development used in digital engineering such as computer aided engineering and data-driven development such as materials informatics. By extension, this will lead to highly efficient development in the automotive industry, which requires a large labor force and energy in an era of a declining working population.

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