Quantification of Vehicle Dynamics by Means of Development of a Multipurpose Simulator*1

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In pursuit of constantly improving the development of the vehicle system and controls by means of quantification of performance for the improvement of vehicle dynamics, we have developed a new simulator. The Dynamic Motion Simulator (DMS) is composed of a modular chassis mounted on five distinct Stewart platform Motion Bases (MB) controlled by real-time models. The chassis integrates mass-produced and prototype systems such as steering, suspension and driveline units along with its own electronic control unit. This paper describes the concept, realization and planned activities as well as report on the new possibilities of using the developed simulator as a research and development tool.

***Key Words**: vehicle development, hardware in the loop simulation, design optimization, vehicle dynamics*

1. Introduction

In the vehicle development of today, each system is developed on the basis of the required specifications of the system, before equipping the system on the vehicle. This kind of development is carried out independently for the respective systems, such as steering and driveline units, therefore differences from the required properties as a vehicle are discovered when the systems are equipped on vehicles and evaluated, meaning that a significant amount of time is required for system improvement. Moreover, although the performance of the components which configure individual systems is improving, a method for quantification of the effect of components on systems has not been established, therefore there is a possibility the performance of the overall system will not improve. To improve these issues, predictive evaluation on test benches such as the Hardware-in-the-Loop (HIL) simulator or computer simulation has been extensively adopted on a broad basis[1-3].

In light of the above issues, we believe that vehicle system development requires the establishment of design methods which satisfy the specification requirements of systems and test bench evaluations which can be conducted with multiple systems equipped. This paper describes the structure and control of the newly developed Dynamic Motion Simulator or DMS, designed with the aim of improving the development process for steering and driveline systems. This paper also gives an example of an analysis for the effect of suspension linkage within the steering system function utilizing DMS.

2. Utilization of Simulators in Vehicle Development

The combination of simulation and bench testing is a well-known and significantly used process for the development of automotive products. It allows the prediction of any component, system, and even entire vehicle dynamics. For example, simulation is utilized at the initial phase of development for the areas of energy consumption, reduction of vehicle weight, cost reduction and so on. In section **2.1**, the utilization of simulators and bench evaluations for steering system and driveline system development is explained. The aim of DMS development is described in **2.2**.

2. 1 Overview of Existing Simulators and Bench Evaluation Tests

In the initial development phase of steering and driveline systems, Model-In-the-Loop (MIL) simulation[4), 5)] is utilized to verify functions on a model. After this, Software-In-the-Loop (SIL) simulation, which has software implemented, is utilized to verify the design of mechanical components and control algorithms on a model.

In bench evaluation tests, the component characteristics, such as actuator static and dynamic responses, stiffness

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and friction property, are measured at a component level. Afterwards, measurements are performed on a subsystem level. An example of this would be powered columns in the case of steering systems and coupling units in the case of driveline systems.

In the next phase of development, a HIL simulator and system bench are used to verify system performance. At this time, control parameters are pre-adjusted and the mechanical properties of steering are tuned. For example, the steering HIL simulator, illustrated in **Fig. 1**, is mainly utilized in the development of motor-assist control strategy, such as active friction compensation in electric power steering[6]. The driver and road inputs are substituted by two actuators located on the steering wheel and tie rod. Simulators for driveline evaluation comprise of an input motor and load motor and used for the analysis of driving force distribution, etc.

In the final phase of development, the developed systems are installed on the vehicle, a test driver evaluates the vehicle performance and each property is finalized.

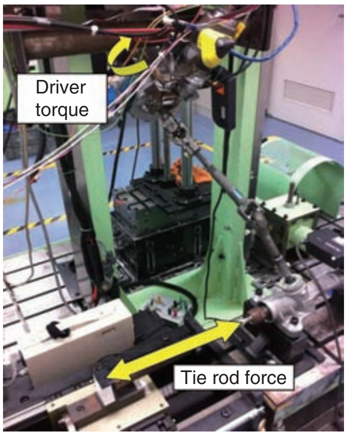

Fig. 1 Steering HIL simulator

2. 2 DMS Development Aim

Until now, the development of components and control for steering and driveline systems has utilized simulators, however due to a lack of knowledge relating to the system environment (chassis) and unmodeled components or systems, a substantial gap between system bench and test vehicle evaluations remains. In order to fulfill this gap, we developed DMS in an attempt to establish a test bench evaluation method in a state including system components such as the chassis and unmodeled components such as the mounting bush. Therefore, understanding of the interaction of the developed systems and surrounding environment helps to improve the design and control which should satisfy multiple requirements such as vehicle dynamics and noise vibration performance.

3. Characteristics of DMS

Figure 2 shows an outline view of DMS. It is comprised of five Stewart platform type Motion Bases (MB) each providing six degrees of freedom (x, y, z linear motion, roll, pitch, yaw rotation motion). It enables a vehicle chassis to be fixed to the central MB (chassis MB), generating the motion corresponding to the vehicle body. The other four MBs are located underneath the wheels, providing the road input for each wheel. Moreover, by connecting the load motors mounted on the wheel MBs to the axle, driveline HIL testing is possible.

DMS controller can be operated in two separated modes. Namely, vehicle RT (Real Time) mode and direct control mode. In vehicle RT mode, the inputs to the model are the driver steering and pedal inputs, measured during vehicle testing or generated by joy stick controllers etc. Then a real time vehicle model generates the commands for MBs and integrated system actuators. Sensors located in MBs and the vehicle feed back to the controller enabling the dynamic representation of simulated vehicle motion. In direct control mode, repeatable command, such as that measured during actual vehicle testing or pre-defined patterns (step, lamp, sine chirp, etc.), enables system performance evaluation.

MB controller combines an open loop position control with a closed loop compliant motion control, overcoming mechanical over constraint issues between MBs, chassis and driveline systems. Driver steering input is provided by an additional motor controlled in torque or angle. The drive wheels are connected to load motors, controlled by angle or torque, via a torque sensor. DMS has an integrated environment as an actual vehicle, therefore is able to express the mechanical interaction between the developed components of steering and driveline systems and chassis.

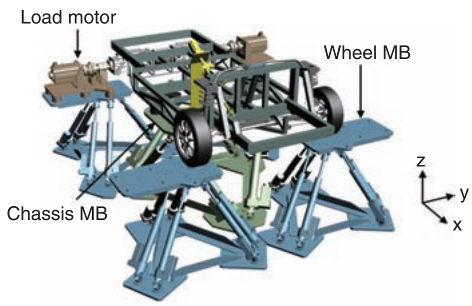

Fig. 2 Outline view of DMS

4. System Interaction Analysis Utilizing DMS

The potential of DMS is illustrated with the introduction of some results on steering and suspension interaction analysis for the purpose of understanding the effect of the suspension linkage on the displacement and force of a steering system.

4. 1 Effect on Wheel Alignment

Wheel alignment is determined by suspension geometry and linkage hard point locations. This paper looks at a MacPherson strut type suspension and compares the wheel alignment results measured on DMS with the simulation results when applying vertical displacement on the left wheel (bump movement). The simulation model is implemented on mechanism analysis software and the link was treated as a rigid joint model. We focused on the caster, camber and toe angle as wheel alignment.

Figure 3, 4 and **5** respectively show a comparison of the caster, camber and toe angle results obtained from DMS measurement and the simulation. For the caster angle, relatively good correlation was observed, however there was a significant difference for both the camber and toe angles. This difference is due to the fact that the link treated as a rigid joint model in the simulation actually accompanied the displacement caused by elastic deformation of the bushes. This means there is a need to incorporate the properties of elastic components such as bushes in simulations in order to predict actual alignment properties with higher accuracy. However, nonlinear characteristics of these components make their accurately quantified modeling difficult.

By utilizing DMS, it is possible to accurately measure the changes in wheel alignment of a system including components with non-linear properties, therefore enabling more efficient development.

4. 2 Effect on Tie Rod Force

The tire force which has a significant effect on vehicle dynamics, is transferred to the driver through the suspension, the chassis, and the steering. The suspension and steering are mechanically linked at the tie rod outer ball joint, representing the road input of steering system. To characterize the propagation of the tire force to the steering, the left tie rod force when applying a relative position difference between two MBs (chassis MB and front left wheel MB) is measured.

Focusing on the tie rod force, we conducted static and dynamic characteristic tests. In the static characteristic test, we fixed the chassis MB, then applied a relative position difference between two MBs in the x, y and z directions. The value of the difference is equal positive/negative values in each of the directions. The

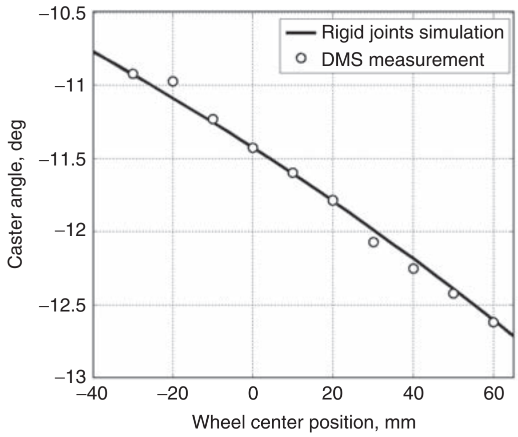

Fig. 3 Caster angle with bump movement

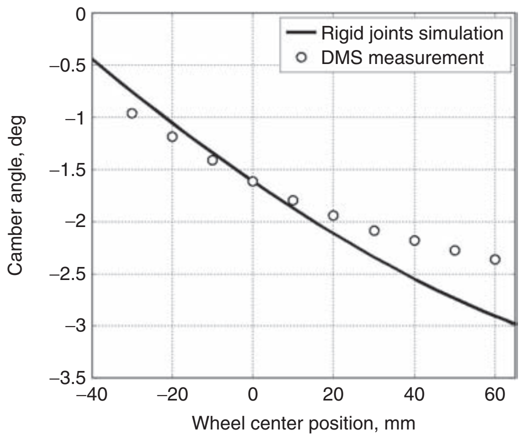

Fig. 4 Camber angle with bump movement

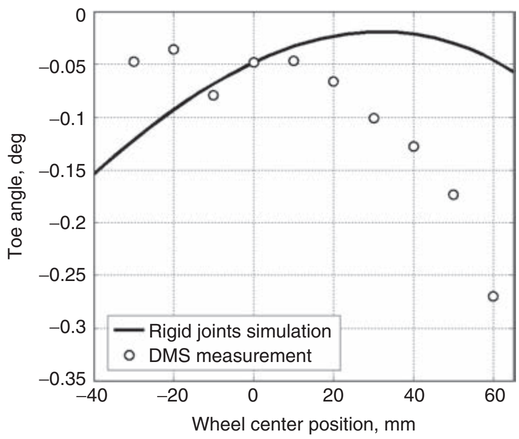

Fig. 5 Toe angle with bump movement

measurement is performed for three initial preload conditions, generated by offset in the specified direction. For the dynamic characteristic test, we fixed the chassis MB, then changed the position of the left front wheel MB by 1 Hz sine wave. The amplitude is equivalent to the value of the relative position difference from the x, y and z directions of the static characteristic test. In this experiment, the tie rod inner ball joint is fixed to the chassis and wheel rotation is locked, enabling the representation of the tire grip force generated at the contact patch. The results are shown below.

At first, the results of a static characteristic test are explained. The tie rod force measured for a relative position difference in the x direction, represented in **Fig. 6** shows that the hysteresis of the tie rod force change is large and non-linear. This is believed to be due to the friction in the damper, ball joints and lower arm mount bushes, etc. Meanwhile, **Fig. 7** shows that, for changes in the y direction, the hysteresis of the tie rod force change is small and there is high rigidity. **Fig. 8** shows that, relatively small variation of the absolute force is observed for displacement in the z direction, due to the suspension geometry, which allows the reduction of the bump-steer effect.

Next, the results of the dynamic characteristic test are described. **Figure 9**, **10** and **11** show the tie rod force when the wheel MB position is changed by 1 Hz for the x, y and z directions respectively. The variation of the relative position in the x direction shows friction effect in the area of direction changes, compared to the almost linear response of the tie rod force to a command in the y direction. Displacement in the z direction shows smaller amplitude of the resulting tie rod force, as was the case with the static characteristic test.

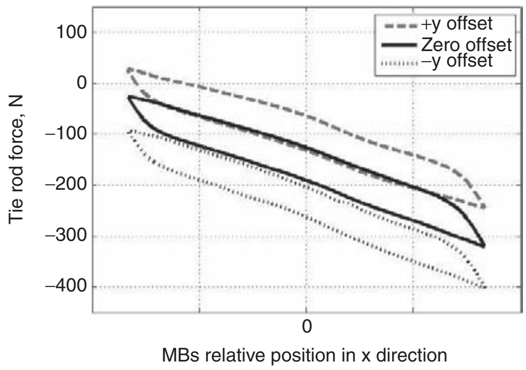

Fig. 6 Left tie rod force versus MB relative position in x direction

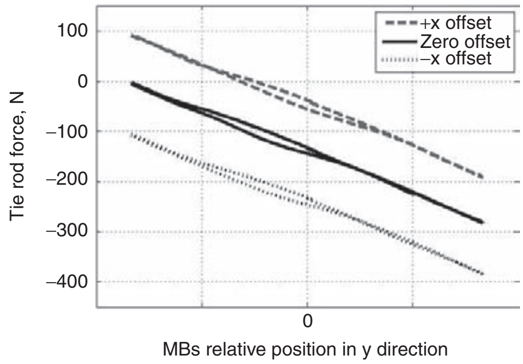

Fig. 7 Left tie rod force versus MB relative position in y direction

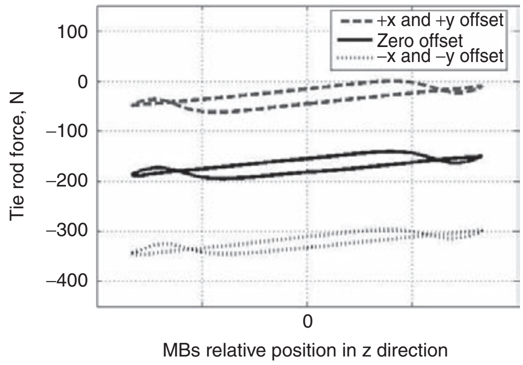

Fig. 8 Left tie rod force versus MB relative position in z direction

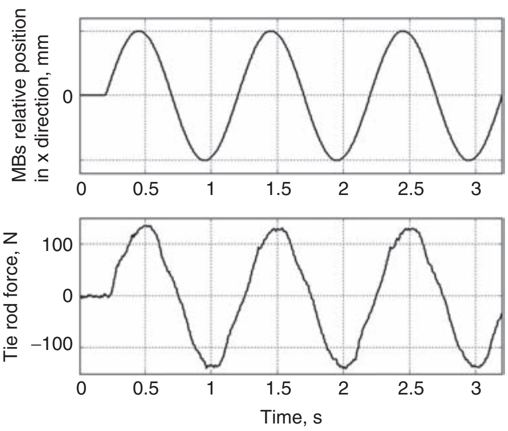

Fig. 9 Left tie rod force to x direction sine position command

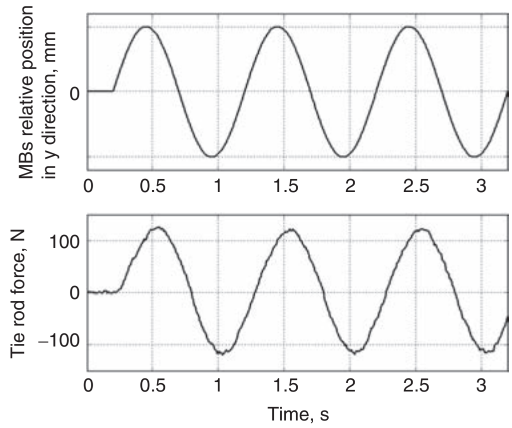

Fig. 10 Left tie rod force to y direction sine position command

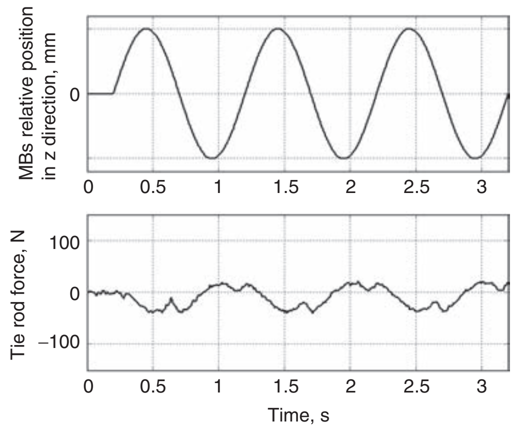

Fig. 11 Left tie rod force to z direction sine position command

5. Conclusion

This paper has introduced DMS developed with the aim of improving the development process for systems installed on vehicles. We provided an example of utilizing DMS to analyze a system including components such as bushes which are difficult to model accurately. By using DMS which can simulate actual vehicle driving conditions in a test bench environment, we were able to perform highly accurate evaluations of developed systems that include properties difficult to evaluate while actually driving and components difficult to model. In the future, we will aim to utilize DMS to analyze the interaction between multiple systems such as steering and driveline systems. Through the DMS, we wish to help improve both vehicle development efficiency and quality.

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