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DEVELOPMENT OF THE INDEPENDENT-TYPE STEER-BY-WIRE SYSTEM USING HILS

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ABSTRACT−The previous paper described the logic tuning, the vehicle manufacture and the evaluation in the HILS system for the purpose of the development of a Steer-By-Wire (SBW) system. This paper describes the content of applying to a new HILS system, the vehicle manufacture and the result of the evaluation performed in Independent-type SBW (I-SBW) system. Here, the SBW indicates the method of steering both tires by using one motor as the steering gear actuator, similar to the conventional steering system. On the other hand, the I-SBW means the method of steering both front tires independently by using dual motors as the steering gear actuator. As a result, the layout and the kinematical mechanism of the I-SBW system are quite different from those of the typical steering mechanism. Nevertheless, there is no change in the steering column motor system. In the report, we first describe the structure and control logic of the I-SBW system, and then the control effect on this system as applied for both the HILS system and a vehicle. Furthermore, our HILS system involves the actuator mechanism which realizes the reaction force of the road surface with a minimized frictional force in operation. Therefore, it is possible for us to tune the control logic via the HILS system and confirm the effect of the tuned control logic by applying it to a vehicle with the I-SBW system.

KEY WORDS : SBW (Steer-By-Wire), HILS (Hardware-in-the-Loop Simulation), I-SBW (Independent-type Steer-By-Wire)

1. INTRODUCTION

The SBW system is a new technology that controls the steering mechanism using electrical signal, instead of linkages between steering column and steering gear.

Many advantages of the SBW system over a conventional steering system make it possible to cooperate with other types of vehicle control technologies. Moreover, the SBW system can contribute largely to future technologies, e.g. ITS and ASV. Because the SBW system has no mechanical connection between a steering column and a steering gear, conducting a vehicle test is not recommended directly. So it is often desirable to find the safety test methods. A relevant alternative might be thought. However, it is too difficult to build an exact mathematical model containing the inertia of a vehicle, the damping characteristics and nonlinear characteristics of a steering system in general.

As a result, the output through a numerical simulation is not so much reliable.

These shortcomings of a vehicle based test and a numeric simulation can be made up for by using the HILS system.

In the HILS system, some elements in numeric simulation are converted to actual hardware of the control system. The HILS system means the closed loop control system which is constructed by numerical models, hardware and numerically integrated in real time (Park and Heo, 2003; Yoon *et al.*, 2005).

We presented an SBW system using one motor as the steering gear actuator in the first report (Jo *et al.*, 2004). This report proposes an SBW system which utilizes dual motors as the steering gear actuator so that each front tire can be steered independently. The HILS system is based on the I-SBW system above. The tuning result of the control logic via this I-SBW HILS system will be described.

A description of the prototype I-SBW vehicle manufacture to which the validated control logic on the HILS system will be applied follows below.

2. VEHICLE MODEL FOR HILS SYSTEM

The vehicle model for the HILS was built up with the CarSim, which enables us to simulate the dynamic behavior of vehicles. As you see in the Figure 1, the dynamic model of vehicles has 15 Degree-Of-Freedom (DOF) which covers the major part of a vehicle.

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DOF	
Sprung body translation (X,Y,Z)	3
Sprung body rotation (X,Y,Z)	3
Unsprung bodies strokes	4
Wheel spin	4
Powertrain	1
Total	15

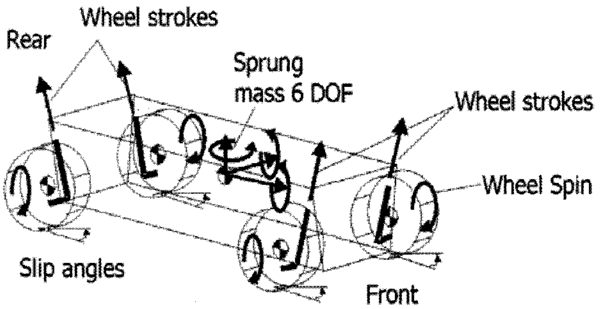
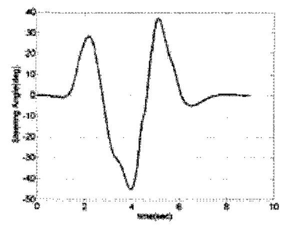


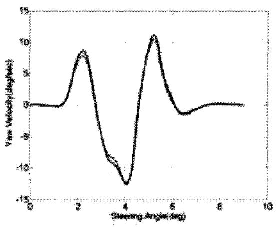
Figure 1. The DOF of vehicle model.

However, contrary to being presented, it represent the geometric (e.g. Toe, Camber) characteristics of suspension according to wheel strokes as maps in the CarSim, so the actual DOF is much higher than 15. The dynamic model of vehicles is written in C programming language, and then included in the SBW Simulink model in the form of an S-Function block. The manufactured vehicle is a small-sized car with 1.5 liter gasoline engine and automatic transmission.

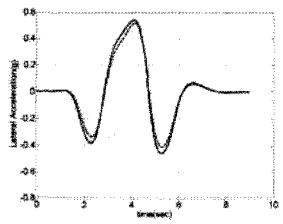
In Figure 2, the analysis results of this vehicle model are compared with those of Adams/Car through the same inputs in order to validate the dynamic model of a vehicle. The lateral axes indicate time and the vertical axes represent steering angle, yaw rate, lateral acceleration, and roll angle respectively. The solid line indicates an analysis result from Adams/Car and the dotted line indicates that from the dynamic model of the vehicle. These results show that there exists difference.



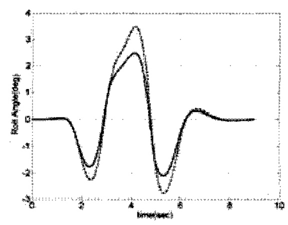
(a) Steering angle



(b) Yaw rate



(c) Lateral acceleration



(d) Roll angle

Figure 2. The correlaton results of the vehicle model.

3. SBW CONTROLLER

Figure 3 represents the configuration of an SBW system. The three main components are the steering column system, the steering gear system and the ECU. We control the steering column system in order to reproduce a similar steering torque generated by conventional power steering system, even though there is no mechanical linkage between the steering column and the steering gear system. Next, the purpose of controlling the steering gear system is to translate the rack gear in accordance with the steering angle by drivers. Here the displacement of the rack is measured by a potentiometer. Lastly, the ECU controls the steering column motor and the dual steering gear motors.

Figure 4 represents the control logic of the steering column motor. The control block diagram means that we obtain the reference torque value via the axial force on tie-rod, and then controls the measured actual torque value aiming at minimizing the error value.

Here, K_1: knuckle arm length
K_2 : steering torque gain
G_1 : transfer function 1
T_{ref}: nominal motor torque
V_{refl} : steering wheel motor voltage

The control block diagram of steering gear motor follows in Figure 5. The reference rack displacement is calculated by multiplying the input steering angle by the steering gear ratio. We control the error value between the reference rack displacement and the actual rack displacement measured from the potentiometer.

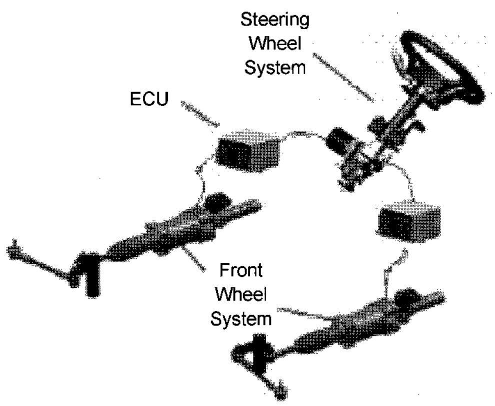


Figure 3. The configuration of the main three components of SBW system.

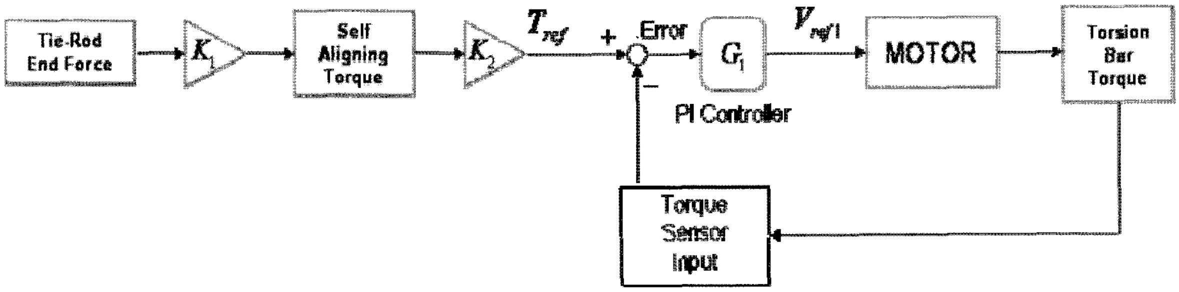


Figure 4. The control block diagram of steering wheel system.

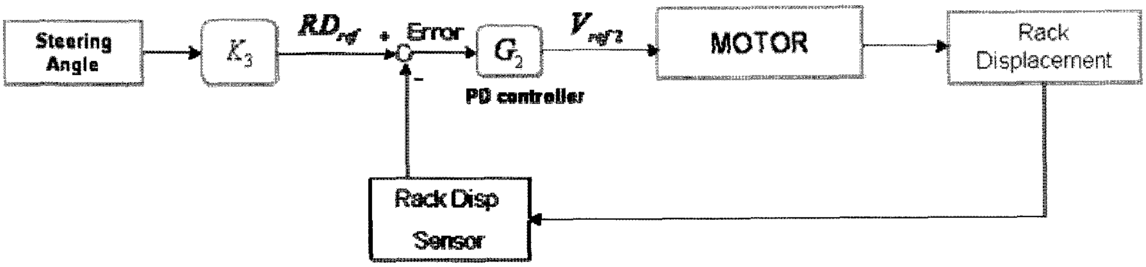


Figure 5. The control block diagram of front wheel system.

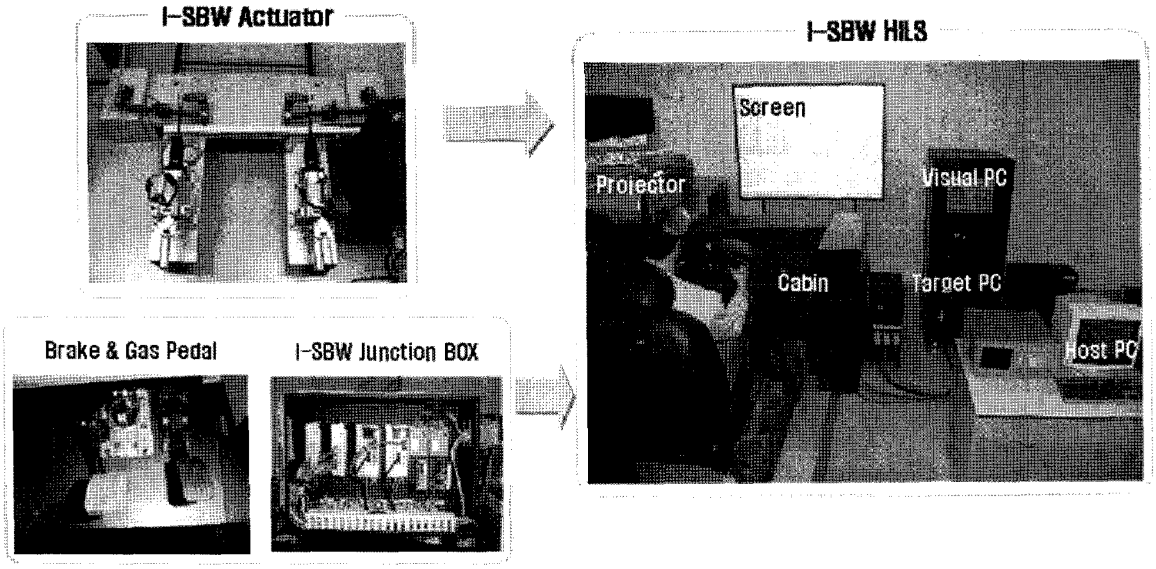


Figure 6. The configuration of the HILS system.

Here, K_3: steering gear ratio
G_2 : transfer function 2
RD_{ref}: nominal rack displacement
V_{ref2} : front wheel motor voltage

4. CONFIGURATION OF HILS SYSTEM

We built the HILS system as a previous step of the vehicle manufacturing. This HILS system is divided into H/W part and S/W part. The H/W part is constituted by the dual actuator of I-SBW, the reaction force system against the road surface, and the cockpit module. The S/W part is made up with real time operating system, the dynamic model of the vehicle, and the visual system. Figure 6 represents the configuration of the HILS system. A detail description of the HILS system will be followed below. During cornering the lateral force on tires causes Self-Aligning Torque (SAT), which exerts axial force on the tie-rod. The reaction force system against the road surface is an actuator which reproduces the axial force on the tie-rod, and operated with being connected into the steering gear system. Meanwhile, while a driver controls the steering wheel, the brake pedal, or the gas pedal in the HILS system, each input value goes into the dynamic model of the vehicle. Based on these inputs, the dynamic model of the vehicle calculates yaw, pitch, roll angle and the position of the vehicle in the absolute coordinate, and send these values to the visual system.

The SAT obtained from the dynamic model of the vehicle is converted to the axial force on the tie-rod, and then sent to the reaction force system against the road surface. The visual system shows the road information on the screen via utilizing the data from the dynamic model of the vehicle. The reaction force system against the road surface changes the axial force of the tie-rod into voltage value and transfer it to the operating driver for the actuator in order to reproduce the reaction force of the road surface. The steering gear system utilizes the steering input by multiplying it by steering gear ratio to compute the reference rack position. The steering column system and the steering gear system are controlled by the ECU including the controller. The control of the reaction force from the road surface is performed by the PID controller built in the SBW Simulink model separately. The information exchanges in input and output between H/W and S/W are realized through the DAQ board (Yun *et al.*, 2002).

5. TEST RESULTS OF THE HILS SYSTEM

In this chapter, we describe the result from the validation of the SBW HILS system. The validation was done by comparing the axial force of the tie-rod from the vehicle test with that from HILS system.

Figure 7 shows the steering angle and the axial force of the tie-rod with vehicle velocity 60 k/m, steering angle 50

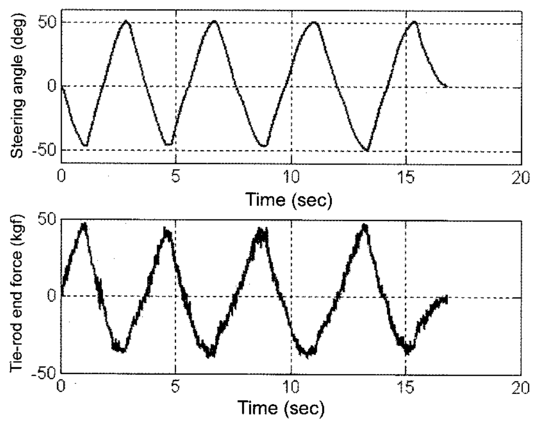


Figure 7. Test results obtaion from vehicle.

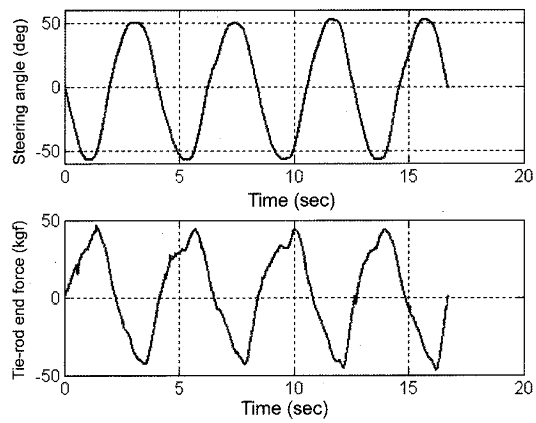


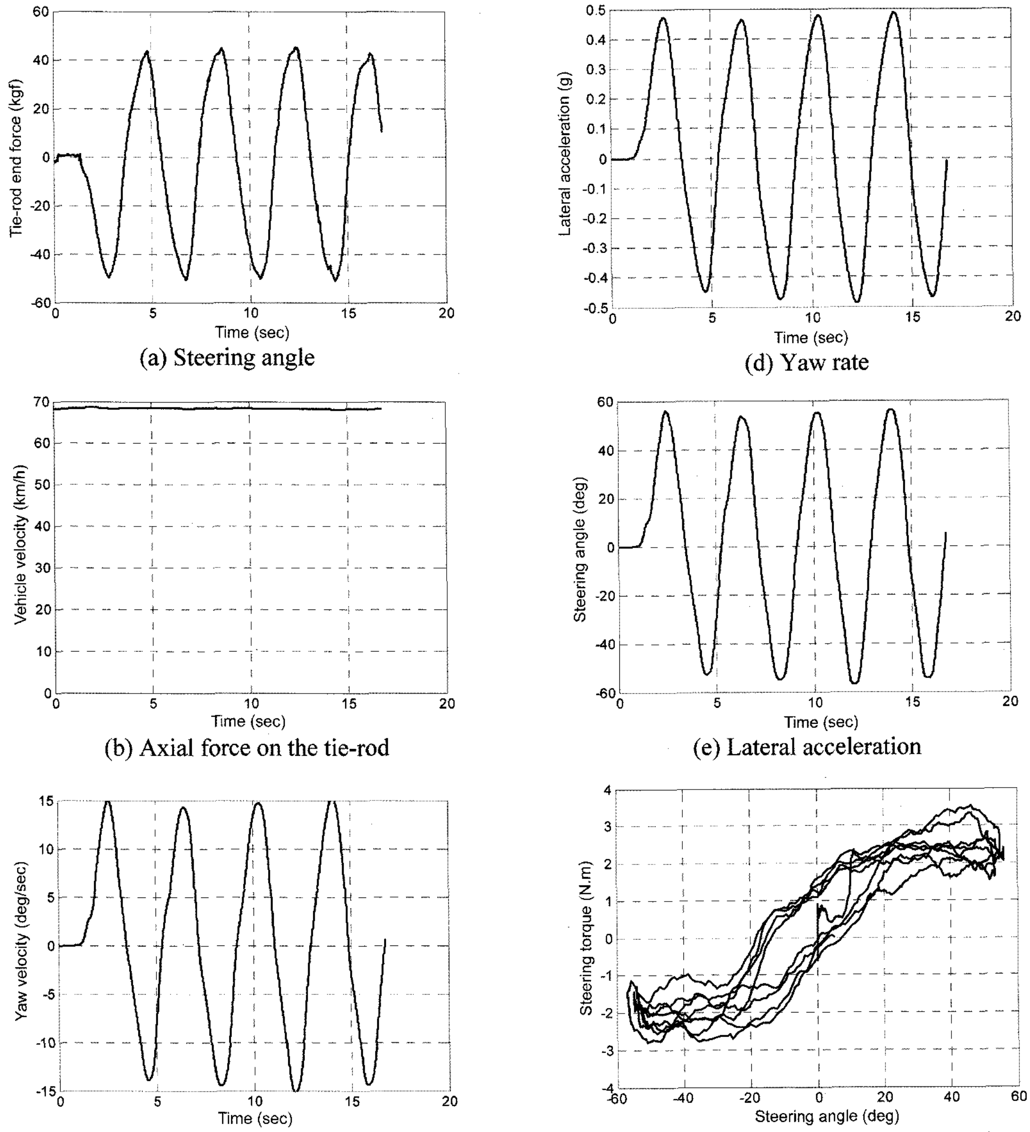
Figure 8. Test results obtaion from the HILS.

deg, 0.25 Hz in slalom test. Figure 8 is the test result in the HILS system with the same slalom input. However, because the test drivers on the vehicle and the HILS system were different from each other, the inputs to the both tests were similar but not same. From this reason it is not easy to overlap two test results. As you see in Figure 7 and Figure 8, two waveforms are different in shape, but their amplitudes are almost the same. For the axial force of tie-rod in the HILS system is similar to that in the vehicle, which shows the validity of the test in the HILS system. In the following, we describe several results measured with the I-SBW HILS system. Figure 9 shows tie-rod axial force, yaw rate, lateral acceleration and steering torque versus steering angle with inputs, (a) steering angle and (c) vehicle velocity. Figure 10. represent steering torque according to the steering angle with vehicle velocity 70 km/h, steering input 40 deg, and 0.25 Hz-slalom. Comparing the characteristic of steering torque on the HILS system in Figure 9 with that of the vehicle, we could find out that there is correspondence with the amplitude of steering torque, not the characteristic of hysteresis. Therefore, the control logic of the steering column system leaves a room for being improved (Segawa *et al.*, 2002).

6. MAMUFACTURING OF THE PROTOTYPE VEHICLE

We have manufactured the independent prototype vehicle in order to verify the stabilized control logic in the vehicle obtained from the above HILS. In the hardware manufacturing process, the layout is arranged with the object of being equipped in the vehicle on CAD tool in utilizing the data which made the actuator design be possible. And then the accessories lay out is changed. The software is installed in the I-SBW.

As the part of the suspension hard point is altered, the characteristic of geometry is changed. So this characteri-



(a) Steering angle

(b) Axial force on the tie-rod

(c) Vehicle velocity

(d) Yaw rate

(e) Lateral acceleration

(f) Steering torque vs. steering angle

Figure 9. Test results from HILS system.

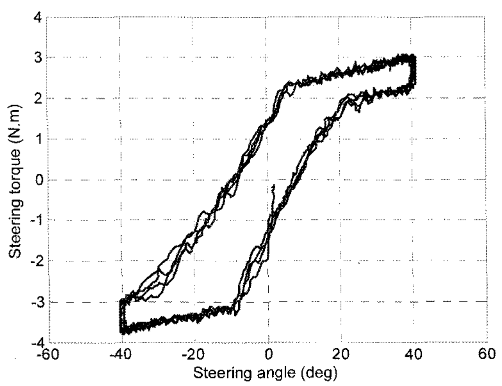


Figure 10. Test result of steering torque vs. steering angle with vehicle.

stic is designed similar to that of the mass production vehicle. Figure 11. indicates the linkage structure of the actuator of the Independent SBW system. The point P is the rotation axis as the hinge axis, the point P1 is the tire's joint, and the P2 is the joint of actuator.

Figure 12 shows the toe angel characteristic, in this moment the lateral axis expresses bump and rebound. It is a little different with the mass production vehicle, but it is similar in the tendency to each other. In the Figure 13, the lateral axis indicates the rack stroke with reflecting on the steered angle characteristics, the prototype vehicle is analogous to the mass production vehicle. There is difference between the two results. As shown in Figure 11. the reason these two results are different is that the

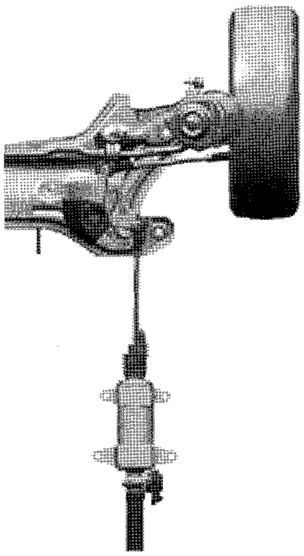


Figure 11. The linkage structure of the I-SBW.

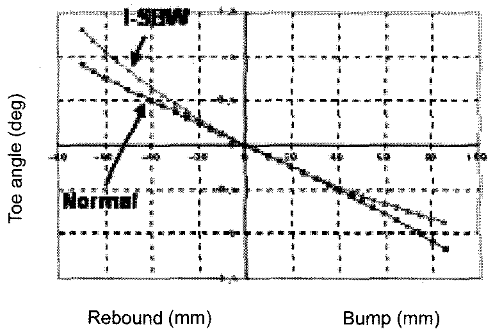


Figure 12. Toe angle characteristics.

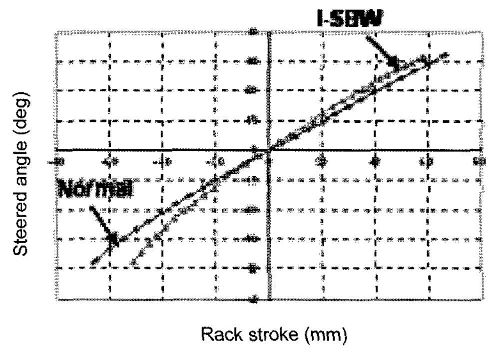


Figure 13. Steered angle characteristics.

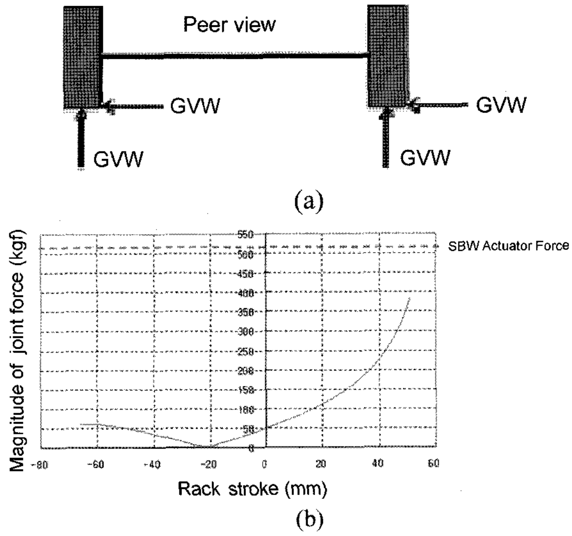


Figure 14. Joint reaction force.

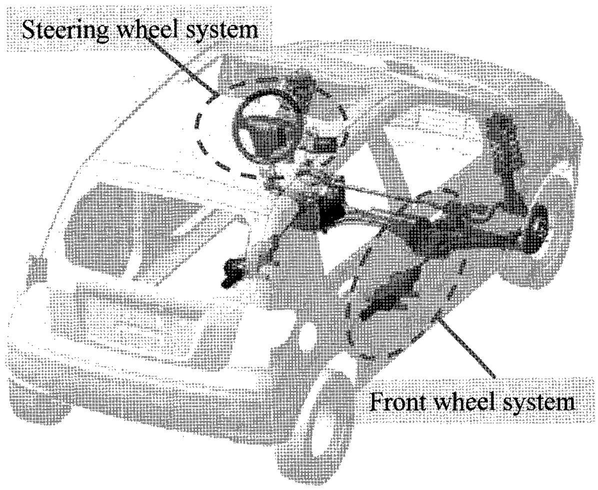


Figure 15. Prototype I-SBW system.

point P1 and P2 move drawing a circle exactly. In the following, we describe the joint reaction force caused by the actuator using Adams/Car.

Figure 14(b) shows the reaction force against the joint when the rack stroke of the actuator is in motion lock to lock with GVW condition in Figure 14(a). As the maximal rack impellent force does not exceed 520 kgf, there is no problem in actuator operating. Because the maximal reaction force against the joint is 386 kgf obtained from the analysis.

Figure 15 indicates the concept of the prototype vehicle of the I-SBW. The steering column is constructed as LHD, and the steering gear is attached to the right and left side-member. Therefore, it is parallel to the longitudinal direction of the vehicle. The ECU is installed in the inner space of crash pad.

7. CONCLUSION

This study has established the HILS which can be used for developing the SBW system efficiently. In the result of securing validity of HILS system in terms of steering gear box, the obtained tie-rod's lateral forces which obtained from actual vehicle and HILS are very similar each other. Furthermore, through the steering column system, the steering torques obtained in vehicle and HILS system in terms of steering sensor value are well matched with each other. In this research, while we have developed the Proto-type vehicle for evaluating the HILS system with tested SBW systems, this study described the results of geometry characteristics and reaction force of the system joints in this experiment.

In the future plan, we will scrutinize the relationship between the motor current of steering gear box and lateral force of tie-rod end, and then we will confirm whether the current data of gear system can be used as the road information, which is capable of giving feedback to control steering force of reactant system. With this effort, we can feel like driving actual vehicle even though driving on the HILS system.

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