

Application and Utilization of HILS for the Development of an Automatic Transmission Control System

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ABSTRACT

In connection with development of an automatic transmission electronic control unit (AT ECU), a development aid technology known as hardware in the loop simulation (HILS) was introduced for testing with the objective of improving AT control reliability and shortening the time required for development. In order to realize the HILS technology, it was necessary to assure the calculation accuracy in AT shift feeling simulation models and to perform real-time simulations using the existing digital signal processors (DSP). The present development improved the method of modeling the AT hydraulic pressure control system. HILS implemented multi-rating, reducing the scheduler overhead, thus making it possible to lighten the calculation burden on the central processing unit (CPU). As a result, it became possible to perform real-time simulations with assured calculation accuracy, which allowed HILS technology to be utilized during the development of the AT shift control system.

1. Introduction

A new version of a development aid technology called hardware in the loop simulation (HILS) was developed and incorporated into current automatic transmissions (AT) simulation technology ⁽¹⁾ to see whether it would be effective in improving the control reliability and reducing development time as part of the development of an electronic control unit (ECU) for AT.

In the flow of development of an AT control system incorporating HILS, the control system parameters are set using HILS before actual vehicle testing begins. HILS is necessary in order to achieve sufficient calculation accuracy to replace part of the testing with actual vehicles.

Real-time simulations have not been traditionally possible even when using the most sophisticated commercial digital signal processors (DSP) because HILS places huge calculation loads on the central processing unit (CPU). However, a new HILS was developed which maintains calculation accuracy in real-time simulations and can be run on an existing DSP. It is described in this paper.

An example of development of a new AT shift control system using the HILS is also described.

2. Outline of HILS System for AT

2.1. System Configuration

The developed HILS system is made up of 6 components, as shown in Fig. 1: A host computer, a DSP system, an interface box, a relay box, an On-board Diagnostic Systems Stage II (OBD II) monitor, and an AT control ECU. The host computer is used for modeling, downloading the model to the DSP system, inputting parameters for the simulation, analysis and displaying the results.

The DSP system performs the real-time simulation on an Alpha CPU for model calculation, a C40 CPU for I/O processing, and a signal processing board. Here, the Alpha was a trademark for COMPAQ, and the C40, for Texas Instruments.

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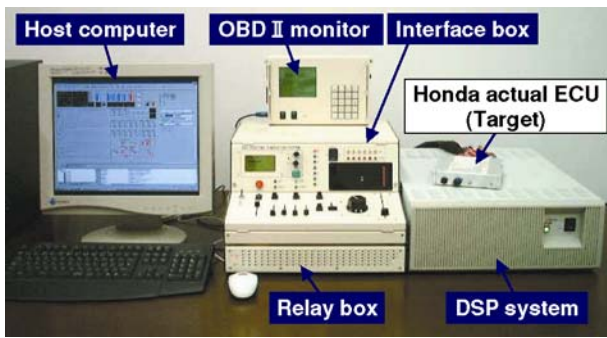


Fig. 1 HILS system overview

The interface box electrically combines the input and output signals from the DSP system line with the signal corresponding to the vehicle connected to the ECU line, and handles processing of the signals corresponding to control actions during manual or automatic driving such as operation of the shift lever, the acceleration pedal, or the

brake.

The relay box gives failure conditions of any of the circuits in all the other units.

The OBD II monitor is connected to the ECU and detects failure and failsafe action conditions. The AT control ECU receives the signals from the interface box and performs shift control every 10 ms.

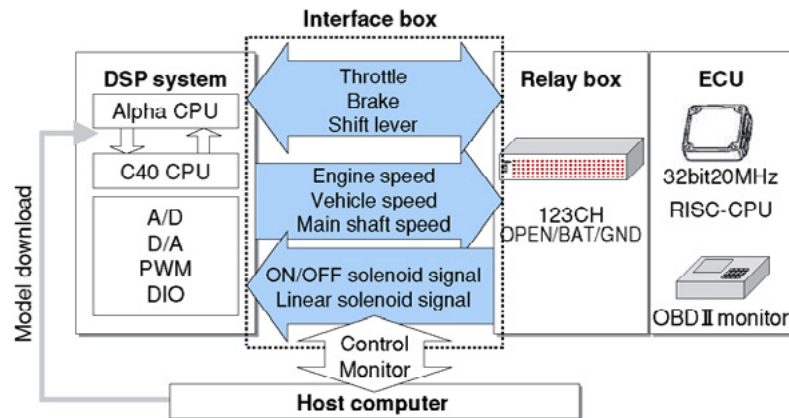
As shown in Fig. 2, the DSP system and ECU are connected via the interface box and relay box.

2.2. AT HILS Model

2.2.1. Model configuration

As indicated in Fig. 3, AT can be divided into the torque transmission system, which is part of the power plant, the hydraulic control system, and the ECU, which is part of the AT electronic element control.

In this HILS, the torque transmission system and the hydraulic control system were mathematically modeled⁽¹⁾, and the HILS was connected to an actual ECU through the



where: PWM = Pulse Width Modulation
DIO = Digital Input and Output
RISC = Reduced Instruction Set Computer

Fig. 2 HILS system schematic

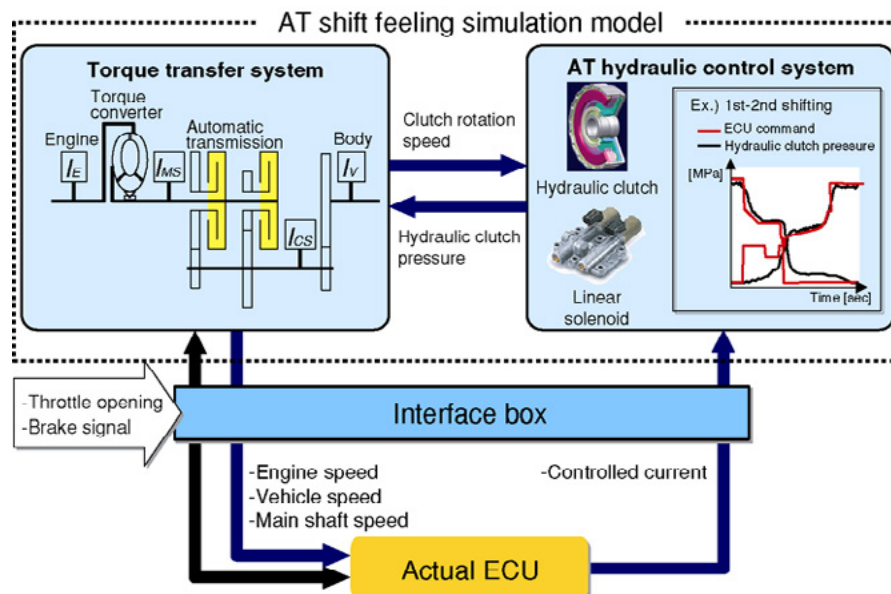


Fig. 3 AT electronic control system schematic

interface box. The following section describes the mathematical models of the torque transmission system and the hydraulic control system.

2.2.2. Model of torque transmission system

Figure 4 illustrates the power flow. Engine torque is supplied by the crankshaft and transmitted through the torque converter to the main shaft. Next, it passes through each gear clutch to the countershaft, and through the final speed reduction gear to the drive shaft. It is possible to calculate the characteristics of the torque transmitted and the rotational speed of each shaft with numerical integration like the Runge-Kutta method.^{(1), (2)} The expressions for this method are shown below:

$$\text{Crank shaft} \quad T_E - T_{MS}/t - I_E \cdot \omega_E = 0 \quad (1)$$

$$\text{Torque converter} \quad T_{MS} = t \cdot c \cdot (\omega_E/1000)^2 \quad (2)$$

$$\text{AT Main shaft} \quad T_{MS} - T_L - T_H - I_{MS} \cdot \omega_{MS} = 0 \quad (3)$$

$$\text{AT Counter shaft} \quad T_L \cdot i_L + T_H \cdot i_H - T_{CS} - I_{CS} \cdot \omega_{CS} = 0 \quad (4)$$

$$\text{Drive shaft} \quad T_{CS} \cdot i_F - T_{LOSS} - I_V \cdot \omega_V = 0 \quad (5)$$

$$\text{Hydraulic clutch} \quad T_{CL} = \mu \cdot n \cdot r (P_{CL} \cdot A_{CL} - F) \quad (6)$$

Nomenclature

I	: Inertia [$\text{N} \cdot \text{m} \cdot \text{s}^2$]
i	: Gear ratio
ω	: Angular velocity [rad/sec]
T	: Torque [$\text{N} \cdot \text{m}$]
t	: Torque ratio of the torque converter
c	: Pump capacity coefficient of the torque converter
μ	: Clutch disk friction coefficient
n	: Number of clutch disk
r	: Clutch disk effective radius
P	: Hydraulic clutch pressure
A	: Hydraulic clutch piston bearing area
F	: Clutch return spring load

Subscripts

E	: Engine
MS	: Main shaft
CS	: Counter shaft
V	: Body
H	: High gear
L	: Low gear
F	: Final gear
CL	: Hydraulic clutch
$LOSS$	: Running resistance

2.2.3. Model of hydraulic control system

Figure 5 represents the structure of the hydraulic control circuit for the AT. The pressure from the oil pump is supplied through the regulator valve to the shift valves, linear solenoids, etc. to control the pressure at the clutches for each shift stage.

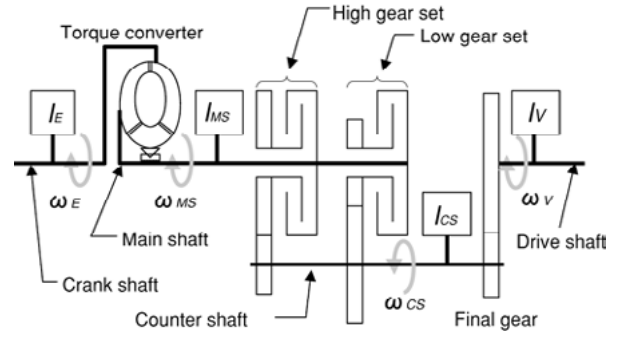


Fig. 4 The parallel shaft type AT schematic

Since applying this hydraulic control circuit within the HILS lightens the calculation load for the model, the transfer function for the hydraulic pressure (Fig. 6) was adopted. As shown in Fig. 7, this transfer function predicts the control pressure at each clutch, in accordance with the hydraulic control command. It defines the settling time, which is the period from the starting time of a control command to the time when the oil in the clutch is completely filled, leaving the deviation with respect to the command within the standard range.

The hydraulic pressure transfer function consists of the adjustable delay time and the variable first-order time-lags. The coefficients for adjustable delay times and the first-order time-lags were each expressed with AT fluid temperature, clutch speed and clutch control pressure in two types of 4-dimensional maps, one for release and one for engagement. The first-order time-lag coefficient maps were determined using a general maximum likelihood estimation method, taking into account the experimentally revealed characteristics of AT oil during transmission shifting.

Figure 8 displays the results of a simulation of the clutch control pressures during 2nd – 3rd upshift, obtained with the model incorporating the hydraulic pressure transfer function. This shows a good match with the experimental results in an actual transmission. The predictions of the clutch control pressures with this simulation method closely reproduce the influence of the dynamics of the hydraulic control system. Also, using the hydraulic pressure transfer function reduced the CPU calculation load to just 1/30 of that necessary with the conventional detailed model at the same level of accuracy.⁽¹⁾

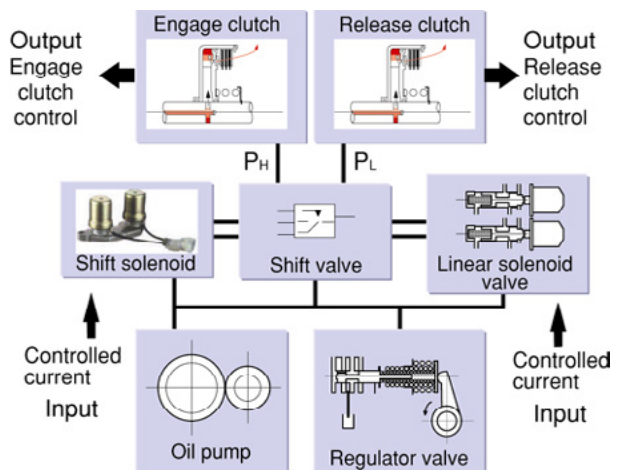


Fig. 5 AT hydraulic control system

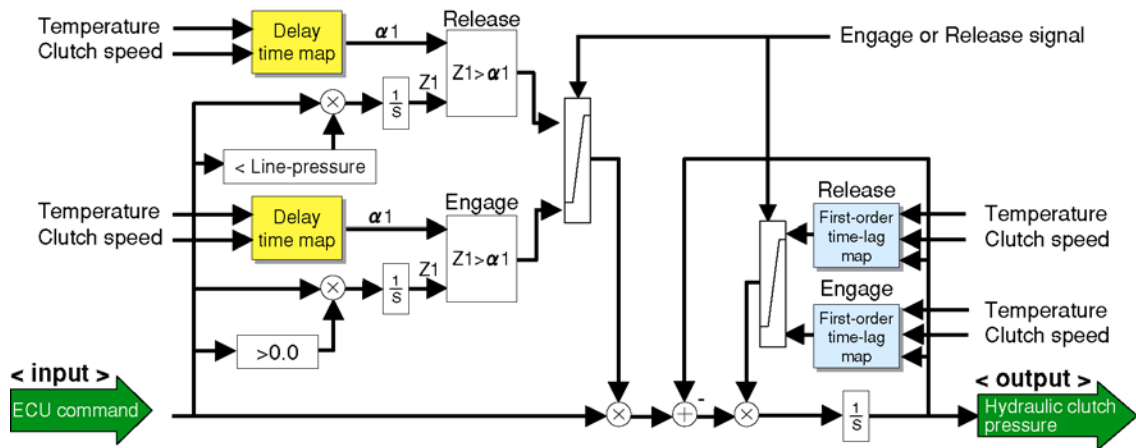


Fig. 6 The transfer function hydraulic pressure

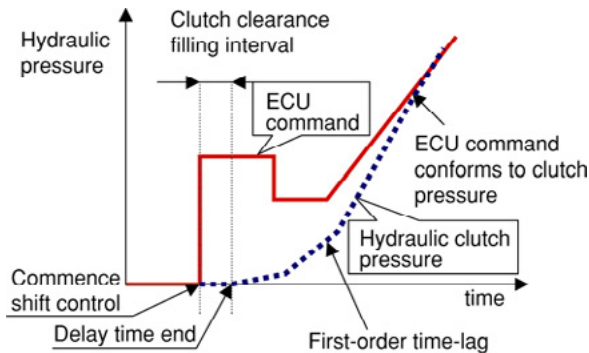


Fig. 7 Delay time and first-order time-lag

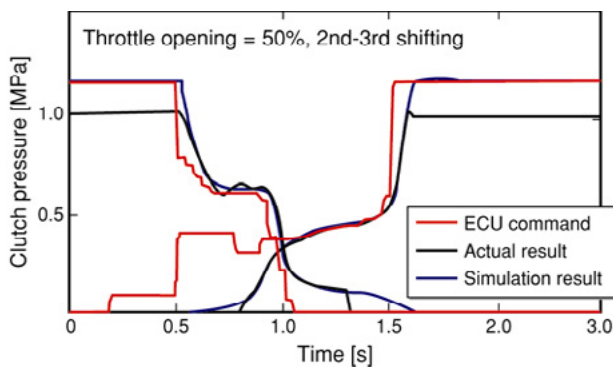


Fig. 8 Verification results of simulation accuracy

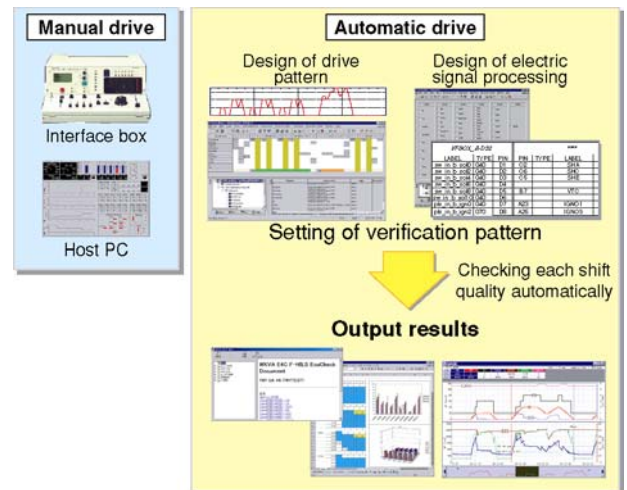


Fig. 9 Environment of HILS test

Table 1 HILS parameters

Classification	Element
Engine	Engine torque irregularity
Clutch	Coefficient of friction
	Clutch clearance
Condition	Vehicle weight
	Grade resistance
Mechanical trouble	Electronic circuit (Short circuit, Broken wires)
	Hydraulic circuit valve

2.3. Environment of HILS Test

This HILS system allows both manual drive tests and automatic drive tests, as shown in Fig. 9.

In the manual drive test, the operator controls the HILS by setting the levers and switches in the interface box, directly operating the interface on the host computer.

In the automatic drive test, the HILS is controlled by activating pre-written programs which set the parameters listed in Table 1 and others, including those of the cruise mode. No further action by the operator is necessary.

In this test mode, the AT shift control system is automatically assessed according to the items in Table 2. The test results are outputted in an HTML-format test report file including tables and graphs.

A data analysis tool was developed which was capable of processing large numbers of data channels with high sampling rates. The analysis tool helped streamline the

Table 2 HILS evaluation method for AT control system

1	The engine speed must not flare while shifting.
2	Heat of the clutch must be lower than standard.
3	Shifting time must be shorter than standard.
4	Change of drive shaft torque must be smaller than standard.
5	The trouble should be able to be judged accurately.
6	It must be able to run.

process, allowing HILS to analyze and process the results from a huge number of tests in a short time.

Verification of the OBD II must use the same automotive situation under many driving conditions. Failure of the ECU must be detected under a large variety of types and patterns of failure, including various combinations in double failures under various timing patterns.

It was confirmed that HILS was an effective development aid technology for conducting tests that would be difficult to create in an actual vehicle. The automatic testing and analysis environment provided by HILS shortened development time and improved control reliability.

3. Adapting Simulation for Real-time Testing

3.1. Issues in Real-Time Simulations

In order to realize a real-time simulation, it is necessary for the CPU execution time to be less than the sampling rate.

The existing torque transmission system model described in section 2.2 was used. The results of a non-real time simulation of a 1st – 2nd upshift are shown in Fig. 10.

The characteristics of the hydraulic pressure observed in a real car were used as the input for this simulation and the output variable was the drive shaft torque. The sampling rate was first set at 20 μ s to obtain the same level of precision as in a test of an actual vehicle; for comparison purposes, it was also set at 200 μ s, one-tenth the precision.

At the sampling rate of 200 μ s, the drive shaft showed a large oscillation in torque, indicating that this sampling rate did not yield enough precision in the calculations.

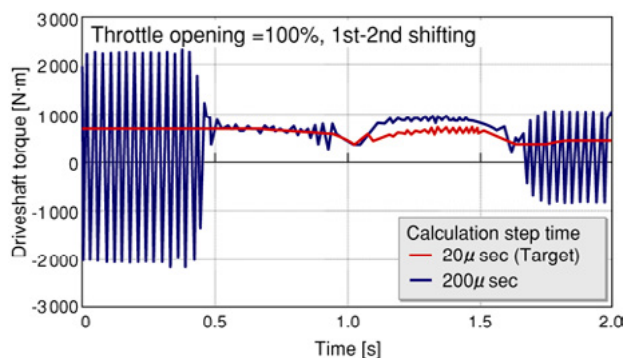


Fig. 10 Non-real-time simulation result

It is notable that when the same test was performed at a single rate in an AT HILS system using a commercial DSP system (Fig. 1), the CPU execution time, corresponding to the sampling rate, was 140 μ s.

These results show that fast CPU execution times are necessary in order to observe the AT shift feeling in real time. Therefore, two improvements were performed; multirating of the HILS model and reduction of the scheduler overhead.

3.2. Multirating

Multirating is a well-known, effective method for obtaining the maximum performance from a CPU with limited execution speed.

The HILS model (2.2) was analyzed in detail to examine the practicality of multirating.

This analysis showed that the time constant of a component consisting of a combined λ function and an integrator was the smallest component of all, and was about 20 μ s. In other words, this component was the dominant factor in the necessity for the very short sampling rate necessary to obtain an accurate reproduction in this model of tests in an actual vehicle.

The reason that a very short sampling rate is required is the component consists of a combined λ function and an integrator representing the rotational inertia of the main

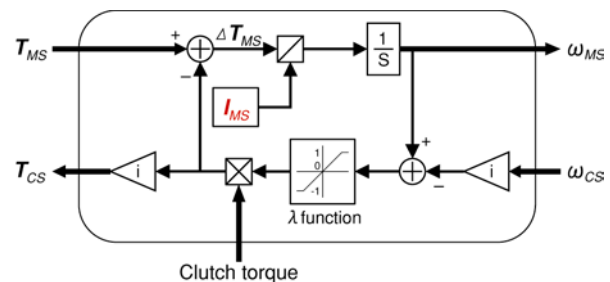


Fig. 11 λ function model for AT torque transfer model

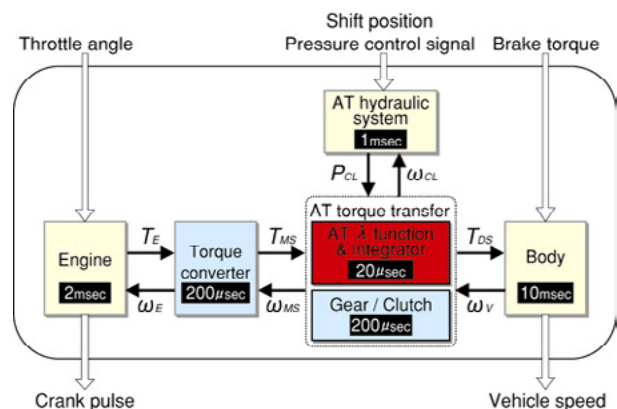


Fig. 12 Multi-rating AT HILS model

shaft (I_{MS}), which is $7.0 \times 10^{-3} \text{ N} \cdot \text{m} \cdot \text{s}^2$ which is much smaller than the inertia of the engine and vehicle body. Since there were no other such factors influencing accuracy in the rest of the model, the sampling rate was increased to longer than $200 \mu\text{s}$. Figure 12 shows the layout of the multirated HILS model and the sampling rates in the other parts of the model.

3.3. Reduction of Scheduler Overhead

Generally, the scheduler overhead must be increased during multirating.

After the multirated HILS model had been actually downloaded and the CPU execution time of the entire model had been measured, it was found to be 108% of the sampling rate of the entire model (upper portion of Fig. 13). This was attributed to the very large fraction of execution time taken up by the scheduler overhead.

The following steps were taken to reduce the scheduler overhead.

As shown in the lower portion of Fig. 13, the only part of the system consisting of the combined λ function and integrator (Fig. 11) which requires minimum sampling rate was programmed to take a certain number of repetitions of sampling; namely 10 times in $200 \mu\text{s}$, as necessary for this component within sampling rate. A user code block was used for this.

When the version of the HILS model with the user code block was downloaded and the CPU execution time for the entire system was measured, it was found to be a maximum of $135 \mu\text{s}$, including the scheduler overhead. The CPU execution time was 68% of the sampling rate for the entire model, which was judged to leave a sufficient margin.

Thus, a high-speed HILS, capable of approximating a sampling interval of $20 \mu\text{s}$, was developed using multirating and by reducing the scheduler overhead.

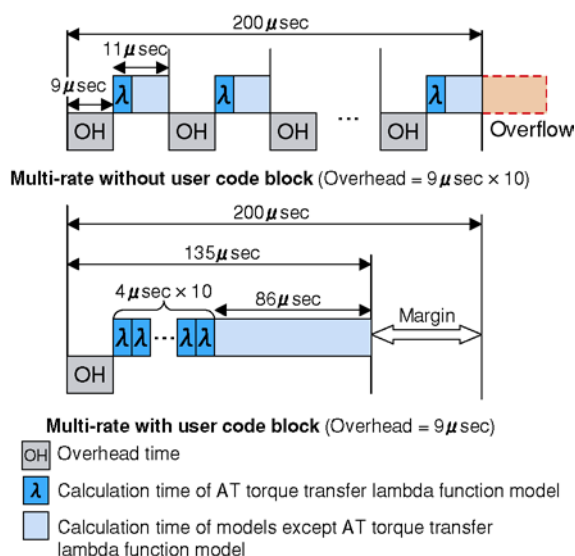


Fig. 13 Measuring results of actual CPU execution times

3.4. Verification of Precision of AT HILS

Calculations in High-Speed Simulation

Figure 14 shows the results of a simulation of a 1st - 2nd upshift, as in section 3.1, by the new HILS with multirating and reduced scheduler overhead.

It is clear from the results of the non-real-time simulation using the $20 \mu\text{s}$ sampling rate, that this simulation method can be used in place of actual vehicle testing. Actual vehicle test data matches well with the results from the HILS model. This means that a real-time simulation for AT shift feeling incorporating a real ECU is accurate enough to replace testing in an actual vehicle.

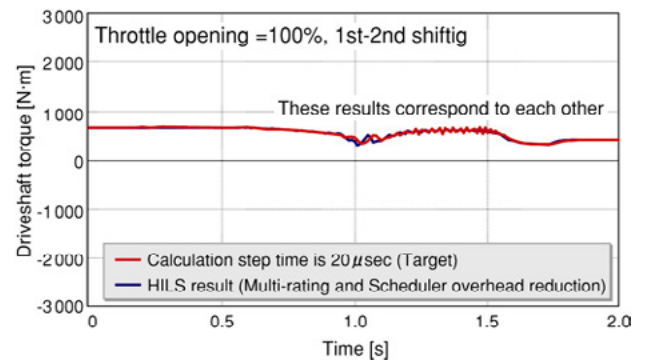


Fig. 14 HILS result

4. Example of Applications

A case of application of HILS in development of an automatic transmission control system is introduced here. Both shift feeling and durability were maximized in optimizing ECU data for this product.

In the conventional development flow shown in Fig. 15, i.e., the pre-HILS process, the durability testing was performed in actual transmissions after the desired data had been preferentially obtained for shift feeling. When malfunctions became evident during durability testing, testing was stopped and ECU data was reset for another round. Testing was repeated so as to find the optimal ECU settings for the product.

In contrast, in the new developmental flow incorporating HILS, ECU data is set by HILS to maximize the reliability of the results in terms of durability after shift feeling tests, prior to the durability tests. A single, final test is then required to verify durability.

Figure 15 shows an example of how the optimized ECU data was identified with HILS after the higher-priority tests of shift feeling had been run to set the data, in the new development flow.

Figure 16 displays the results of the test for a 2nd – 3rd upshift with the throttle opening set at 50%; ECU data had been set to prioritize shift feeling. Figure 17 displays the same results, except that both shift feeling and durability had been given high priority.

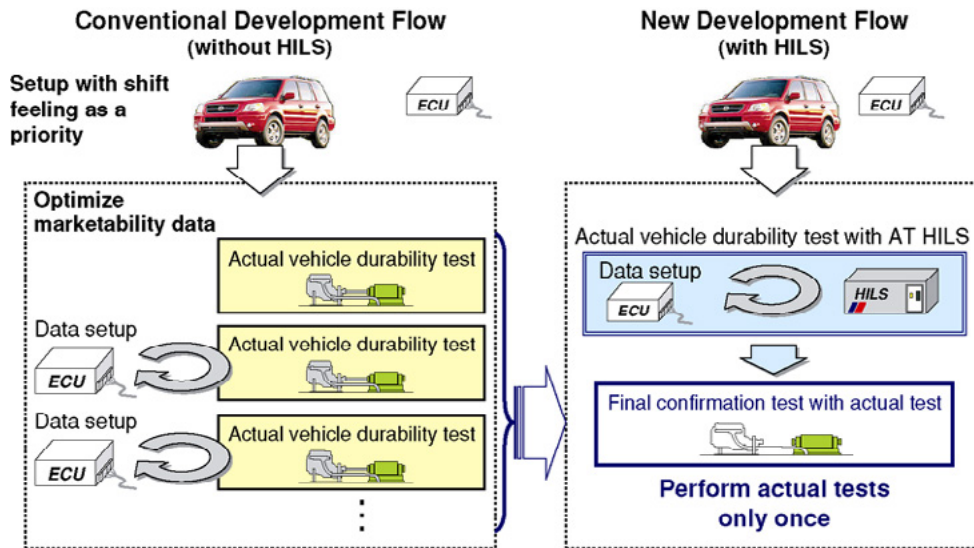


Fig. 15 Optimum data setup balancing shift feeling and durability

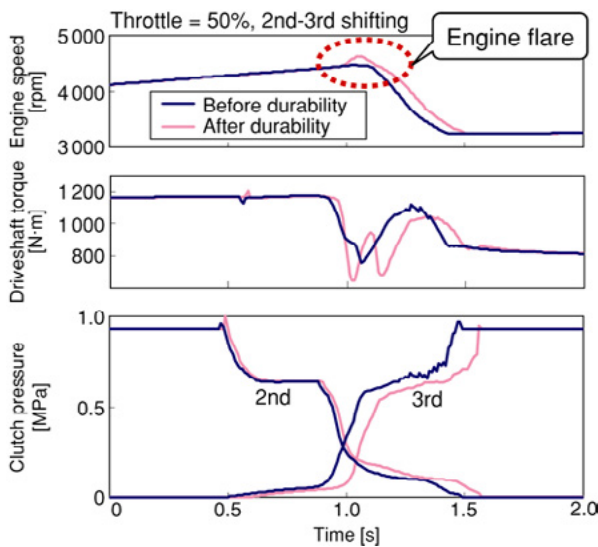


Fig.16 HILS results with initial ECU data

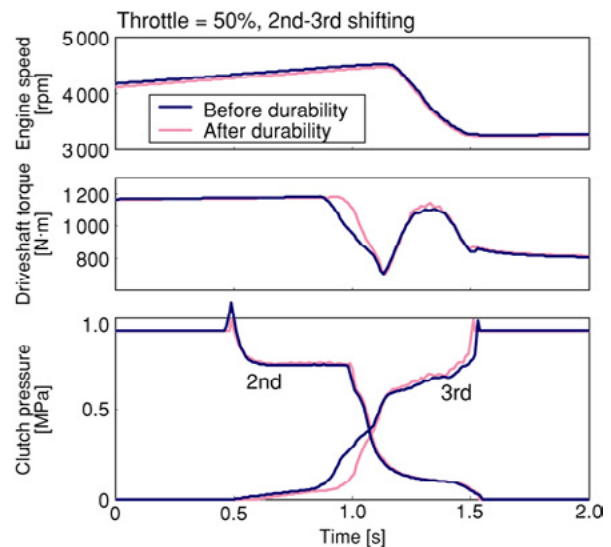


Fig.17 HILS results with refined ECU data

The figures show that the predicted variation in performance after the effects of use had changed the factor of clutch clearance, according to the ECU settings and analysis with HILS.

A good shift feeling was initially obtained, but this deteriorated with use and there was eventually an engine flare during shifting, as shown in Fig. 16. The ECU data were reset, because of this malfunction; specifically, the feedback gain of the 2nd and 3rd hydraulic clutch pressure control was optimized.

As a result, the shift feeling was good both initially and after wear (Fig. 17).

The durability test of an actual transmission was run after the ECU data had been optimized with HILS. This confirmed the maintenance of good shift feeling.

Thus, it has become possible to develop optimized product ECU data in a short time, without waiting for a time-consuming durability test of an actual transmission.

5. Summary

- (1) A transfer function of hydraulic pressure composed of an adjustable delay time and variable first-order time-lags was created in order to reduce CPU calculation load in transmission modeling; CPU load was found to be 1/30 that in conventional detail modeling methods.
- (2) Multitasking and reduction of the scheduler overhead were accomplished in order to attain a high-speed 20 μ s execution time, which allowed use of a commercial DSP to carry out real-time simulations of AT shift feeling with

sufficient accuracy to replace testing with actual transmissions.

- (3) By applying HILS to the development of the AT control system, it has been proved that real model testing can be replaced with desktop testing, which in turn can shorten development time while simultaneously improving AT control systems.

The HILS method will be applied in all types of AT control system development because it shortens the development times for reliability improvements in AT control systems.

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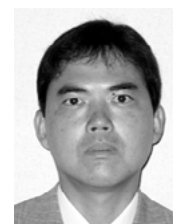
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