One of the objectives in developing simulation methods is to gain the ability to develop steering systems efficiently. Thus, simulation methods have been developed with the objective of providing efficient evaluation phases. For further efficiency, design accuracy at the planning stage of system development is essential. Thus, it is required to quantify influence by mechanical or electrical performance of components on the system performance to distribute the performance subsequently. This study has an objective of qualitatively evaluating the influences to reflect the result on the design of the system performance. This report describes basic research results regarding performance of a developed HIL simulator.

Key Words: simulator, electric power steering, system architecture, dynamics

1. Introduction

In evaluating steering systems, there still are many aspects such as steering feeling regarding which definite evaluation cannot be made without actual vehicle tests. If more accurate bench testing is available prior to actual vehicle tests, however, it will be instrumental for earlier debugging and faster feedback for development of new steering systems. Though many studies have been carried out in order to improve the accuracy of bench testing with simulation technologies, it is difficult to simulate the entirety of mechanical and electrical characteristics of steering systems. Due to these factors, it becomes difficult for computer simulations generally used for vehicle motion systems to achieve the evaluation accuracy of actual vehicle tests.

In this study, the Hardware-in-the-Loop simulator, in which an actual steering system was installed, was developed\(^1\). Electrical and mechanical characteristics, simulation of which is difficult, can be evaluated easily on bench testing using this simulator.

Improvement of the steering system development cycle is one of the purposes in this study. It is necessary to optimize the system architecture in the planning and development period. It is well known that the mechanical dynamics of the steering system influence the various characteristics concerning the vehicle including its steering performance. However, the architecture of steering system specifications has not been examined based on the relationship between the dynamics of the steering system and the steering performance of the vehicle. The design criterion of each steering component has not been optimized enough to realize that steering architecture. In this paper, the result of preliminary research on the influence of mechanical dynamics on steering system performance is reported.

In that regard, the aim of this study is to construct a simulator for steering evaluation that enables bench testing to satisfy such requirements. This paper presents an outline of this simulator for steering evaluation as well as a comparison between the test results with this simulator and those of vehicle tests. Moreover, this paper describes preliminary studies concerning the advanced HIL simulator to optimize steering system architecture including mechanical dynamics and concerning the integrated simulator for the evaluation of steering systems with vehicle behavior.

2. HIL Simulator

The torque that the driver feels when turning the steering wheel is based on the recovery moment of the front tires. This torque is generated in proportion to the sideslip angle of the front tires, and is almost the same as aligning torque. This recovery moment is transmitted to the steering gear rack as force, and drivers can feel it through the steering system. This torque is called "reaction torque" in this paper.

Reaction torque is generally simulated as rotation torque applied to the steering wheel\(^2\), but in this study, an actual steering system was installed into the HIL simulator, so the aim was to achieve the torque loaded on the tie rod (rack force). Figure 1 shows the construction of the HIL simulator used in this study.
In this study, a linear tire model is used. The lateral force is calculated with the equations introducing the dynamic characteristic of the lateral force to the slip angle of tires. In this paper, roll steer angle \( \alpha_G \) and \( \alpha_S \) are assumed to correspond to roll angle, so \( \dot{\theta}_u \) and \( \dot{\phi} \) are defined as constants.

Aligning torque, which drivers feel as the reaction torque, is generated owing to the difference between the rotation center of the supporting surface of the tires and the power point of the lateral force of the tires. Rack force loading on the tie rod is defined as the force that is calculated based on the value of aligning torque divided by the length of the knuckle arm.

4. Model Identification

The efficiency of the analytical model described above is examined in this section. The output from the simulation model is compared with the experimental result using an actual vehicle equipped with the same steering system as the HIL simulator. When comparing these results, Bode diagrams of rack force response, yaw rate response and roll angle response against steering wheel angle are used.

The rack force of an actual vehicle is the sum of the forces on both tie rods, and is measured with a load cell. Actual vehicle test conditions were as follows: Vehicle speed was maintained at 20 km/h, 40 km/h, 60 km/h, 80 km/h, and 100 km/h on a dry asphalt road, and the steering wheel angle input was a sine wave. Each Bode diagram is obtained by FFT analysis of time-history measurement data. Figure 3 (a) shows a Bode diagram of rack force response against steering wheel angle, and Fig. 3 (b) shows that of yaw rate.

From this result, although the phase of rack force and yaw rate is leading, vehicle behavior is reproduced until around the steering wheel turning frequency of 1 Hz. Therefore both simulation of rack force and comparison to actual vehicle testing is carried out at vehicle speeds of 100 km/h and under and at steering wheel turning frequency around 1 Hz.

Further accuracy is necessary to evaluate the steering system in the case of rapid steering action, which is a future technical issue to be investigated.
5. Simulation of Reaction Torque

5.1 Reaction Torque Control

In order to load the rack force on the tie rod in this HIL simulator, an AC servomotor and ball screw are used as the actuator to generate reaction torque because they are easily controlled and their efficiencies are good. The value of the target rack force, which is determined from the vehicle model, is sent to the AC servomotor.

However, a difference between actual rack force and target rack force appears owing to the friction in the transmission system of reaction torque when the target rack force is low. The reaction torque control system has a PI controller to feedback the force to the tie rod so that the friction is eliminated. And it has a feed forward controller in order to improve the characteristic of follow-up control to the target force.

Next the reaction torque actually felt by the driver was studied. The frequency characteristic of the rack force against steering wheel angle measured in the HIL simulator was compared with the target rack force calculated from the vehicle model installed into the HIL simulator. In this test, vehicle speed was set at 40 km/h, 60 km/h and 100 km/h. The Bode diagram of rack force is shown in Fig. 4, and the Lissajou’s figure of rack force against steering wheel angle is shown in Fig. 5.

From these results, at steering wheel turning frequency around 2 Hz, the phase and gain of the rack force on this HIL simulator matches the target rack force. There is no deviation of rack force according to the mechanical or electrical characteristics of this simulator.

5.2 Simulate Steering Feeling

In addition to rack force, the steering wheel torque that the driver feels was evaluated. The Lissajou’s figure of steering torque against steering wheel angle, which is considered to indicate steering feeling, was applied to evaluate steering torque. Evaluation was carried out by comparison of the result in actual vehicle testing and the result in the HIL simulator testing. In each test, vehicle speed is set at 40 km/h, and the steering angle input is a
6. Basic Analysis for Quantitative Evaluation of Steering Feeling

It was clarified that this HIL simulator can reproduce steering torque similar to the steering torque in the actual vehicle in the previous section. The influence of the transient characteristic of the rack force on the performance of steering systems was investigated in order to evaluate steering feeling quantitatively.

The steering torque on this HIL simulator is compared to the steering torque on a test bench with a spring load that has no phase delay or lead to the steering wheel angle. Test conditions were as follows: vehicle speed at 40 km/h and steering wheel angle frequency of 0.4 Hz. In the preliminary study, the spring constant of the bench is adjusted to the condition of the HIL simulator testing. Figure 7 shows the comparison of steering torque between the HIL simulator and spring load. Steering torque near 50 deg is same, but there is difference of steering torque at the center position. From this result, it is considered that the difference of steering torque is caused by the phase characteristic of rack force. In order to reproduce the characteristic of steering torque, not only the characteristics of the steering system and control algorithm, but also the transient characteristic of the load of the actual vehicle is necessary. It is clarified that only the characteristic of a steering system can be evaluated properly by HIL simulator.

7. HIL Simulator for Optimizing Steering System Architecture

It is known that the mechanical dynamics of a steering system influence the various characteristics concerning the vehicle including its steering performance. However, the architecture of the steering system specifications has not been examined based on the relationship between the dynamics of the steering system and the steering performance of the vehicle. The design criterion of each steering component has not been optimized enough to realize that steering architecture.

The appropriate tool for the optimization of steering system architecture is proposed by improving this HIL simulator. This simulator can optimize not only the mechanical dynamics but also electrical dynamics on steering systems.

This paper describes the result of preliminary research on the influence of mechanical dynamics on steering system performance.

A steering model that represents the elements of steering systems was constructed. This steering model can simulate the effects of the value and location of the dynamics on the steering system. The electric power steering system that is the same as the one installed in the HIL simulator was modeled.

The performance of a steering system installed into a vehicle can be simulated by the integrated model that consists of this steering model and the developed vehicle model.

Figure 8 shows the comparison between the result of the simulation with the steering model and that of the bench testing of the actual steering system.
Figure 8 Lissajou's figure of steering torque with respect to steering wheel angle

In this simulation and bench testing, the steering wheel angle was given as the input signal. The steering tie rod was connected to a proportional spring load in order to confirm if the developed steering model could represent the performance the same as the actual steering system. From this result, it is confirmed that this developed steering model nearly reproduces the performance of the steering system.

The influence of the friction elements of the steering column shaft on the characteristics of the steering system and the steering performance of the vehicle was simulated.

The coefficients of friction $R_1$ and $R_2$, which were located around each side of the torsion bar as shown in the Fig. 9, were changed.

The characteristics of the steering system itself were simulated when the steering wheel angle was given to the steering model as the input signal, and the characteristics of the steering system and the steering performance of the vehicle were simulated when the disturbance torque was given to the model as the input signal. The specification of this disturbance torque was determined from measured rack force during driving on a rough road.

Figure 10 shows the result of the simulation when the steering wheel angle was given. Figures 11 and 12 show the result of the simulation when the disturbance torque was given. This result shows that the characteristics between steering wheel angle and steering torque were not influenced by those dynamics, as shown in Fig. 10. When the input signal was disturbance torque, the change of the steering rack stroke was different between the locations of the friction element on the steering column shaft as shown in Fig. 11. In Fig. 12, it is clarified that the element of friction can work as a mask against the disturbance torque according to its location, when each yaw rate of the vehicle is compared.

From these results, it is clarified that there is the difference of the steering performance of the vehicle owing to the location of the dynamics even if the characteristics against the driver's input are the same. It is considered that this difference influences the steering architecture and the steering control logic. But this influence is not quantified precisely.

In the future, the characteristics of the steering system will be investigated, when not only the mechanical parameters but also the electrical parameters are changed. Moreover, the studies concerning the optimization method of those parameters from the viewpoint of the steering system performance and the steering performance of the vehicle will be carried out.

Figure 9 Steering simulation model

Figure 10 Lissajou's figure of steering torque with respect to steering wheel angle by simulation
Fig. 11 Simulation result of rack stroke against disturbance torque (V = 40 km/h, Disturbance: +600 N, 10 Hz)

Fig. 12 Simulation result of yaw rate against disturbance torque (V = 40 km/h, Disturbance: +600 N, 10 Hz)

8. Conclusion

In this paper, steering system evaluations were carried out as a preliminary study for the quantitative analysis of steering characteristics. It is clarified that the transient characteristic of the rack force influences the steering torque against steering angle. Moreover, only the characteristic of the steering system can be evaluated properly using this HIL simulator.

In order to improve this HIL simulator, the influences of mechanical dynamics of the steering system were investigated using the developed simulation model as a preliminary study. It is clarified that the location of the dynamics is important in designing steering system architecture considering the steering performance of the vehicle.

In the future, technical issues identified in this study will be resolved. Also, a study concerning steering simulators that are useful for the development of new steering systems will be carried out.

References