

Development of High-performance Engine Plant Model and Sequential System Identification Environment for Realization of Model-based Development

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ABSTRACT

Attempts to realize more efficient development by combining the V-model, a method used in software development, with model-based development (MBD) are proceeding among automotive manufacturers. The design and test processes for this combined development method are organized into corresponding levels, and different plant models are used for each level. Attempts to employ an MBD-V-model combination in engine development presented the issues of mismatches between models on the same level, and lack of consistency between models on different levels. A high-performance plant model able to be used in both design and test procedures on the same level was therefore developed, and an environment was created making it possible to use consistent plant models at all levels by means of sequential system identification of models for different levels. The functioning of models generated by this environment was studied in MILS and HILS environments, verifying the effectiveness of the developed environment.

1. Introduction

The V-model, which organizes the relationship of correspondence between design procedures and test procedures as a V shape, has been applied in standard software development⁽¹⁾ for some time.

In the V-model shown in Fig. 1,⁽²⁾ processes are represented as an aligned diagram, with the design process in the left half of the diagram moving to the lower right, and the test process in the right half of the diagram moving to the upper right. In addition to expressing the software development process as a whole through the connection between processes, the diagram shows which aspect of the design process corresponds to which procedure of the test process via the relationship between left and right. Test procedures verify and validate the achievement of the demands set for the corresponding design procedure.

The vertical divisions of the left-right relationships of correspondence are termed levels. Goals and focal perspectives differ for each level, and design demands and test items therefore also differ.

Model-based development (MBD) has attracted attention as a means of helping to enable front-loading in order to increase the speed and quality of developments.⁽³⁾ In MBD of standard control ECU, the controller and the functions of the plant that represent the object of control are

modeled, and these models are employed in each procedure from the initial stage of development. Using these models, some of the verification procedures that had previously been conducted during the test process can be front-loaded in the design process, reducing the burden represented by extensive reworking such as modification of specifications, thus increasing the quality of the ECU and reducing development time.

Today, efforts to increase the efficiency of model use by combining V-model-based development and MBD and creating models for each level of the V-model are being advanced by automakers.⁽⁴⁾

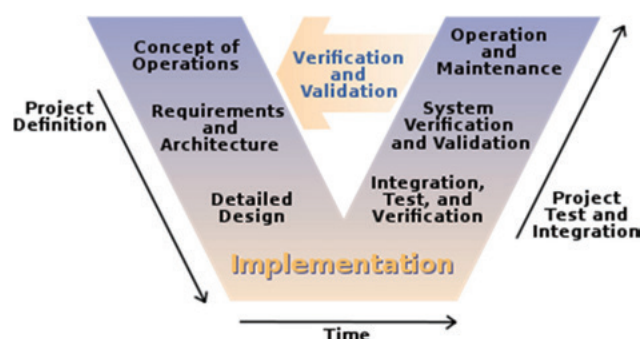


Fig. 1 Standard V-model

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Honda has also been working to push ahead with such an MBD-V-model fusion for some time. Figure 2 shows an overview of the combination of MBD and V-model-based development in an engine development process. The levels for the V-model are, from the top, vehicle, system, hardware and controller, and implementation. This development represented an attempt to realize a development process using models fitted to the goals of the procedures conducted at each of these levels.

However, in implementing this MBD-V-model combination, the plant models used to model the engine, the object of control, presented certain issues.

One of these was the fact that the plant models for the same level did not match. In order to front-load verification procedures in a development using an MBD-V-model combination, it is necessary to employ identical plant models for the same level. However, at the controller level, because there were severe restrictions on the speed of computation demanded from the plant model on the test process side due to use of a real-time simulator in the hardware-in-the-loop simulation (HILS), it was challenging to use the same plant model in the model-in-the-loop simulation (MILS) on the design process side.

The second problem was inconsistency between plant models for different levels. Conventionally, because goals and focal perspectives differ for each level, unique plant models have been formulated for each level and used in the development. Because of this, consistency has not been achieved between the behavior of plant models for different levels, and it has not been possible to directly reflect system conditions studied using plant models for the system level at the controller level. As a result, it has been challenging to front-load controller verification using MBD.

In order to resolve these two issues, a high-performance plant model able to be used for the controller level in both

the design and test processes was first developed, following which an environment was created in which the behavior of different plant models could be harmonized between levels by employing this model in sequential system identification from the system level. This paper will discuss this development.

2. Development Goals

This section discusses the necessary conditions for the developed high-performance engine plant model (HPEM), provides an overview of the sequential system identification environment, and discusses the criteria established for judgment of the realization of goals.

2.1. Necessary Conditions for HPEM Development

For the development of a plant model able to be used in both HILS and MILS at the controller level, certain necessary conditions existed for model behavior and computation speed.

Necessary conditions for model behavior will be considered first. Due to increases in the number of actuators and sensors needing to be controlled and the need to respond to stringent laws and regulations, the complexity of control logic is increasing in today's engines. To take air-fuel ratio feedback control applied in order to respond to exhaust gas regulations as an example, control logics based on adaptive control theory using state estimators are being employed,⁽⁵⁾ and in order to verify the functioning of these control logics, it is necessary for engine plant models to be able to reproduce dynamic behavior (dead time and lag elements) along with the course of time.

Necessary conditions for computation speed will now be considered. The purpose of HILS is to verify the functioning of ECUs. It operates in real time, using actual ECUs connected to a computer input with plant models.

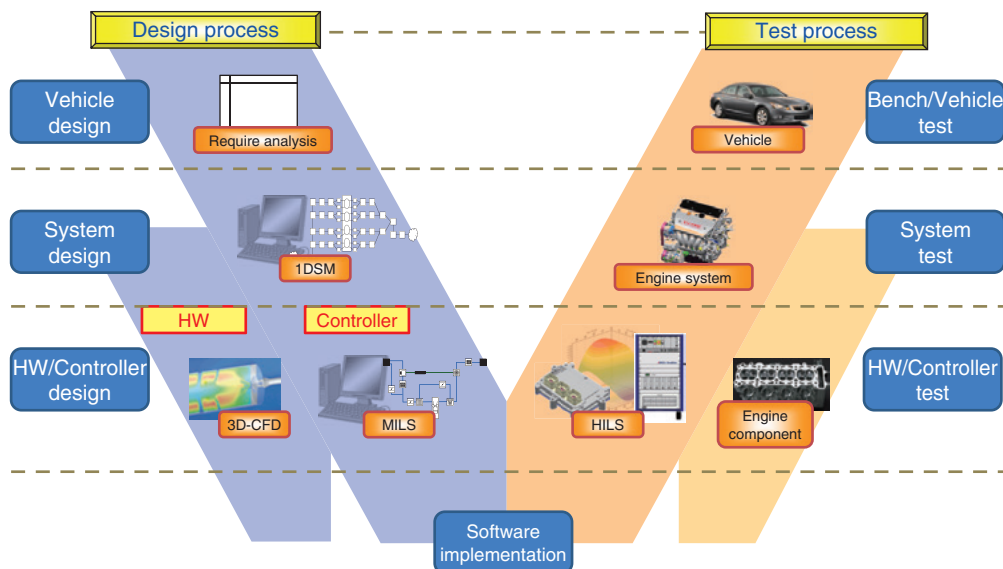


Fig. 2 Model-based development combined with V-model

Because of this, if the computation load for the plant models input to the computer is high, the engine state cannot be calculated in real time, and it is not possible to verify ECU performance. Whether calculations can be conducted in real time or not is dependent on the performance of the computer, but the processing power of real-time simulators available on the market at present is basically equivalent to that of standard PCs. It is necessary to formulate plant models that are able to conduct calculations in real time under these computation speed conditions.

Based on these necessary conditions for model behavior and computation speed, an HPEM was developed by customization of a standard mean value engine model (MVEM)⁽⁶⁾ in response to engine specifications.

2.2. Overview of Sequential System Identification Environment

This section will discuss engine plant models and the purpose of their use.

2.2.1. 1D simulation model (1DSM)

The 1DSM is a model that performs computational fluid dynamics (CFD) analysis in the radial direction only. The model has a light computation load in comparison to 3D CFD, and is able to predict the performance of a system as a whole. Because of this, it is used in the system design process, chiefly for the consideration of intake and exhaust specifications, driving cycle of fuel efficiency calculations, and simple combustion evaluations.

2.2.2. Mean value engine model (MVEM)

This model averages and calculates the output of each combustion cycle on the time axis using a lumped parameter

system that does not consider spatial extension. Because it does not perform CFD calculations, its computation load is even lighter than that of the 1DSM. However, the model cannot reproduce behavior for each crank angle, and therefore is not useful in hardware design. For this reason, it is used in MILS in the controller design process as a model for verification of control logic operation.

2.2.3. MAP engine model

A MAP engine model is a model that expresses the characteristics of each component of the engine as a simple map of input and output based on test results. These models are able to refer to values for the various engine states at high speeds, but to formulate the models it is necessary to perform measurements for all engine operating states or prepare calculation data in advance. These models are used in HILS for the verification of ECU performance in the controller test process, but today, when the number of actuators and sensors being employed is increasing, it is difficult to exhaustively input all engine states, and the models are therefore chiefly used in a limited range of applications, specifically debugging of control logic and verification of on-board diagnosis.

2.2.4. Flow of sequential system identification

The project discussed in this paper focused on the flow of controller development, and created an environment able to harmonize the behavior of different plant models between levels by using HPEM to perform the roles of MVEM and MAP engine models and sequentially identifying 1DSM and HPEM from an existing engine.

Figure 3 shows the flow of sequential system identification proposed in this project in order to harmonize plant models between levels. This figure shows the model

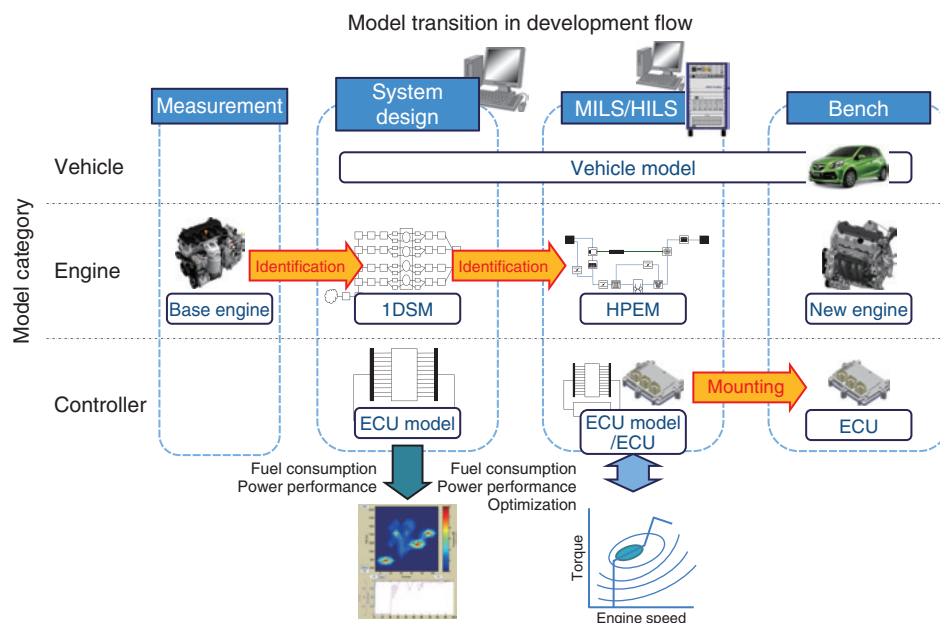


Fig. 3 Identification flow for engine plant model

categories and the transformation of the models in the development process. Considering the engine plant models that are the control objects, first a 1DSM is identified from bench measurement results for an existing engine. Next, the specifications of the 1DSM are changed to match the engine in development. Following this, the HPEM is identified from calculation results produced by the modified 1DSM. The use of the plant model obtained by means of this sequential identification in HILS and MILS makes it possible to directly reflect system conditions verified at the system level at the controller level, thus helping to enable front-loading of verification of ECU performance.

2.3. Criteria for Judgment of the Realization of Goals in Plant Models

The verification procedures and criteria for judgment of the realization of goals used to verify the validity of the sequential system identification environment and the HPEM discussed in Section 2.1 are discussed below.

2.3.1. Criteria for sequential system identification

In order to verify the functioning of the sequential system identification environment, first the results of identification of an existing engine and a 1DSM were compared in order to determine whether error fell within an acceptable range. The results of identification of 1DSM and an HPEM were then compared, and it was similarly determined that error was within an acceptable range. As criteria for judgment of the realization of goals, the range of error for the comparison of the existing engine and the 1DSM was set at an error of within 3% for the intake and exhaust system, and the range of error for the comparison of the 1DSM and the HPEM was set at an error of within 3% for BSFC.

The criterion for the comparison of the existing engine and the 1DSM was limited to the intake and exhaust systems because the combustion system of the 1DSM directly incorporated measurement results for the existing engine as empirical formulae, and therefore there was no need for a comparison of accuracy. The range of acceptable error was set at 3% in each case because the variation in measurements on an actual engine bench is around 3%, and if this figure were achieved, the plant model could be considered to have achieved sufficient accuracy as a control object.

2.3.2. Criteria for HPEM

In order to verify the performance of the HPEM, the plant model obtained through sequential system identification was first employed in MILS with a simple ECU simulation, and its operation was verified in each of the driving cycles used for calculation of fuel efficiency. Next, the same plant model was used in HILS, and its operation was again verified, this time connected to a real ECU. The criterion for judgment was the ability to conduct calculations in real time in the largest time steps for convergence of the calculations, using an HIL simulator available in the market. This was because the performance verification focused chiefly on the plant model's

ability to function in actual use despite the fact that the time steps for convergence of calculations differ depending on the types of models and solvers employed in the computation.

3. Development of HPEM

3.1. Composition of HPEM

By contrast with the 1DSM used in the system design process, which successively calculates the intake and exhaust air and combustion state for each crank angle, a standard MVEM is an average value model that averages output for each combustion cycle on the time axis. Because MVEM do not conduct one-dimensional or three-dimensional CFD calculations, their computation load is low, and by contrast with MAP engine models, they are able to express dynamic behavior through the use of differential equations. For these reasons, they are employed as control object models during controller design.

In order to reduce the computation burden for the HILS, using an MVEM as a base, the HPEM empirical formulae and response surfaces created from formulae and measurement values widely known from standard textbooks and papers were sorted through based on considerations of calculation accuracy and computation load. With regard to the expression of characteristics by means of the formulae, the throttle valve, intake manifold, cylinder, exhaust manifold, turbine, compressor, intercooler, catalyzer and other parts were modeled individually in detail to make it possible to reflect the predicted values from the 1DSM (Fig. 4). Simplification of the large number of formulae employed for the individual components using formula processing software further reduced the computation load, and helped enable calculations to be performed in real time.

3.2. Overview of HPEM Calculations

The HPEM is composed of an intake and exhaust system model that calculates the flow of air and EGR gas and a combustion system model that performs calculations for combustion in the cylinders. Calculations are performed with the engine speed and ECU command values as the points of origin.

Air is taken into the cylinders by means of engine rotation, and this reduces intake manifold pressure. Indicated mean effective pressure (IMEP) is calculated from the volume of air taken into the cylinders and ECU command values fuel injection amount and ignition timing, and engine speed is calculated from this IMEP, pumping mean effective pressure (PMEP), friction mean effective pressure (FMEP), and load torque from the transmission and the engine's moment of inertia. In addition, turbine and compressor work is calculated from the exhaust gas from the cylinders and the degree of opening of the wastegate, an ECU command value, and the intake air is supercharged. The volume of air passing through the throttle is calculated from this supercharging before and after the throttle, the intake manifold pressure, and the opening of the throttle valve, an ECU command value.

3.2.1. Intake system model

The intake system model is a zero-dimension model using a lumped parameter system that does not consider spatial extension. Using equations of state for gases ($PV = mRT$), equations of continuity (conservation of mass), the relationship of quantity of heat, and orifice equations, this model is made up of receivers and orifices.

The throttle model formulae⁽⁶⁾ are shown below for reference.

$$\dot{m} = C_d \cdot A(t) \cdot \frac{p_{in}(t)}{R \cdot \mathcal{G}_{in}(t)} \cdot \Psi \left(\frac{p_{in}(t)}{p_{out}(t)} \right)$$

$$\Psi \left(\frac{p_{in}(t)}{p_{out}(t)} \right) = \begin{cases} \sqrt{\kappa \left[\frac{2}{\kappa+1} \right]^{\frac{\kappa+1}{\kappa-1}}} & \text{for } p_{out} < p_{cr} \\ \left(\frac{p_{out}}{p_{in}} \right)^{\frac{1}{\kappa}} \cdot \sqrt{\frac{2\kappa}{\kappa-1} \cdot \left[1 - \left(\frac{p_{out}}{p_{in}} \right)^{\frac{\kappa-1}{\kappa}} \right]} & \text{for } p_{out} \geq p_{cr} \end{cases}$$

$$p_{cr} = \left(\frac{2}{\kappa+1} \right)^{\frac{\kappa+1}{\kappa-1}} \cdot p_{in}$$

t : Time
 $\dot{m}(t)$: Mass flow through the valve
 C_d : Discharge coefficient
 $A(t)$: Open area of the valve
 $p_{in}(t)$: Pressure upstream of the valve
 $p_{out}(t)$: Pressure downstream of the valve
 p_{cr} : Critical pressure where the flow reaches sonic conditions
 R : Gas constant
 $\mathcal{G}_{in}(t)$: Air temperature
 κ : Ratio of specific heats

3.2.2. Combustion system model

The combustion system model calculates in-cylinder pressure by substituting rate of heat generation and cylinder capacity defined by empirical formulae in the first law of thermodynamics, equations of state, and relationships of specific heat, and calculates IMEP by integrating this in-cylinder pressure based on changes in volume. This combustion model is also able to calculate changes in output due to ignition timing and combustion parameters such as location of 50% mass fraction burned and amount of heat generation.

4. Construction of Sequential System Identification Environment

Generally speaking, two methods of system identification are available depending on the object of the identification.

The first of these is gray box model identification. A gray box model is a model described by formulae based on the physical equations that govern the object of identification when the system structure is almost entirely clear. Parameters also exist for which the physical characteristics cannot be measured via this model, and system identification is conducted in order to estimate these parameters. This method is termed correlation.

The other method is black box model identification. A black box model is modeled based exclusively on numerical relationships in input and output without consideration of details of what is actually occurring in a system when the system structure is unclear or complex, making description difficult. For the identification of these models, approximation equations are formulated to match input and output using methods including the least squares method. This method is called response surface generation.

Depending on the characteristics of the individual

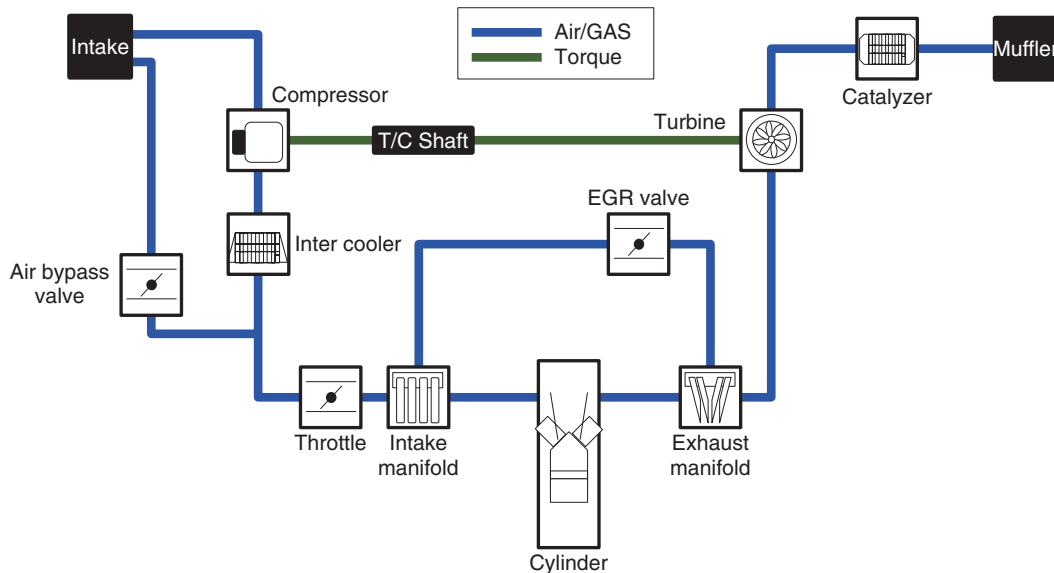


Fig. 4 High Performance Engine Plant Model (HPEM)

sections of the plant models, the correlation described above and the generation of response surfaces were employed in combination in the sequential identification of the 1DSM and HPEM from the existing engine.

Turning to actual identification procedures, first, the flow of identification of the engine intake and exhaust systems is shown in Fig. 5(a). Initially, correlation was performed with the cylinder wall temperature of the 1DSM as an identification parameter in order to match the volumetric efficiency of the 1DSM with the volumetric efficiency of the actual engine, set as an index value, within a specified range of error. The optimum value search method using a genetic algorithm (GA) was employed as the correlation algorithm. Next, response surfaces for the volumetric efficiency characteristic were generated from the 1DMS using Design of Experiments (DOE), with engine speed, target intake air pressure, ignition timing, VTC and other parameters as design variables. The formulae generated here were incorporated in the HPEM.

Figure 5(b) shows the flow of identification of the combustion system. Response surfaces for combustion center of gravity and combustion period are generated from the in-cylinder pressure waveform measured in the existing engine, with operation amounts that affect the combustion state as design variables. The equations for these response surfaces were incorporated in the Wiebe equations⁽⁷⁾ in the 1DSM combustion model. The identification parameters were correlated using a GA to match the output of the HPEM combustion model with the output for combustion from the 1DSM, set as an index value, within a specified range of error.

Finally, parameters such as the detailed characteristics of each component and friction loss were determined by sequential system identification for the existing engine,

1DSM and HPEM, and engine plant models were produced in which output torque and BSFC matched within an acceptable range of error.

5. Operational Verification of Plant Model

Studies were conducted to verify the effectiveness of both the HPEM and the sequential system identification environment.

5.1. Verification of Effectiveness of Identification

In order to verify the effectiveness of the sequential system identification environment, the results of system identification for the intake and exhaust systems of a prototype engine and the 1DSM were first compared. Figure 6 shows a comparison of volumetric efficiency for the engine and the model.

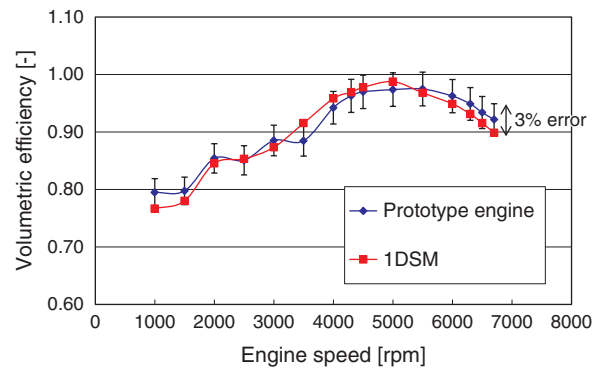


Fig. 6 Comparison between prototype engine and 1DSM

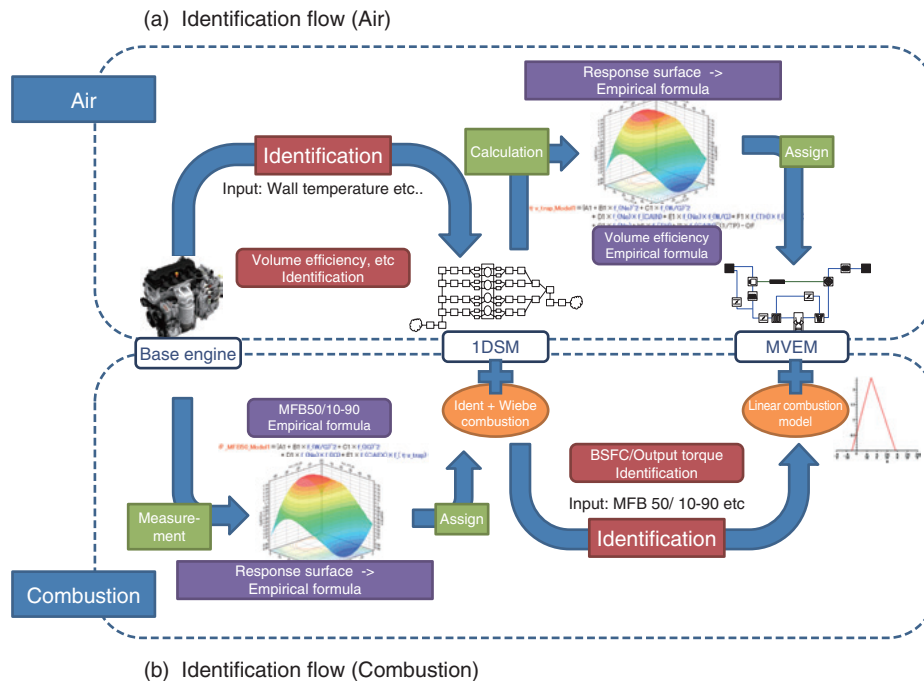


Fig. 5 Identification flow

The horizontal axis of the graph shows engine speed, and the vertical axis shows volumetric efficiency. These results indicate that error is within the acceptable range of up to 3%.

Next, the results of system identification for the 1DSM and the HPEM were compared. Figure 7 shows the results of a comparison of BSFC for both models. Results for BSFC are similarly within the acceptable range of error of up to 3% at all engine speeds.

In addition to this, input and output was studied for each component, and the behavior of the plant models was found to match within the acceptable range of error.

5.2. Verification of Effectiveness of Model

In order to verify the functioning of the HPEM, the plant model following sequential system identification was first employed in an MILS with a simple controller model, and its operation was verified in driving cycles employed for the calculation of fuel efficiency and acceleration performance. Next, the same plant model was employed in an HILS (the configuration will be discussed below), in which it was connected to an actual ECU, and put through the same operational verification.

Figure 8 shows the configuration of the HILS. The ECU and a real-time simulator were connected by means of a load rack. The load rack functioned to supplement signals that it was difficult to model in the simulator through actual devices, and contained elements including a linear solenoid, an injector, DBW, a heater resistance and a dummy load resistance.

Figure 9 shows results obtained by operating the prototype engine and the HILS plant model in two different fuel efficiency driving cycles, JC08 and NEDC. The volume of intake air for the engine bench and the HILS were compared for both operating driving cycles. The engine plant model displayed dynamic behavior close to that of the actual engine in both driving cycles, indicating that it possesses sufficient accuracy to be used in the verification

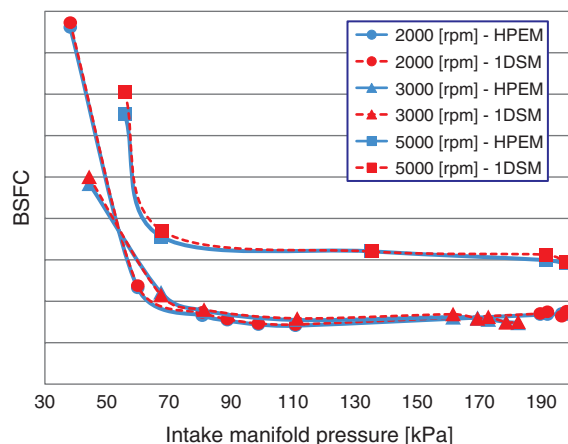


Fig. 7 Comparison of 1DSM and HPEM

of ECU performance without necessitating the employment of specific driving cycles.

Figure 10 shows the computation time for the HILS using the plant model. The graphs show how much actual computation time was necessary for each time step. The verification that produced these results used a sampling time of 200 μ sec in order to converge the calculations. The computation time for the plant model for each sample in both driving cycles was less than 90 μ sec, indicating the achievement of sufficient computation speed for real-time computation.

The results discussed above demonstrate that the developed HPEM realizes sufficient accuracy and computation speed for use in both the MILS and HILS employed in the controller level of the design and test processes.

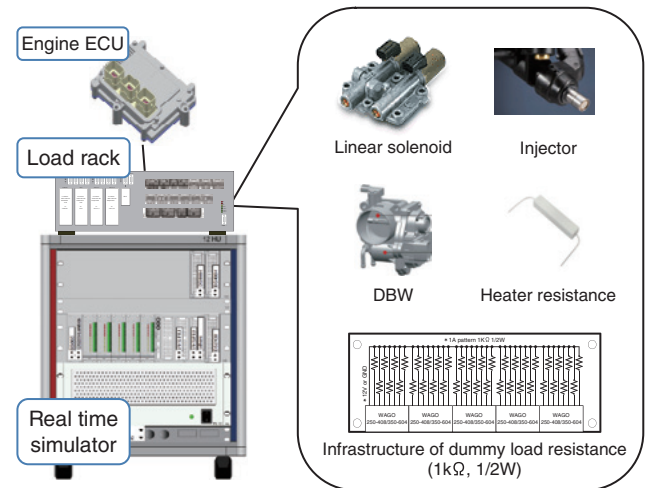


Fig. 8 Hardware-in-the-Loop Simulation (HILS)

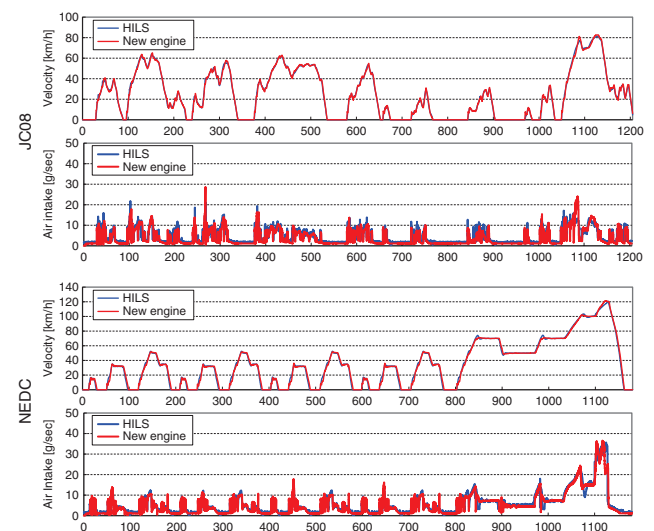


Fig. 9 HIL simulation result

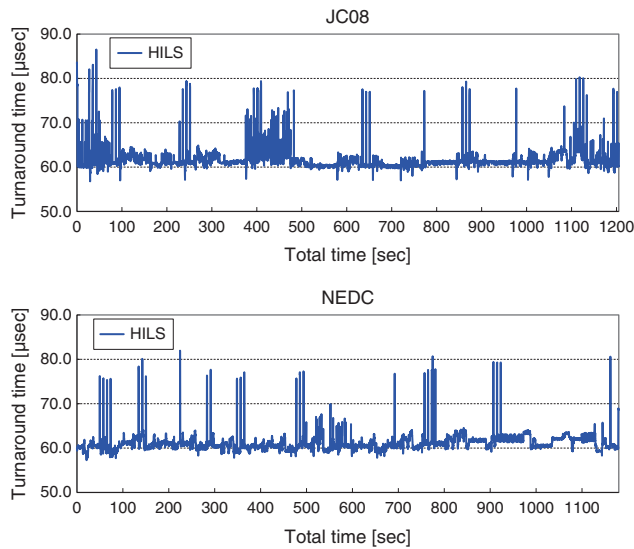


Fig. 10 Turnaround time of HIL simulation

6. Conclusion

In order to address the plant model-related issues of mismatches between models at the same level and inconsistency between models at different levels when realizing a combination of MBD and V-model-based development at Honda, the following technologies were developed and their effectiveness was verified.

- (1) An HPEM able to be used in both the design and test processes at the controller level was developed, and its functioning was verified in MILS and HILS. This technology made it possible to realize a match between models at the same level.
- (2) An environment making possible sequential system identification of 1DSM and HPEM from an existing engine was created, helping to enable the realization of consistency between models at different levels.

7. Afterword

The use of the developed HPEM and sequential system identification environment is expected to increase the efficiency of developments employing a combination of MBD and V-model-based development. In future the effectiveness of combined MBD and V-model-based development will be verified through the use of new control logics created using the new environment in developments.

The continued operation and management of these environments will be important in attempting to ensure that the combination of MBD and V-model-based development takes root. The education of engineers will also raise numerous issues, and the authors believe that it will be necessary for all development staff to share a vision of the future and strategically promote the new development method in order to address these issues.

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