

Driving Simulator for Power Plant Controller Development

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ABSTRACT

A driving simulator environment with the minimum configuration considered necessary for power plant controller development was added to a Hardware in the Loop Simulation environment that mounts the plant model created in the previous report (Development of High-performance Engine Plant Model and Sequential System Identification Environment for Realization of Model-based Development). This created a development environment that makes it possible to incorporate situational maneuvers performed by humans, which were previously acquired through actual vehicle tests in the final process of model-based development, into the virtual vehicle tests in the upstream processes. Driving maneuvers performed by humans were measured using the created driving simulator, and it was confirmed that maneuvers performed by humans in response to various surrounding situations can be acquired, which was not possible with a driver model. In addition, the created driving simulator was applied to actual controller development, and was verified to be useful in discovering control issues that occur in everyday driving situations, and to increase the accuracy of model-based development.

1. Introduction

In model-based development (MBD), the actual vehicle tests that are performed in the final process of development are performed virtually in each upstream process by reproducing non-existent components as plant models in the upstream processes. This made it possible to increase the accuracy of the output in each process, reduce development reworking requiring to return from downstream to upstream processes, reduce development costs, and increase the speed and quality of development by front-loading development.

Figure 1 shows the relationship between the controller, plant model and driver. The High Performance Engine plant Model (HPEM) created in the previous report⁽¹⁾ was used to create an environment in which controller design can be performed using the response from a plant model that exhibits real behavior relative to the control command values of the controller. This enabled more accurate controller design in the upstream processes of development compared to the previous method. Among the inputs to the power plant controller, the new environment increased the accuracy of the response from the plant model, which is the controlled object. However, the driving maneuvers input

from a separate route to the controller continue to use the previous method, with the result that reworking process time still occurs.

The virtual vehicle tests performed in the upstream processes of MBD use the evaluation drive-patterns used by

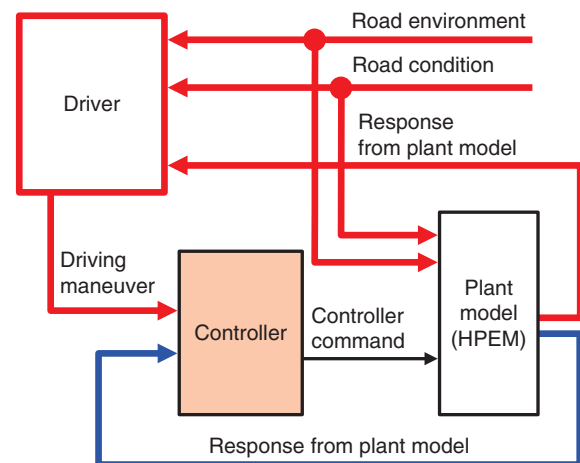


Fig. 1 Input and output of controller

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each country to measure exhaust emissions and evaluation drive-patterns that reproduce specific conditions extracted by requirements analysis and Fault Tree Analysis (FTA). Driving maneuvers are generated as before from a simple driver model that performs accelerator pedal operations so that the vehicle speed-tracks the target vehicle speeds of the drive-patterns. In the actual vehicle tests performed in the final process, evaluation is performed using the above-noted evaluation drive-patterns, under special conditions on test courses, and in various road environments under road conditions that take into account constantly changing weather and road surface conditions and the effects of traffic flow such as surrounding vehicles and pedestrians. In this case, the driving maneuvers are generated by humans actually driving vehicles under these conditions. As a result, the maneuvers include situational maneuvers performed by humans in response to various surrounding circumstances and that reflect the driver's personality, mental state and driving skills, so control issues may also be discovered through these situational maneuvers. In this manner, the evaluation conditions used for virtual vehicle tests in the upstream processes of current MBD differ from the evaluation conditions used for actual vehicle tests in the final process. This difference in evaluation conditions is a factor resulting in development reworking and an issue for front-loading of development.

Issues rooted in differences in evaluation conditions are not unique to MBD of power plant control. For this reason, approaches are recently being made in the automotive industry to increase the accuracy of MBD by reproducing the driver maneuvers obtained through actual vehicle tests in the final process of MBD in the virtual vehicle tests performed in the upstream processes⁽²⁾. In order to satisfy the evaluation conditions, it is necessary to reproduce various road environments and road conditions, including weather, road surface, surrounding vehicles and pedestrians, and to prepare a lineup of drivers to operate the vehicles. Ideally, to efficiently perform MBD, all of these elements should be modeled and multiple driver models with diverse characteristics should be used to perform evaluation on roads around the world under various conditions. Like understanding the operating range of each component comprising a vehicle, it is not so challenging to apply a driver model to evaluation that requires typical maneuvers in response to various road environments and road conditions. In contrast, power plant control that performs calculations at high frequency based on driving maneuvers should function adequately for all conceivable driving maneuvers. For this reason, there are demands that the driver maneuvers used for this evaluation include all situational maneuvers that humans might perform in response to various surrounding situations. However, a driver model capable of performing these maneuvers requires the creation of auto-driving control that performs ideal driving⁽³⁾ and control that takes into account human personalities, experience and emotions, presenting quite a challenge. Furthermore, the accuracy

of the driver model behavior in various situations would be constantly questioned when analyzing the various evaluation results.

Therefore, this study virtually reproduced road environments and road conditions using a model. However, the driver lineup was not modeled, and instead a driving simulator environment was created where humans drive on virtually reproduced roads.

2. Development Goals

Examples of applying driving simulators for R&D purposes include the following. Driving simulators are used to analyze driver behavior under conditions that cannot be reproduced using an actual vehicle, such as when a person suddenly runs into the road⁽⁴⁾. In the development of Human Machine Interfaces (HMI) such as the switches and meters inside a vehicle, driving simulators are used to investigate operability and visibility. In addition, driving simulators are used in controller development to investigate autopilot and active safety functions such as autonomous emergency braking and Electronic Stability Control of vehicles. Recently, use is also increasing for vehicle dynamics that require simulator environments that can reproduce real vehicle body behavior such as vehicle handling stability and ride comfort.

The emphasized driving simulator functions differ according to the application. In analysis of driver behavior and HMI development, visual information and the tactile sensation of the equipment surrounding the driver are emphasized. In vehicle dynamics, calculation of real vehicle body behavior and the ability to have drivers experience real bodily sensations such as acceleration and vibration are emphasized. Therefore, actual vehicles or driver's seats reproduced by cutting out a part of an actual vehicle are used for the former, and a plant model that accurately calculates the body behavior of an actual vehicle and a motion device that lets humans experience the results of those calculations as bodily sensations are used for the latter.

The ideal case is a driving simulator that reproduces the entire vehicle in a realistic manner and can be used regardless of the application. However, using a driver's seat equivalent to an actual vehicle increases the weight, thereby increasing the load capability required of the actuators in the motion device. Thus, accurate reproduction of acceleration involves tradeoffs such as the need for more powerful actuators, so large and expensive facilities would be needed to satisfy all requirements. Furthermore, accurately reproducing an entire vehicle with a plant model requires vast amounts of creation and identification time and also increases the calculation load. This means that expensive arithmetic units are needed to perform calculations in real time.

As described above, pursuit of the ideal driving simulator environment increases both the process time and cost. The goals of MBD are to reduce development costs by

reducing development reworking and to increase the speed and quality of development by front-loading development. This means that these goals cannot be achieved if the cost required to create a driving simulator exceeds the cost reduction effects of MBD or if creation requires so much process time that it adversely affects the front-loading of development. Therefore, it is necessary to create a driving simulator environment that is appropriate for the purpose in order to achieve the maximum MBD effects with a low cost and a short process time.

3. Creation of a Driving Simulator for Controller Development

3.1. Functions Required for Controller Development

Controller development can be broadly divided into the steps of understanding the dynamic characteristics of the controlled object, creation of the control logic, and calibration of the setting values. Therefore, the plant model used in the driving simulator must support these steps.

With regards to understanding the dynamic characteristics of the controlled object and creation of control logic, the plant model is used to confirm the dynamic characteristics extracted from the overall vehicle that are related to the control being developed, and to confirm the validity of the created control logic. Therefore, the plant model should be able to express unexpected dynamic characteristics in addition to the dynamic characteristics understood by the controller developers. In order to express unexpected dynamic characteristics, the plant model should be able to output responses to inputs in accordance with rules and principles. This demands configurations that are based on physical rules and empirical formulas rather than map combinations of characteristics understood by the controller developers.

When calibrating setting values, accuracy of the absolute values of responses is also demanded in addition to responses that follow rules and principles. However, while there are differences due to the degree of detail of the model, plant models are merely simplified representations of the dynamic characteristics of actual objects. This means that it is not possible to calibrate setting values at an accuracy equal to that for an actual vehicle, and the calibration value accuracy that can be set is proportional to the accuracy of the plant model. There are also cases where a developed power plant is applied to multiple vehicle body types and the number of body variations increases after the completion of development. Therefore, even if setting values are calibrated exactly for a specific vehicle body type in the upstream development processes, this does not lead to reduced development reworking or to front-loading of development. For this reason, when calibrating the setting values in the upstream development processes, it is considered sufficient if tentative calibration can be performed to limit the setting value ranges. Thus, accuracy is not necessarily required for the absolute values of the responses from the plant model

used in the driving simulator.

Figure 2 shows the relationship between the plant model, controller, external information, and the driver. The plant model behavior is conveyed to drivers using the broad categories of visual information, auditory information and bodily sensations, and is a source of information for situational maneuvers by humans.

Visual information is conveyed as the vehicle traveling speed, cornering and inclination states, and auditory information is conveyed as changes in the engine noise relative to the engine speed and changes in the road noise relative to the vehicle speed. Differences between this virtual information and reality are interpreted by humans as a feeling of unnaturalness, so the highest accuracy that can be obtained at present is demanded.

In contrast, bodily sensations are affected by differences in the vehicle body, and humans misinterpret differences from reality as being due to differences in the vehicle body, so it is thought that accuracy of bodily sensations is not as important in power plant controller development. This means that it is sufficient if humans can physically sense changes in vehicle body behavior relative to changes in the power plant output and vibrations or other phenomena rooted in power plant issues.

In addition to the plant model response, drivers also determine maneuvers in accordance with the external visual information, that is to say the road environment and road conditions. In most cases this visual information is provided regardless of the driver's wishes. Furthermore, the more unexpected the provided visual information, the more noticeable the influence of the driver's personality, mental state and driving skills, and the greater the difference from normal driving. This increases the likelihood of driving maneuvers that cannot be acquired by having the simple

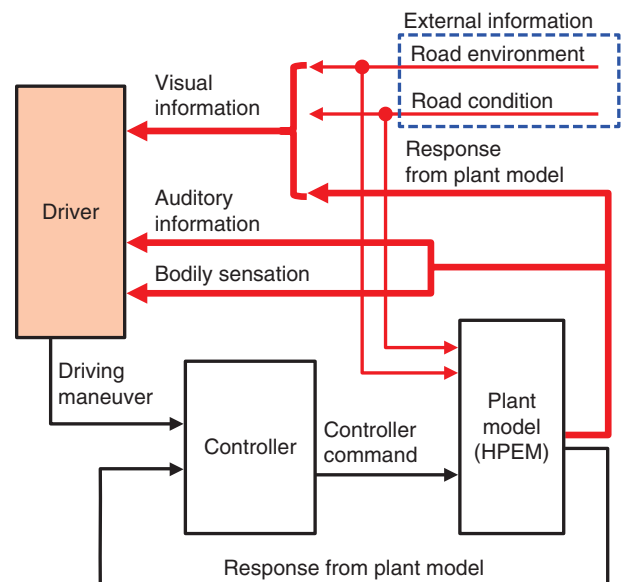


Fig. 2 Input and output of driver

driver model described previously travel in accordance with evaluation drive-patterns, and is useful for discovering control issues. This means that a video library and driving scenarios that can reproduce uncommon driving situations in addition to everyday driving situations are also necessary.

3.2. Driving Simulator Configuration

Figure 3 shows an overview and Fig. 4 shows the configuration of the driving simulator created for power plant controller development. The driving simulator consists of a commercially available visual simulator for R&D purposes, a Hardware in the Loop Simulation (HILS) that performs the calculations for the plant model that is the virtual vehicle, a driver's seat used by a human driver to perform driving maneuvers, and an ECU that mounts power plant controller.



Fig. 3 Overview of driving simulator

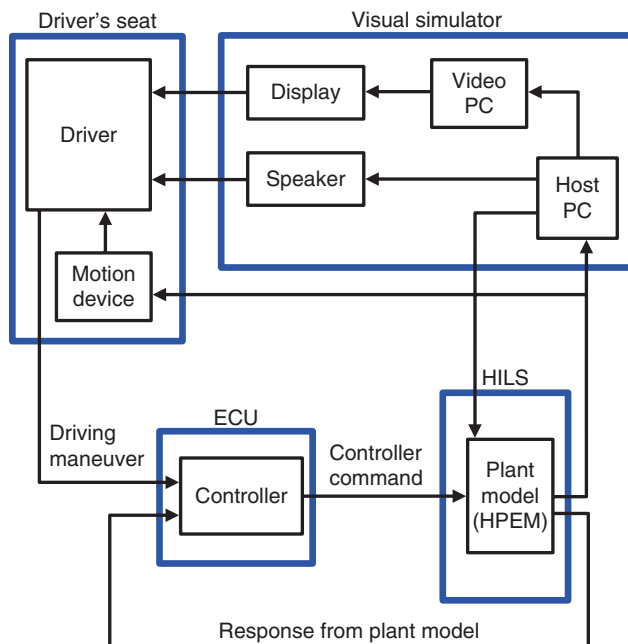


Fig. 4 Configuration of driving simulator

The visual simulator consists of a host PC that calculates the driving conditions and sound effects of the driver's vehicle and the surrounding traffic flow status, a video PC that calculates the surrounding scenery, a video display unit that displays the various calculation results, and a speaker.

The host PC calculates the driving conditions such as the gradient and coefficient of friction of the road to be traveled, the wind velocity, the position of the driver's vehicle, and the arbitrarily set surrounding traffic flow. Specifically, the host PC can reproduce elements such as vehicles that drive in accordance with traffic rules, vehicles that perform special behaviors such as sudden braking or weaving, maneuvers in accordance with arbitrarily set signal timings, and pedestrians. Diverse scenarios from everyday driving situations to uncommon driving situations can be set by combining these elements. In addition, sound effects are calculated and output in accordance with the plant model behavior.

The video PC is equipped with a video library that includes video of actual urban districts, expressways and mountain roads, and also virtual urban districts and virtual expressways that can be arbitrarily created, making it possible to reproduce various road environments. In addition, light and shade conditions can be changed according to the time period, weather conditions such as rain or snow can be selected, and various car and motorcycle models and pedestrians can also be displayed.

The video display unit used five 55-inch LCD displays to secure a viewing angle of approximately 210 degrees in consideration of the viewing angle when checking the blind spots when making a turn or lane change.

The HILS calculates the behavior of the virtual vehicle using the ECU controller command values and the driving conditions calculated by the host PC. The plant model mounted in the HILS uses the HPEM created in the previous report for the power plant, and a commercially available full-vehicle dynamics model for the vehicle body. The plant model for the power plant is required to produce responses to controller command values in accordance with rules and principles, and to perform accurate real-time calculations in order to match the human sense of time. The HPEM is described using physical rules and empirical formulas, and its behavior satisfies the requirements for use in the MBD controller hierarchy test. The HPEM can also stably perform real-time calculations on the HILS, so it can be applied without special modification. As described in the previous report, the plant model output values have an error accuracy of 3% or less compared to actual power plant measurements, which is sufficiently accurate for tentative calibration of the control setting values.

The plant model for the vehicle body is a kinetic model consisting of 10 rigid bodies such as the sprung mass, unsprung mass and wheels, and has a total of 27 degrees of freedom for the movement and axis of rotation of these rigid bodies. The dynamic behavior of the vehicle can be simulated by setting parameters such as the aerodynamic

characteristics of the body, the kinematic and dynamic characteristics of the suspension and steering, and the longitudinal and lateral force characteristics, rolling resistance and relaxation length of the tires.

In addition, use of the HILS realized connection between an actual ECU and the plant model, and enabled smooth transfer of power plant controller developed using the driving simulator to the actual vehicle phase.

The driver's seat did not use expensive items sold for R&D purposes, and was instead created by combining commercially available products marketed to hard-core players of PC-platform racing games. These products provided a sufficiently realistic operation feeling and enabled acquisition of bodily sensations such as changes in vehicle body behavior and vibration. In addition, the steering wheel, pedal and shift lever feelings and the vehicle behavior differ according to the model genre and vehicle size class, so the created driver's seat is thought to possess the necessary functions for power plant controller development applications.

4. Effects of the Driving Simulator

An example of situational maneuvers by humans that were acquired using the created driving simulator is described below.

Figure 5 shows the vehicle speed, accelerator pedal position, and transmission gear (shift) position measured using the condition when following a vehicle in front that is traveling at the prescribed vehicle speed pattern. The human measurements were obtained by the development team members using the driving simulator. The test condition was for each subject to drive normally as in everyday life.

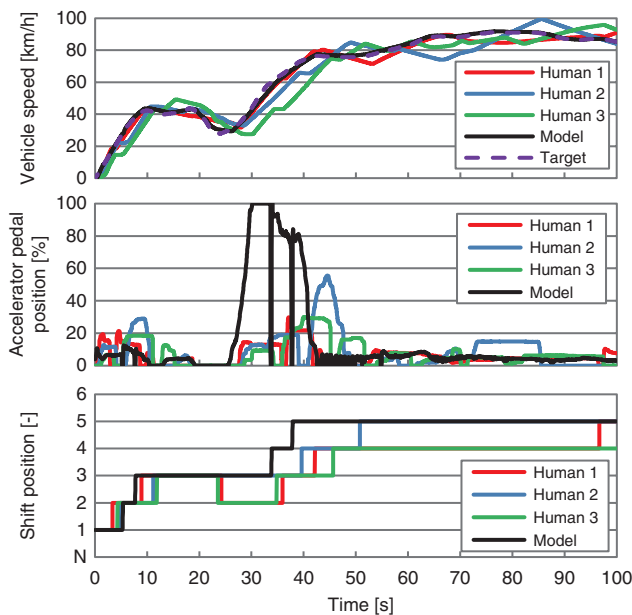


Fig. 5 Following traveling test results

The driver model assumed traveling at a constant distance following the vehicle in front, and shows the results when the accelerator pedal was operated by Proportional Integral Derivative (PID) control using the vehicle speed pattern of the vehicle in front as the target value.

The human results for vehicle speed obtained by this test exhibit differences with a long variation cycle from the vehicle speed pattern during gradual acceleration and deceleration from the 40 s mark onward. These differences differ for each test subject, which is thought to be because the situational maneuvers performed by humans in response to changes in the distance between the vehicles obtained from the visual information differ for each person. In contrast, the driver model performed driving that accurately traced the drive-pattern, so there was no difference in vehicle speed from the drive-pattern.

Comparison of the accelerator pedal position also showed differences so large between drivers that it did not appear as if they traveled using the same drive-patterns. These differences are thought to have occurred because the gear selection and the method of adjusting the distance from the vehicle in front differ according to driving characteristics based on the personality and experience of each driver.

In addition, the driver model differs from humans in that the amount of change in the accelerator pedal position per unit time is more prominent as shown in Fig. 6. No major difference was observed between 0 s and 30 s during which there was clear acceleration and deceleration. However, during gradual acceleration and deceleration after the 40 s indicated by the dashed line, the human subjects determined the distance from the vehicle in front as the situation

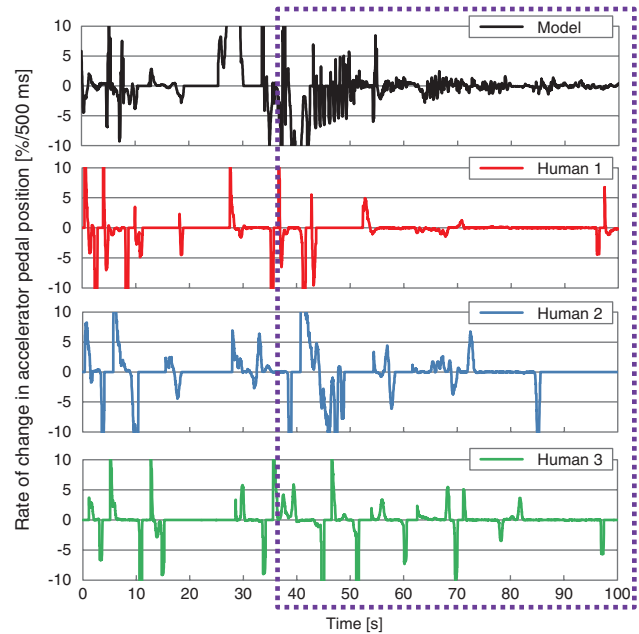


Fig. 6 Comparison of rate of change in accelerator pedal position between human and model

developed, so they held the accelerator pedal position for a longer time, resulting in operation with greater speed variation. In contrast, the driver model constantly performs minute accelerator pedal operations in order to more accurately trace the vehicle speed pattern.

As described above, the maneuvers performed by the driver model were mechanical maneuvers that perfectly followed the vehicle traveling in front. In contrast, the maneuvers performed by humans differ each time, even when driving under identical test conditions. This confirmed that the created driving simulator can be used to acquire situational maneuvers that humans perform in response to various surrounding situations and that are influenced by the driver's personality, mental state and driving skills.

5. Example of Application to Controller Development

An example of a control issue identified by applying the created driving simulator to controller development is described below.

Figure 7 shows a block diagram of a simple engine torque controller in which issues were identified.

This controller uses the feedback engine torque to control the throttle angle to achieve the target torque value. In addition, the throttle angle and the engine torque have a nonlinear relationship, so a response surface model⁽⁵⁾ that outputs the throttle angle relative to the intake airflow and the engine speed is used to enhance the control characteristics. This enables the PID controller to treat the intake airflow, which has a strong linear relationship with the engine torque, as the controlled object.

The driving simulator was used to drive a manual transmission virtual test vehicle in an urban district, and a control issue was discovered in the following type of driving situation. Figure 8 shows a driving situation in which the vehicle traveling in front decelerated and made a right turn to enter the parking lot of a shop on the opposite side of the road. In this case, the vehicle in front decelerated to wait for an oncoming vehicle to pass in the condition without the turn signal activated. As a result, the driver performed unexpected strong deceleration, and then gradually accelerated.

As shown in Fig. 9, the engine speed dropped due to the deceleration, so under normal conditions the driver

would shift down and then accelerate. However, due to the influence of the unexpected strong deceleration on the driver's mental state, the driver pressed the accelerator pedal without shifting down, which produced fluctuation in the engine output torque. When driving was performed again thereafter under the same conditions to confirm the issue, the output torque fluctuation did not occur. Comparison of the data for the cases with and without output torque fluctuation showed that in the latter case, the acceleration started from a state with less deceleration and a smaller drop in the engine speed compared to the initial case. This is thought to be because the driver knew in advance that the vehicle in front would decelerate strongly, so the driver unconsciously increased the distance between the vehicles.



Fig. 8 Test situation reproduced by driving simulator

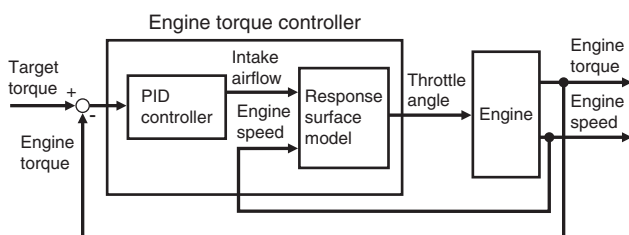


Fig. 7 Engine torque controller block diagram

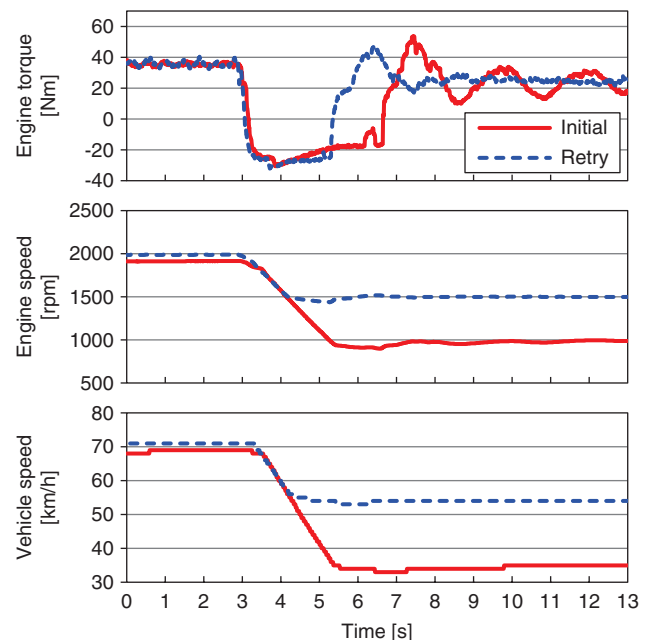


Fig. 9 Original controller behavior

The reason for this result was investigated, and an issue was found in the settings of the response surface model shown in Fig. 10. The throttle angle was large relative to the intake airflow and there was an area with insufficient linearity at the operating point where the issue occurred. As a result, the controller operated the throttle by more than the amount of change in the throttle angle that was physically necessary relative to the intake airflow, and the engine output torque also changed greatly. This triggered hunting in the feedback control, which produced fluctuation in the engine output torque.

Previously, the validity of the response surface was confirmed in the initial stages of controller development. However, one reason for this was that numerical judgment using a coefficient of multiple determination⁽⁵⁾ that expresses the approximate accuracy of the response surface was emphasized in order to clarify the basis for judgment. Therefore, the control specification requirements table was revised so that judgment is performed by both confirming the detailed response surface shape from a physical perspective and according to the value of the coefficient of multiple determination.

In addition, the overall controller was also evaluated using the evaluation drive-patterns used by each country to measure exhaust emissions and evaluation drive-patterns when starting acceleration that were created based on conditions extracted by requirements analysis and FTA. However, some evaluation conditions were not covered by the evaluation drive-patterns of each country, and even in the evaluation drive-patterns when starting acceleration,

the ranges where issues occurred were narrower than the evaluation point interval (10-Nm increments) for the target torque, so issues could not be discovered.

However, the engine output torque fluctuation could be eliminated as shown in Fig. 12 by using the modified response surface shown in Fig. 11.

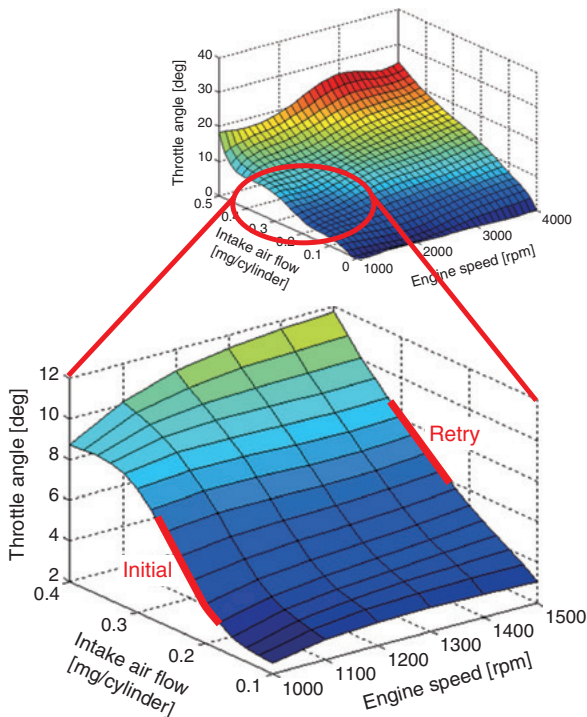


Fig. 10 Original response surface model

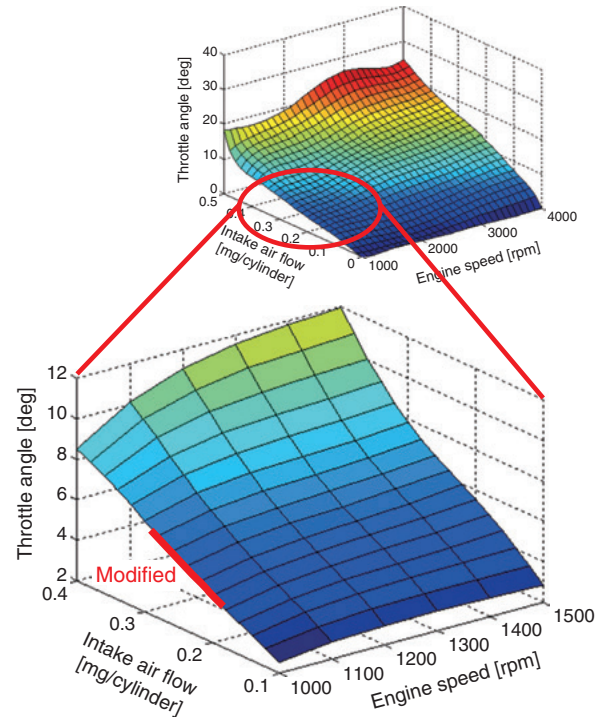


Fig. 11 Modified response surface model

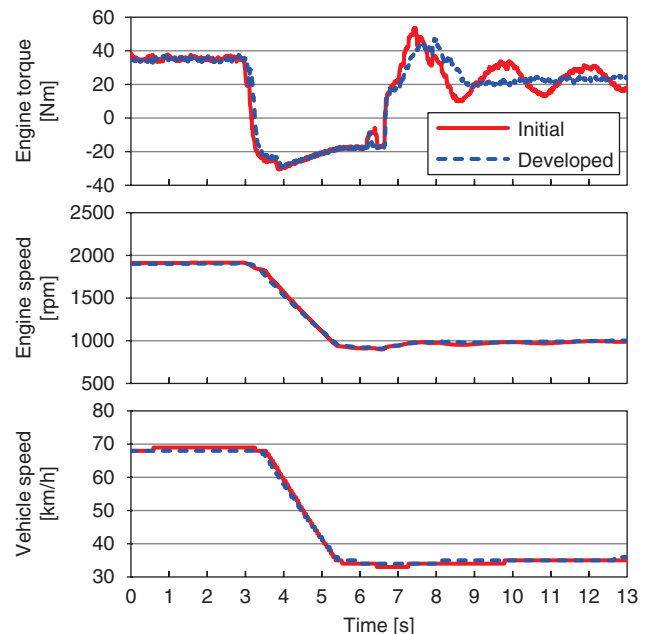


Fig. 12 Behavior of developed controller

As described above, the control issue in this study occurred as a result of a situational maneuver performed by humans in response to a driving situation present in the everyday driving of automobile users. However, this driving situation could not be reproduced in evaluation that was previously performed using virtual vehicles and driver models in evaluation drive-patterns in the upstream processes of MBD. In addition, it is thought that the issue would not have been easily discovered even in evaluation performed using actual vehicles on a test course that does not assume actual traffic flows.

As shown by this example, when developing new controllers, omissions may occur in the control specification requirements tables created based on the results of requirement analysis and FTA. The use of a driving simulator to evaluate the controller makes it possible to discover control issues in the upstream processes of MBD that would be a challenge to discover prior to evaluation using actual vehicles that assumes traffic flows on ordinary roads, which is the final stage of the conventional development method.

6. Conclusion

In power plant controller development, the following items were performed to reduce development reworking and issues with front-loading of development that occur due to differences between the evaluation conditions of virtual vehicle tests in the upstream processes of MBD and the evaluation conditions of actual vehicle tests in the final process of MDB.

- (1) Evaluation using situational maneuvers performed by drivers in various driving situations was incorporated into the upstream processes of MBD.
- (2) A driving simulator environment with the main objective of power plant control development was created as a means of acquiring situational maneuvers performed by drivers.
- (3) The created driving simulator environment was confirmed to help increase the MBD accuracy.

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