

Development of a Vehicle Dynamics Simulation System under a Running Mechanical Control Device

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ABSTRACT

A coupled simulation using concurrent execution of mechanical and control simulations was developed and applied to help predict vehicle behavior while under mechanical control. Also, a technique was developed for the automatic generation of real-time programs based on mechanical models applicable to HIL simulators, which require real-time executable calculations. This greatly eased accounting for the influence of vehicle body mechanisms in the behavior of suspensions and other systems. Thus, it is now possible to carry out “paper experimental tries” and HIL simulator tries of simulations of full vehicle behavior under the control of systems such as EPS or VSA. Formerly difficult predictions of vehicle behavior due to steering wheel torque or in non-linear regions have now become possible.

1. Introduction

During the initial stage of design of automotive suspensions, several modifications are performed to improve the steering stability and feeling of the vehicle. Many parameters are modified: stiffness of bushings, suspension mechanisms and structure, etc. Meanwhile, the functional range of vehicle mechanism control devices has been expanded with systems like electric power steering (EPS) and the vehicle stability assist (VSA) system. These contribute much to vehicle behavior.

No simulation technologies have yet been established, however, for predicting vehicle behavior while these mechanism control devices are functioning. This has restricted designers from considering the influence of the dynamic characteristics of the suspension during braking in development of related devices, for example, an ABS controller. A technique for coupled simulation of mechanisms and their controls using a simple mechanical model has been reported⁽¹⁾, but there have not been any examples of application to an automobile chassis.

In the present research, a technology enabling concurrent execution of simulations of mechanisms and controls including a hardware in the loop (HIL) simulator was

developed in order to enable prediction of vehicle behavior while mechanism control devices are functioning. The results indicated that it allows consideration of the influences of the non-linear and dynamic characteristics of suspension and steering linkages on control systems.

2. Simulation Types

Two technologies were developed, for application in the appropriate methods or stages of development of the automobile control systems:

- (1) Coupled simulation for mechanism controls; and
- (2) Automatic generation of real-time executable programs for the HIL simulator.

Generally, when the control logic is already determined at the upper stages of development and a block diagram or other model can be made, this can be formulated and simulated off-line in a paper experimental try. Simulation (1) above is used when there is control-mechanism coupling. However, when the control logic is a blackbox, for example, or when the ECU hardware itself is to be investigated, tasks which usually occur in later stages of development, modeling must be done with an HIL simulator for the application to a

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mechanism control.

Formerly, it was necessary to obtain many kinds of data in preliminary simulations and measurements in real systems in order to model mechanically coupled systems with an HIL simulator, but the tool in (2) above would enable direct incorporation of the influence of component mechanisms from design drawing information.

3. Coupled Simulation of Mechanism Control

3.1. Outline

The following describes an example of application to an EPS system as an outline of how a coupled simulation of a mechanism control is used. Figure 1 shows a schematic of the model. In the simulation software, DADS was used to model the mechanical portion (the vehicle) and MATLAB was used to model the control system. To model the EPS motor, MATLAB was used for the electrical circuitry, and DADS, for the rotor. DADS/Plant was used for transfer of the sensor signals, motor torque and other parameters in the models on both software bases, which were run concurrently.

Models of the steering torque and disturbances were created in MATLAB; noise signals, fail-safe signals and other components were also added to the latter as necessary.

3.2. Tire Model

The tire models were based on Magic Formula⁽²⁾. The tires exert a key influence on vehicle behavior simulations. The models and solvers were modified as necessary to allow coupled simulations.

3.3. Development of Fast Solver

A full-vehicle simulation generally includes large numbers of bushings and other components, which increase the calculation load. Therefore, in the fixed time step solver

in DADS/Plant, of which a typical example is the Runge-Kutta method, it is necessary to make the sampling time, or calculation period, extremely short; this is impractical as it greatly lengthens the calculation time.

It was therefore made possible to use a solver with a variable time step for the coupled simulations. The resulting calculation times were considerably shorter than those in the fixed time step solvers, as shown in Table 1.

Table 1 Elapsed times for 5 second slalom simulation

Model	Number of bush	Fixed time step		Variable time step
		Sample time [sec]	Elapsed time [sec]	Elapsed time [sec]
A	5	0.0005	343.51	401.17
B	7	0.00025	604.06	326.22
C	30	0.00004	1 962	488.54
D	63	2.00E-07	∞	662.42

3.4. Method for Creating Mechanical Model

Conventional methods for creating full vehicle mechanical models are very time-consuming; therefore, a tool was made for automatically converting the suspension model created during design to a vehicle model capable of immediate use in coupled simulations.

Figure 2 shows a screen image of the GUI. For EPS systems, the user can select between rack-assist and pinion-assist steering mechanisms. Some parameters such as the gear ratio and moment of inertia of the EPS motor are pre-determined and are added automatically. It is also possible to specify the initial vehicle speed and other run conditions for the simulation.

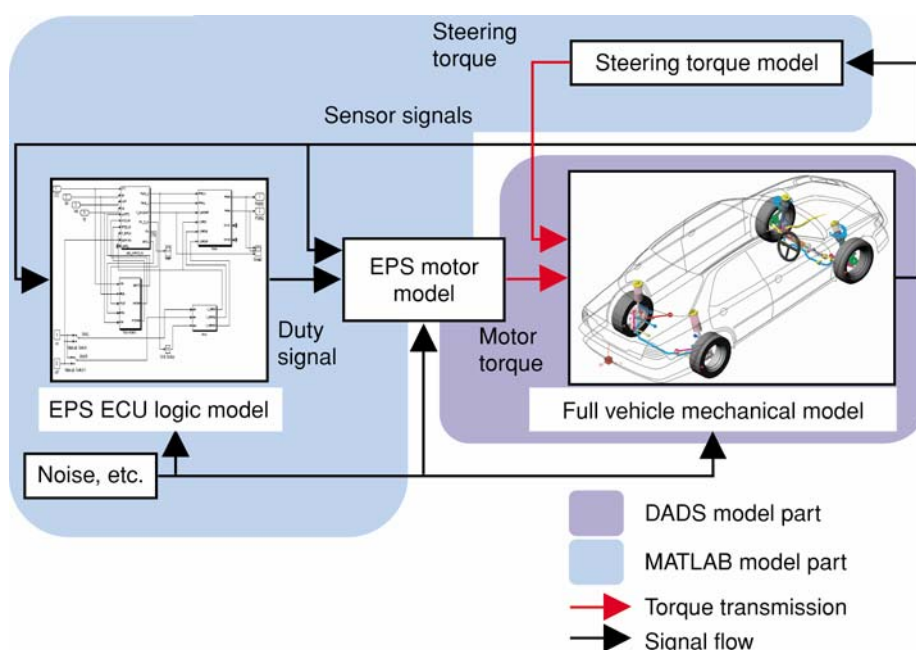


Fig. 1 System flow in coupled simulation

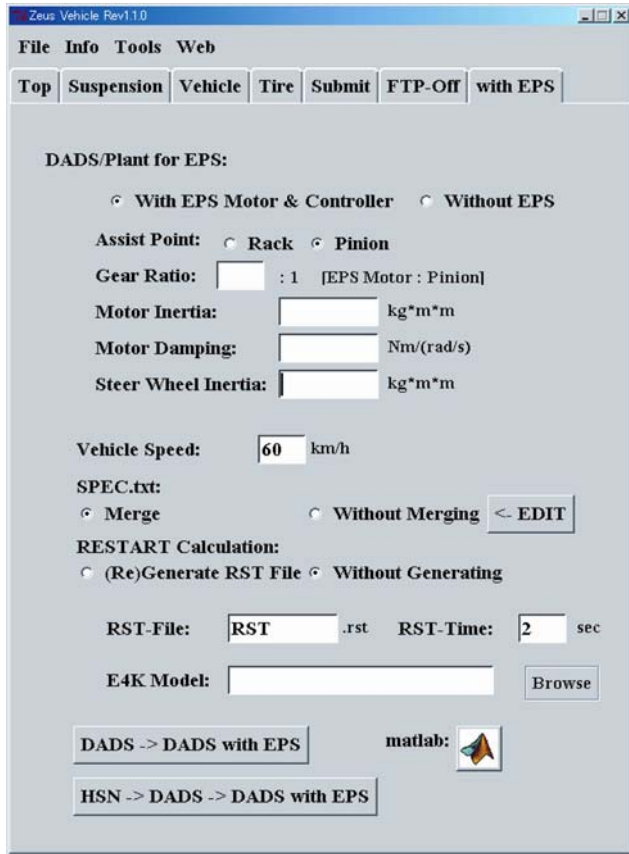


Fig. 2 Graphical user interface

3.5. Calculation Results

This section shows some examples of comparison of the results of the coupled simulation of the mechanism control with the results in an actual car under similar conditions. The test conditions were a slalom task with a vehicle speed of 100 kph, a steering wheel angle of 30° and a steering wheel oscillation frequency of 0.25 Hz. The EPS was set at a standard mode of control.

The measured and calculated variations in yaw rate of the vehicle with steering angle are presented in Fig. 3 and a time series of the measured and calculated forces on the tie rod ends on both sides (TFl, TFr) of the vehicle are presented in Fig. 4. Both graphs of simulation results show good matches with the observed results. This method has enabled highly accurate prediction of dynamic vehicle characteristics in a full vehicle mechanical model.

Next, Fig. 5 shows the simulation and the actually observed values of the current supplied to the EPS motor during a slalom task under EPS control.

It is clear that accurate predictions were provided, even for simulations of a control system including feedback, by coupling the reaction forces from the road surface, as they are manifested in the steering gearbox, the EPS motor condition, and the ECU internal control logic.

Figure 6 shows the characteristics of the variation in steering torque with steering wheel angle during the same slalom task.

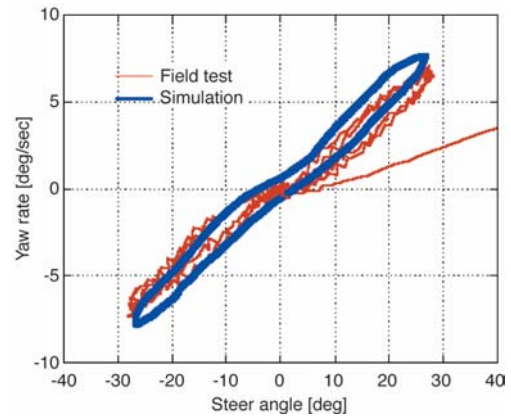


Fig. 3 Steer angle vs. yaw rate

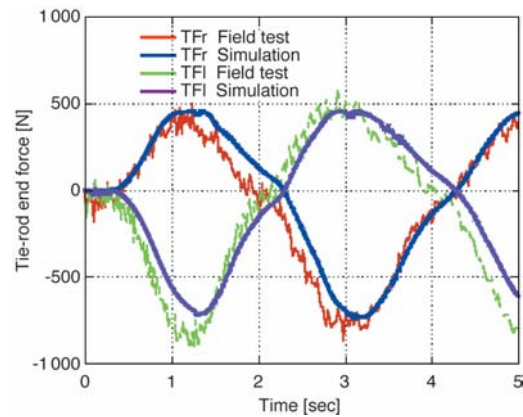


Fig. 4 Tie-rod end force

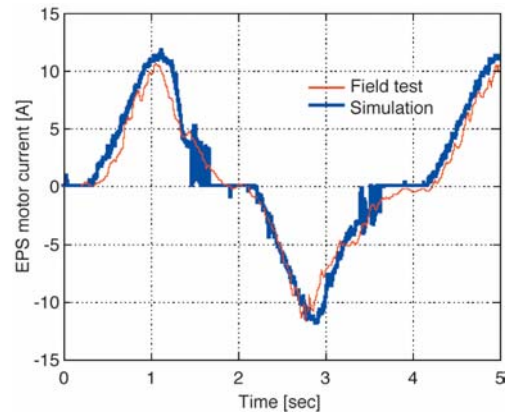


Fig. 5 EPS motor current under slalom

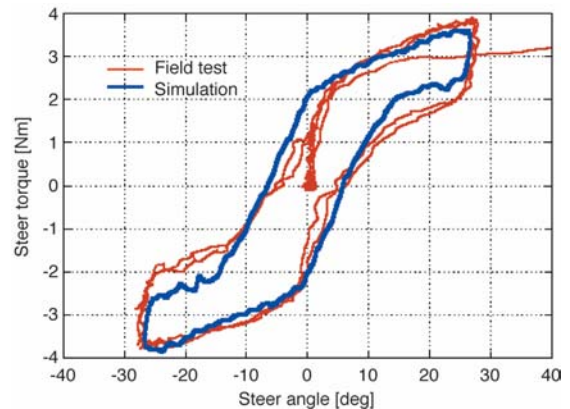


Fig. 6 Steer angle vs. steer torque

It can be verified that the observed hysteresis curves for each of the above characteristics were simulated quite well. The coupled simulations with mechanisms and control show that it has become possible to quite accurately predict not only the vehicle yaw rate but also the steering torque under EPS control.

4. Automatic Generation of Real-time Executable Programs

4.1. Outline

The overall construction of the HIL simulator used during development of a VSA is depicted in Fig. 7. The operation of the simulator is as follows. The VSA includes ABS and a traction control system (TCS)⁽³⁾. The HILS CPU in the figure performs the calculations of vehicle behavior and transmits the demand signals to the VSA ECU via an I/O board. Based on that information, the VSA ECU performs the calculations for the appropriate control actions for vehicle yawing behavior and the brake fluid pressure is fed back to the HILS CPU.

In order to perform a precise HIL simulation and to broaden the application of this method, it is essential to supply similar signals to the VSA ECU as in an actual vehicle, and to create a highly faithful model of the vehicle under conceivable driving condition.

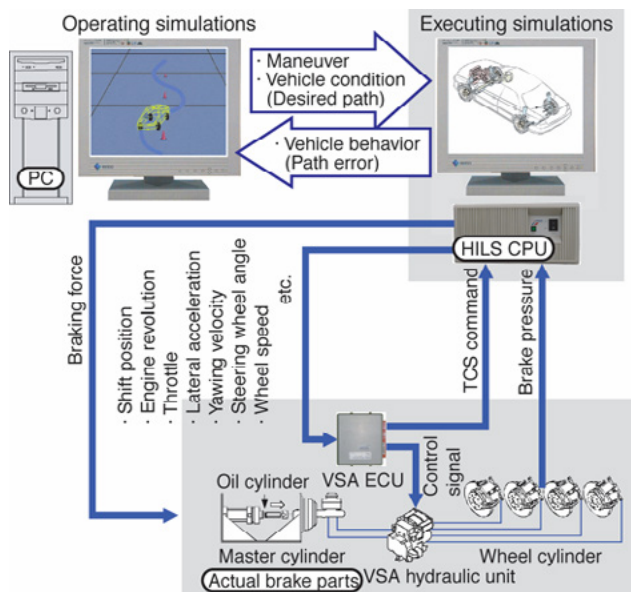


Fig. 7 Construction of HIL simulator for VSA⁽³⁾

4.2. Automatic Generation of Programs

A tool was developed for the generation of real-time executable programs capable of direct download into the HILS CPU from the mechanical model. The advantage of using an automatic tool is not only that non-linear and dynamic characteristics can be considered, but also that HIL simulation models are easily made with drawing information.

This tool was used in the present research with the objective of generating a suspension linkage unit model as a MATLAB block and treating the variations in toe angle and in vertical load of tire as nonlinear functions of suspension stroke.

4.3. Model Structure

Figure 8 presents the structure of the HIL simulation model. It was based on a MATLAB model expressing the equations of motion of an automobile body with 6 degrees of freedom. In conventional models, suspension components were modeled by superposing with the toe angle map. This was replaced with the automatically generated real-time executable program shown in Section 4.2.

Also, in order to distribute the calculation load, the model was divided so as to run parallel calculations in the CPU for the left and right suspensions.

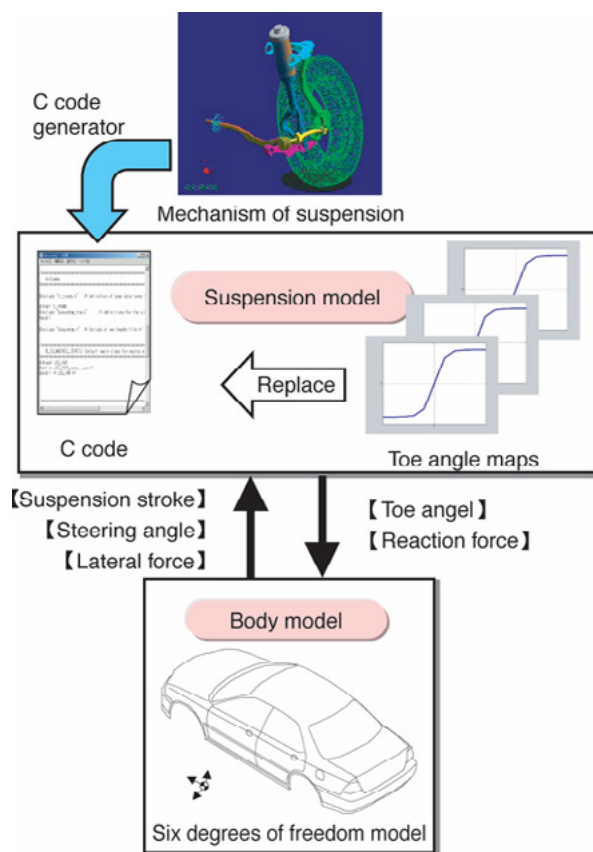


Fig. 8 Divided mechanical model

4.4. Hardware Structure

It is necessary to run the vehicle model in real time on the HILS CPU. The structure of the hardware in the HILS CPU used in this research is shown in Fig. 9.

A multi-board system with three Power PC 600 MHz boards (480 MFlops) was used as the processor board⁽⁴⁾. The automatic generated programs were installed on each of the boards. This structure enabled real-time calculations for this model, with a distributed calculation load.

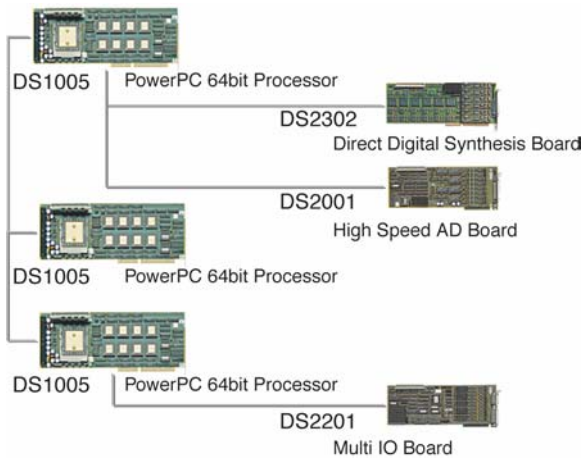


Fig. 9 Hardware layout in HILS CPU

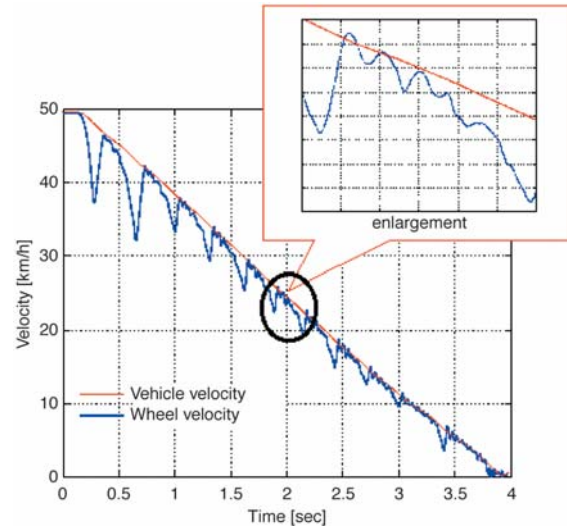


Fig. 11 Compliance vibration on mechanical HIL simulator

4.5. Results of HIL Simulator Execution

The vehicle model was set to drive in the steady state circular test for 30 m radius on a dry asphalt pavement on the conventional HIL simulator and the mechanical HIL simulator incorporating suspension linkage calculations; the results were compared with those from a vehicle test. The variation in the gains of yaw rate per steering wheel angle versus lateral acceleration, one characteristic of vehicle dynamics, is shown in Fig. 10. The red squares in the figure are the plot of results in the real vehicle, the black line is the results from the conventional simulator, and the blue line is the results with the present method.

The present model maintained good accuracy even in the lateral acceleration region above 0.5 G. Good results are shown here in automobile behavior where non-linear characteristics have a great influence, a problematic region for the conventional HIL model.

Next, a graph of the variation in wheel velocity during braking, as predicted by the HIL simulator, is shown in Fig. 11. The test conditions were entry at a speed of 50 kph on dry asphalt. ABS control was already activated at entry. The wheel velocity vibrations visible on an enlarged section

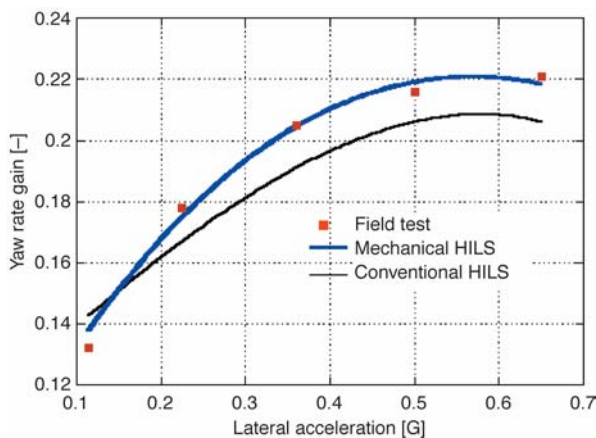


Fig. 10 Steady state circular test

of the trace in the figure appear to indicate vibrations in compliance of the tires in response to the longitudinal force; these are also seen in tests of real vehicles.

The results indicate that using the present model allows expression of the vibration characteristics of the suspension. The HIL simulator with the mechanical model can be used for considerations of dynamic characteristics.

The results of the simulation of excitation of the suspension linkage unit model, shown in Fig. 12, indicate the frequency response for longitudinal vibrations.

The resonant frequency around 15 Hz seen in the actual vehicle is reproduced here, confirming the validity of this automatically generated model for predicting dynamic characteristics.

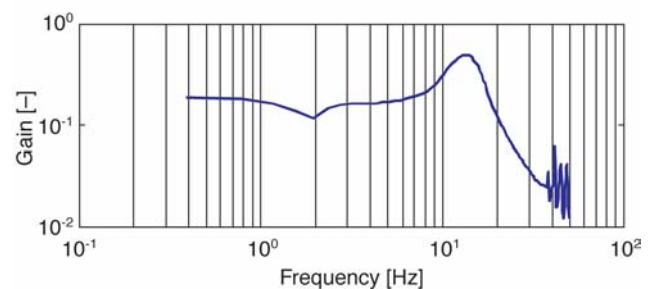


Fig. 12 Frequency response of suspension vibration on simulation

5. Summary

The following technologies were constructed and tools developed for making predictions of vehicle behavior while mechanism control devices are activated:

- (1) Coupled simulation for mechanism controls
- (2) Automatic generation of real-time executable programs for the HIL simulator.

It was possible to predict phenomena in the non-linear and dynamic effects of suspension and steering linkages and other components on the control system. Characteristics were also successfully predicted in relation to steering torque.

It is planned to extend this research with coupled simulation and HIL simulators to sophisticated vehicle control devices, such as steer-by-wire.

6. Acknowledgements

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