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DEVELOPMENT OF A HARDWARE IN THE LOOP SIMULATION SYSTEM FOR ELECTRIC POWER STEERING IN VEHICLES

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ABSTRACT−In this paper, a hardware-in-the-loop simulation (HILS) system was developed before the development of an electric power steering (EPS) system in a vehicle. This study was focused on the establishment of the HILS system. Driving conditions are simulated with the HILS system. The actual steering input parameters are confirmed on the monitor while driving the HILS system. The steering forces observed in the simulation with the developed HILS system are similar to those in real vehicle tests. The developed HILS system can be applied in the development of various types of EPS systems.

KEY WORDS : Electric power steering (EPS), HILS, Steering force, Real vehicle test

1. INTRODUCTION

The main goal in the automobile industry is the development of safe and comfortable vehicles. The percentage of electronic parts in cars has increased to 20%, due to their use in enhancing functionality and convenience and in replacing other parts. The durability and simplicity of mechanical parts is giving way to the convenience and efficiency of electronic parts (Burton, 2003).

Steering systems have recently undergone major developments. When driving at low speeds or when parking the vehicle, a large amount of power is needed to steer. To improve this requirement, hydraulic power steering systems were developed (Adams, 1983). During low speed driving, the power steering system reduces the power needed to steer. When driving at high speeds, on-center steering feel is provided for stability (Adams, 1983; Sergio and Leigh, 2000; Camuffo *et al*., 2002; Kim and Song, 2002; Nobuo *et al*., 1997; Sanket *et al*., 2000).

Existing hydraulic power steering systems use engine power to operate the hydraulic pump, which allows the driver to steer (Kokotovic *et al*., 1999). This type of system is equipped with a hydraulic pipe and various nozzles that are complicated and are difficult to maintain. Electric power steering (EPS) systems have improved on the drawbacks of hydraulic power steering systems (Burton, 2003).

EPS systems operate regardless of engine power and do not require a complicated and heavy hydraulic system (Kokotovic *et al*., 1999). EPS systems are characterized by better maintenance, easier loading, and a 3~5% reduction in fuel consumption. They also make it easier to design the interior of the vehicle and are simpler to apply to future vehicles and intelligent transportation systems. Finally, air pollution is reduced by EPS systems (Burton, 2003).

EPS systems are installed in one of three locations based on the size and type of the vehicle. In compact cars, a column-type EPS is usually used. A pinion-type system is used in semi-compact vehicles, while a rack-type system is used in large vehicles. Research to completely replace conventional steering systems with steer-by-wire systems is ongoing (Jo *et al*., 2006; Kim *et al*., 2001; Jung *et al*., 2008; Koo *et al*., 2005; Kim *et al*., 2005, 2004a, 2004b). However, motor reliability is still an issue that hinders the commercialization of steer-by-wire systems.

The need for EPS systems was recognized in the early 1980s, and pinion-type EPS systems were applied in compact cars in the late 1980s. The development of the column-type EPS system was completed in the early 1990s and was applied to compact and small cars. Due to the limited size of the motor, column-type EPS systems are mostly applied to small cars, but, with an increase in motor

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*Corresponding author. e-mail: mahlee@pusan.ac.kr torque, they will be applied to larger vehicles.

EPS systems increase fuel efficiency and are easier to maintain. With the increasing interest in intelligent transport systems (ITS) and advanced safety vehicles (ASV) (Ryu and Kim, 1999), EPS technology is becoming the basis of these systems.

To apply EPS systems in real vehicles, simulations are necessary for the development of control algorithms and during the design of faster and easier systems. However, applications to real vehicles are difficult to determine using only simulations, so numerous experiments on an actual vehicle are required. This process is costly and time-consuming (Roh *et al*., 2004; Jang, 2003; Park *et al*., 2002; Isermann *et al*., 1999; Wade *et al*., 1998; Ludger, 1996; Ryu *et al*., 1999).

The use of hardware-in-the-loop-simulation (HILS) systems to develop EPS systems allows the testing of simulations and gives credibility to using a hardware system (Hanselmann, 1993). The HILS system in this paper consists of mechanical hardware, which extends from the steering wheel to the steering rack bar, and software that simulates the lateral force caused by the tires (Ryu *et al*., 1999).

Various control algorithms can be tested with the HILS system, and numerous repetitions of the test are possible. Performance can be evaluated with other EPS systems. The mechanical portion of the EPS used in this study is derived from a currently available system. For this study, the control algorithm was developed, and the electronic control unit (ECU) of the steering system was designed and produced.

In EPS systems, when the driver operates the steering wheel to change the direction of the tires, the friction force of the tire surface causes a lateral force in the opposite direction in the steering wheel. The sensor in the column senses this force and feeds it back to the ECU. Next, the ECU supports the driver's steering with power from the motor. The functions of the ECU are to control the motor to support the steering effort and to detect malfunctions. The ECU is also a diagnostic system.

During the development of an EPS, various potential malfunctions are tested with the HILS system. To examine the safety and performance of the developed EPS, it was installed in a vehicle and five categories of malfunctions from an existing steering test were selected and tested.

The HILS system designed in this study was used throughout the development of the EPS. The advantages and disadvantages of the HILS in this process were determined, and the problems and priorities in the development of the EPS were analyzed.

2. HILS SYSTEM IN THE DEVELOPMENT OF THE EPS SYSTEM

2.1. Hardware-In-the-Loop-Simulation System

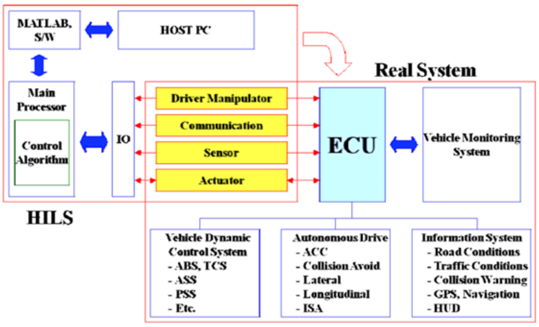


Figure 1. HILS (Hardware-In-the-Loop-Simulation) system.

In the development and modeling of control algorithms, various methods are being tested and applied in the field of mechatronics. Software-in-the-loop-simulations or trial and error methods are used to verify the modeling and performance of the developed control system. Difficulties with trial and error methods include having to test numerous real vehicles individually, excessive expense, and time requirements (Badwy *et al*., 1999).

The accuracy of the nonlinear simulation of the tire and road surface cannot be confirmed during the development and modeling of the control algorithm; therefore, actual vehicle testing is needed. The system validation is performed in numerous car tests and measurements in real vehicle experiments. The use of a HILS system in the development of an EPS, as shown in Figure 1, reduces time and cost.

Normally, the steering system consists of a steering wheel, steering column, rack, and pinion. The rotary motion of the pinion is converted to the linear movement of the rack, which is transferred to the tie-rod. The tie-rod is connected to the knuckle, which rotates the kingpin to operate the tires (Badwy *et al*., 1999).

The user of the HILS system determines the velocity of the vehicle to be developed and tested before the steering starts. The hydraulics required for the maximum tire lateral force is 140 kg, which is transferred at 50 kgf/cm^2 to the cylinder valve through the filter, as shown in Figure 3. The HILS system is fed the velocity and steering wheel angle, and the tire lateral force is calculated from the 17 degrees of freedom of the vehicle model. The calculated force is the movement of the hydraulic cylinder, which influences the steering effort of the driver through the hardware of the steering system.

If the HILS system can simulate the EPS that will be installed in the real vehicle, the development and modification of the EPS control algorithm does not need to be repeated in real vehicle testing. Therefore, the advantage of applying the HILS system in the development of the EPS is that when developing for a different type of vehicle, only the vehicle model of the HILS system needs to be changed. In the case of the EPS system, problems that occur in the steering system can be solved, and repetitive testing and designing of situations is easier, making it

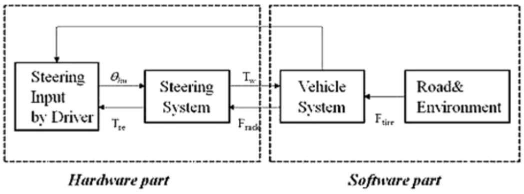


Figure 2. Structural diagram of HILS.

possible to evaluate and test the performance of the developed EPS (Isermann *et al*., 1999).

2.2. HILS System Organization for the EPS System

The existing hydraulic steering system uses the oil pump in proportion to the steering effort to operate the cylinder. In the case of the column-type EPS (C-type EPS), the operation of the steering wheel is entered into the column as torsion, which is sensed by the torque sensor to control the torque of the motor that operates the steering.

The HILS system consists of the simulation where the steering input angle θ_{hw} moves the tie-rod, as in Figure 2. The simulated vehicle system applies the tire lateral force F_{tire} that occurs between the tires and road surface and uses the hydraulic system to transfer the virtual result to the hardware. This result is transferred to the column, where the force that influences the steering system F_{rack} is produced. The driver forms the closed circuit that receives the repulsive force during steering (Ludger, 1996; Hanselmann, 1993).

The hardware component of the HILS system consists of the steering wheel, steering column, rack, and pinion. These are produced at full scale with actual products. The software component of the system, or the simulation component, consists of the tie-rod, kingpin, tires, the lateral force produced from the road surface and tires, and the 17-degree-of-freedom steering power model. These components are simulated in the computer in real time and consist of the closed circuit that enables the driver to drive in a virtual environment.

The HILS needs to be realistically expressed when the vehicle is at a standstill, when the vehicle is lifted by the camber angle depending on the steering angle, or when resistance occurs due to a lateral force. In addition, the difference in the reaction force depending on the velocity needs to be considered. Therefore, for the realistic implementation of the HILS system, the interface between the actual model and the simulation is crucial.

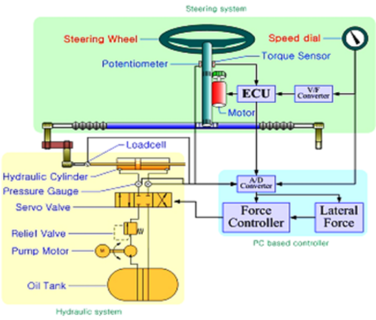


Figure 3. Diagram HILS system for EPS system.

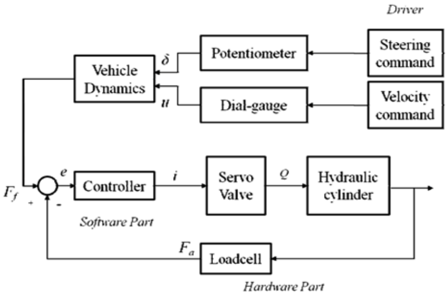


Figure 4. Control block diagram of HILS system.

2.3. Implementation of the HILS System

The HILS system consists of the steering wheel and the column connected to the pinion and the rack. The mechanical structure is shown in Figure 3. The resistance between the steering wheel and the road surface and tires, as well as the force due to the camber angle, are input into the computer based controller and expressed through the hydraulic system (Park *et al*., 2002; Hanselmann, 1993).

The hydraulic system receives the servo valve control signal from the controller installed on the computer to control the hydraulics and to transfer the power (Lee *et al*., 1999). The feedback signal to the controller uses the loadcell shown in Figure 4.

The computer based controller receives the angle of the wheel, the angular velocity, and the vehicle speed. Based on the installed vehicle model angle with 17 degrees of freedom and real vehicle data, realistic enactment of the tires' lateral force due to the vehicle operation is observed (Bertollini and Hogan, 1999; Gillespi, 1992).

The inputs of the computer based control are the driver's steering angle and the vehicle speed. The tire lateral force of the vehicle serves as the desired value and controls the servo valve with the same force. The servo valve is controlled at the same force value and is conveyed to the driver (Ryu *et al*., 1999).

2.4. Hydraulics System

The pressure loss and/or friction of the hydraulic cylinder needed in the HILS system are shown in Table 1.

The tank capacity is 80 L, and the installed motor has a

Table 1. Specification of hydraulic cylinder.

Parameter	Value	Unit
Maximum stroke	250	Mm
Maximum load force	1500	Kgf
Maximum pump pressure	140	Kgf/cm^2
Loss pressure	10	Kgf/cm^2

Table 2. Specification of proportional servo-valve.

Parameter		Valve	Unit
Nominal voltage		+24	V
Maximum flow rate	ΔP = 30bar	27	/min
	ΔP = 70bar	40	/min
	ΔP_{max}= 200bar	70	/min
Input voltage			V
Hysteresis			%
Response time			ms

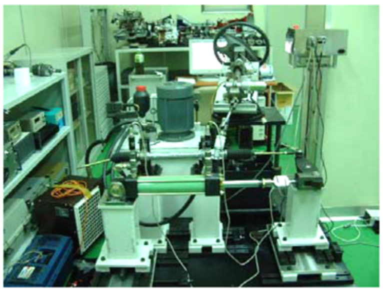


Figure 5. Picture of the hydraulic cylinder.

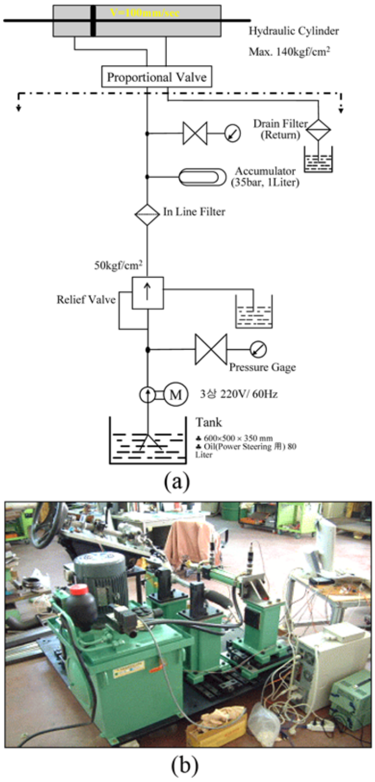


Figure 6. (a) Conceptional schematic diagram hydraulic system and (b) Hydraulic system of HILS system.

speed of 1800 rpm and a power of 3.86 horsepower. At a maximum pressure of 140 kgf/cm^2, the generating capacity is 20 L/min.

Figure 5 presents a direct drive proportional servo valve that operates as a non-supplementary-type valve in both directions according to the electric signal level. The signal level is controlled proportionally depending on the given electric signal. The valve has four spools and, depending on the solenoid, five chambers are operated. The valve specifications are presented in Table 2.

To embody a tire lateral force similar to that of a real vehicle, a loadcell was attached to the rack bar to measure and control the force. The cylinder uses a 250 mm maximum bidirectional stroke cylinder. The actual operating stroke range is 150 mm, which is the operating range of the rack bar in a vehicle.

Hydraulics is created from the oil tank using a three-phase induction motor. The maximum tire lateral force of 140 kg is the maximum hydraulic force needed in the HILS system. This force is filtered at 50 kgf/cm^2 and transferred to the valve of the cylinder. The hydraulic cylinder is shown in Figure 6. This cylinder operates proportionally to the voltage applied to the servo valve. To demonstrate the operating vehicle state, the force applied to the rack bar is implemented with the load being applied by the hydraulic cylinder to the kingpin.

2.5. Power Supply and Sensors of the HILS System

2.5.1. Power supply

The actuator and sensing systems of the HILS system each need their own power supply. The power supply needed for each component is shown in Table 3. Individual transformers and regulators are used to provide stable power supplies.

2.5.2. Voltage-frequency converter in the vehicle

To demonstrate that the operation of the ECU of the EPS system is similar to that of a real vehicle, the signal in the vehicle is used to induce the HILS system. The EPS system is made up of the ECU and the electronic motor. The necessary power and signals are separate from the HILS system. However, the speed input of the HILS system must be the same as that of the ECU that is operating in the

Table 3. Supplied voltages for each sensor and actuator.

Sensors and actuators	Voltage [V]
Hydraulic cylinder	24
Pressure sensor	24
Load-cell	AC 220
Potentiometer	15
Current sensor	±12
V/F converter	15
Torque sensor	5

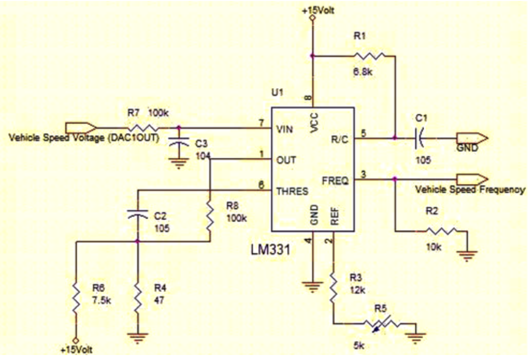


Figure 7. Schematic circuit for voltage to frequency convert.

Table 4. Specification of potentiometer.

Parameter	Value	Unit
Resistance range	10	kΩ
Standard tolerance	± 5	%
Linearity	± 0.25	%
Rotation	3600	Deg

vehicle.

The ECU perceives the speed as a 12V pulse signal. While in the HILS system, it is input to the analog-digital converter (ADC) shown in Figure 7 in which the voltage input is converted to a frequency. The frequency value of the ECU and that of the HILS system are set together. The driver of the HILS system controls the speed with the ten rotation volume resistance in the interface box. The set speed is indicated in the graphic user interface (GUI) of the HILS system. When the speed is entered into the HILS system, it is used to convert the output of the potentiometer into km/h.

Even though the output of the potentiometer is linear, the output of the voltage-frequency converter circuit changes it into a nonlinear frequency. Table 4 shows the specification of the potentiometer used for the input of the speed and steering wheel angle.

2.5.3. Steering wheel angle sensor

To measure the angle and angular velocity of the steering wheel, the voltage is induced on the potentiometer at a 2:1 gear ratio, which is subsequently fed to the HILS system through the ADC. According to the behavior of the steering wheel, the angle is used to convert the analog input to a steering wheel angle.

Table 5. Specification of current sensor.

Model	PLIA040-04D12	
Parameter	Value	Unit
Adj. voltage	40	V
Supply voltage	± 12	V
Output voltage	0~10	V
Frequency range	0~50	kHz

2.5.4. Current sensor

When driving along a curve in a real vehicle, an assist force is created to maintain a constant steering angle. The HILS system operates the hydraulic cylinder using the speed, wheel angle, and steering angular velocity as inputs into the model vehicle formula; therefore, reproducing the assist force is difficult. The amount of torque and current induced on the motor by the ECU controller is observed in the EPS. To compensate for the assist force created during the curve, the current sensor shown in Table 5 is connected to the motor and input with the ADC.

2.5.5. Loadcell

The HILS system attempts to reproduce the lateral force created from the tires while driving the virtual vehicle. The lateral force obtained from the model vehicle operates the servo valve. The loadcell is used to control the force applied to the rack bar by the actuator. The loadcell is selected at twice the force of the lateral force. An indicator is attached to confirm the movement state of the cylinder and the steering effort of the driver of the HILS system. The electrical characteristics of the loadcell are presented in Table 6.

2.5.6. Pressure sensor

A pressure sensor is used to measure the force created in the hydraulic cylinder. The pressure of the hydraulic cylinder and the actual movement pressure measured in the loadcell control the hydraulic system. The electric characteristics of

Table 6. Specification of loadcell.

Parameter	Value	Unit
Capacity	1	Tonf
Output voltage	2	mV
Input voltage	10	V
Hysteresis	0.03	%
Nonlinearity	0.03	%

Table 7. Specification of pressure sensor.

Model	PHHK0100KAAA
Adj. pressure	100 kgf/cm^2
Full scale(FS)	10.014 Vdc
Nonlinearity	0.08 % FS
Hysteresis	0.04 % FS
Repeatability	0.03 % FS
Accuracy	0.094 % FS

the pressure sensor are presented in Table 7.

Figure 8. Picture of HILS system interface.

Table 8. Specification of data acquisition board.

Parameters	Value
Input channel	16
Sampling rate	500 KS/s
Output rate	1 MS/s
Resolution	12 bit
Digital I/O channel	8
Digital output channel	2
Output voltage range	± 10V dc

2.5.7. Interface

An interface between the actuator and the sensors (Lee et al., 1999) allows the driver to operate the HILS system externally and to verify the movements. The interface includes an indicator showing the physical output values of the sensors, an emergency button in case of actuator malfunction, and a dial to set the vehicle's speed.

Figure 8 shows the interface of the HILS system. In the upper left is the valve switch, speed input dial, and emergency button. The steering wheel angle, loadcell measurement value, and motor current during EPS operation are indicated below.

2.5.8. Data input device

A data acquisition (DAQ) device is used to drive the sensor and actuator. The specifications of the acquisition board are presented in Table 8.

The vehicle model was developed using Visual C++. The software used in the DAQ device also uses Visual C++ and includes the necessary controls in its library.

2.5.9. Jig

To prepare for unpredictable situations in the hydraulic cylinder operation, the HILS system needs mechanical rigidity. The ends of the rack bar are welded and are semi-permanent. The rack bar is a screw type to allow free movement and easy installation.

3. SIMULATION OF A VEHICLE MODEL

Table 9. Seventeen-DOF vehicle model.

Seventeen-Degree-Freedom Vehicle Model for HILS
· three rotations of the vehicle about the body axis · three translations of the vehicle's center of mass · four wheel spins · four wheel-suspension deflections · two front-wheel rotations about the kingpins · one steering connecting-rod displacement

The HILS system consists of a hardware portion for steering and a software portion for real time simulation. In other words, it consists of a real-time vehicle kinetics model and convenient testing of the EPS and programming (Ludger, 1996; Zaremba and Davis, 1995; Choi *et al*., 1995).

3.1. Vehicle Modeling of the HILS System

Vehicle modeling started with the bicycle model in the 1950s and progressed to various degree-of-freedom models that move in three dimensions. Since the 1970s, vehicles have become faster, smaller, lighter, and more efficient. Accordingly, more precise models for driving efficiency are now required.

The details of the accurate dynamic movement model consider the effects of moving loads, comfort, control, safety, various nonlinear characteristics, and coupling effects (Adams and Topping, 2001).

The speed and wheel angle input in the HILS system are used to calculate the tire lateral force in real time; therefore, real-time simulation is needed. If this real-time simulation model is excessively simple, the calculation takes little time or the accuracy drops and limits the useful range. If the simulation is too complicated or uses a multi-object dynamic model, a high-performance system is required (Wade *et al*., 1998; Adams and Topping, 2001; Kim and Park, 2004).

The vehicle model used to test the EPS system was based on the model developed at the University of Michigan for the National Highway Traffic Safety Administration (NHTSA). This model uses an anti-lock brake system and active suspension system. A 17-degree-of-freedom vehicle model, shown in Figure 9, is used to obtain the control target value of the hydraulic cylinder, which is used to

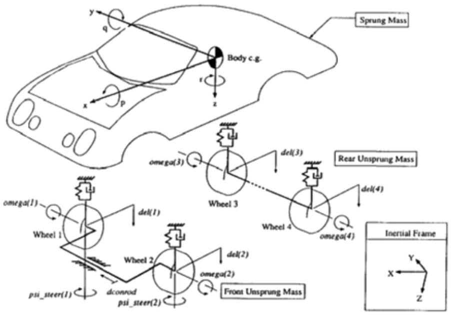


Figure 9. 17-D.O.F vehicle model.

calculate the tire lateral force. All simulations use SI units.

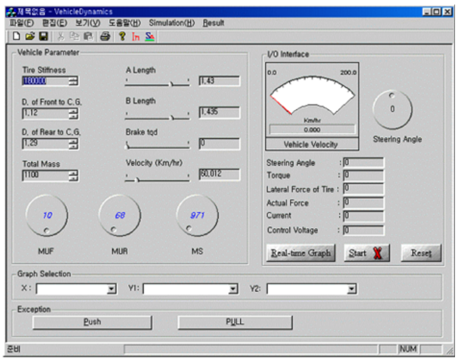
The inputs to the vehicle model are steering angle, brake pressure, vehicle speed, wind velocity, and the condition of the road. In the HILS system needed in the development of the EPS system, the steering angle and vehicle speed is received to output the tire lateral force (Choi *et al*., 2002; Salaani *et al*., 2002).

The vehicle used in the modeling has the following mechanical systems, as shown in Figure 9. The sprung mass has three translating and three rotating movements. The front unsprung mass, which includes the front suspension, axis, and wheel servo system, has the two front suspension deflections, two front wheel spins, two wheel rotations centered on the kingpin, and a steering connected rod displacement. The rear unsprung mass, including the rear suspension, axis, and rear tires, has two wheel spins and two suspension displacements.

The mathematical model of the 17-degree-of-freedom vehicle model used in the HILS system is processed in four parts: the steering equation, wheel orientations, vehicle kinematics, and wheel forces and moments. Each mathematical model is calculated in the same order to acquire the tire lateral force.

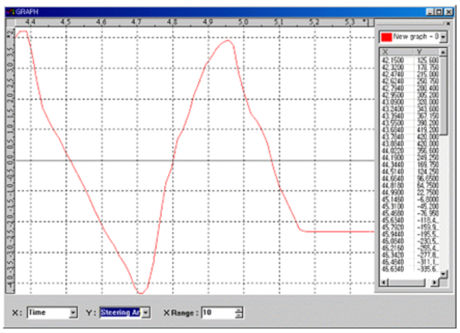
3.2. HILS System Simulation

The graphical user interface (GUI) environment is established to verify the results of the vehicle model, as well as for the HILS system driver to operate the system simultaneously. The parameters of the vehicle where the HILS system will be installed are simulated to compare the force needed in the steering effort with the force created by the HILS system (Ludger, 1996; Salaani *et al*., 2002). The driving conditions are also simulated with the HILS system.



Tire Stiffness 180000
D. of Front to C.G. 1.12
D. of Rear to C.G. 1.29
Total Mass 1100
A Length 1.43
B Length 1.435
Brake tqd 0
Velocity (Km/hr) 60.012
Vehicle Velocity 0.000
Steering Angle 0
MUF 10
MUR 68
MS 971
Steering Angle : 0
Torque : 0
Lateral Force of Tire : 0
Actual Force : 0
Current : 0
Control Voltage : 0

Figure 10. Interface menu for HILS system simulation.



X	Y
42.1500	125.600
42.3200	170.750
42.4740	215.000
42.6240	250.750
42.7940	280.400
42.9500	305.200
43.0900	320.000
43.2400	343.600
43.3940	367.150
43.5500	398.200
43.6840	419.200
43.7840	420.000
43.8840	420.000
44.0220	356.600
44.1900	249.250
44.3440	169.750
44.5140	124.250
44.6640	96.6500
44.8180	64.7500
44.9900	22.7500
45.1450	-6.8000
45.3100	-45.200
45.4680	-76.950
45.6340	-118.4..
45.7920	-159.9..
45.9440	-195.5..
46.0840	-230.5..
46.2160	-255.4..
46.3420	-277.8..
46.4840	-311.1..
46.6340	-335.6..

X : Time
Y : Steering An
X Range : 10

Figure 11. Graphical display of HILS system simulation.

Table 10. Test vehicle manual steering force test specification.

Slalom test (continuous sinusoidal steering input)	
Test objective	Frequency response as a steering frequency
	Yaw velocity as a steering angle
	Lateral acceleration as a steering angle
	Speed control : 0 ~ 50 km/h (10 km/h degree)
Test specification	Steering angle : steady state lateral acceleration comparison of steering angle as a function of time during test of SR (10 km/h) (for a velocity of 4 m/s)
Measuring data	Steering frequency : 0.2 Hz
	Steering angle
	Steering torque
	Longitudinal velocity
	Sampling rate : Min. 100 Hz

The parameters are set with the information of the target vehicle. In the program, the vehicle moves in real time, while the actuator does not. The parameters are examined to see if they satisfy the general conditions in this state and whether the tire lateral force is within the working conditions of the HILS system. The HILS simulation program is activated, as shown in Figure 10. The actual steering input parameters are confirmed on the monitor while driving the HILS, and the results of the simulation are confirmed, as shown in Figure 11.

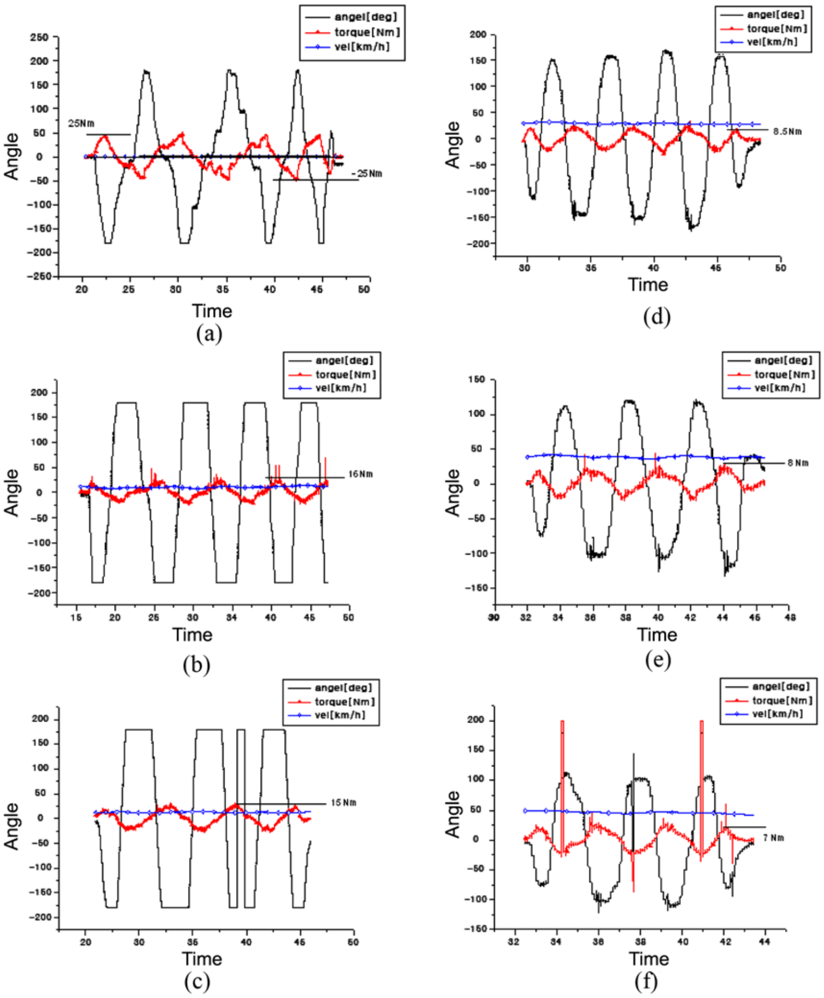
3.3. Manual State Real Vehicle Test

The HILS system is tested manually on the vehicle model where the system is to be installed. Based on the extracted values, for realistic simulations, the various parameters are the same as in the real vehicle.

The EPS was installed in a KIA Rio to perform manual steering tests (Hugo *et al*., 1997; Ha, 2006). Manual testing was performed to simulate the steering efforts in real time in order to confirm that the calculated tire lateral force is the same as in the real vehicle and to inspect the vehicle model. In addition, the unconfirmed parameters are estimated to tune the HILS system.

During the experiments, the real vehicle steering force is measured during a slalom test on a two-lane road at 10 km/h, 20 km/h, 30 km/h, 40 km/h, and 50 km/h. The developed EPS does not operate at speeds greater than 50 km/h. Common EPS systems are set for increased steering force at speeds over that limit. However, this system was tested manually at 50 km/h and stably steered at high speeds.

The peaks in Figure 12(f) are due to the abnormal



(a)
(b)
(c)
(d)
(e)
(f)

Figure 12. Torque and angel as a function of time to (a) 0 km/h, (b) 10 km/h, (c) 20 km/h, (d) 30 km/h, (e) 40 km/h and (f) 50 km/h.

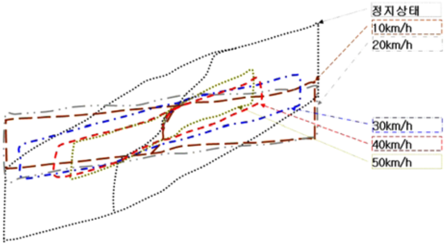


Figure 13. Graph of torque as a function of angle (0~50 km/h).

Table 11. Steering force of manual steering test.

Vehicle velocity	Steering torque
10~15 km/h	0.50 kgfm
15~20 km/h	0.60 kgfm
25~30 km/h	0.72 kgfm
35~40 km/h	0.78 kgfm

signals that occur when exceeding the threshold value of the instrument that measures torque. This graph was used to describe precisely the actual measurement values because it satisfies the overall tendency.

The averages of the manual state real vehicle experiment results are shown in Table 11.

The output value unit of the steering force used in the real vehicle experiment was in Nm and was converted to kgfm units for use in the simulation, as follows.

$$1 \text{ Nm} = 0.101972 \text{ kgfm} = 10.1972 \text{ kgfcm} \qquad (4)$$

4. ELECTRONIC CONTROL UNIT OF THE EPS SYSTEM

The ECU of the EPS system was able to tune the steering force and, when applied to the HILS system and/or real vehicles, requires adjustment.

The functions of the ECU include measuring the deflec-

Table 12. Input and output of the EPS ECU.

In/Out	Value	Function
Input	Speed	Steering force as a function of speed, motor control
	Torque	Steering torque input, motor control
	rpm	Error monitor
	Ig. switch	Start key
	Power	Battery 12 V
Output	Motor	Steering force control
	Clutch	Emergency disconnect (Column and motor)
	Dig. code	Pulse output, function of error monitoring

Table 13. Specification of EPS ECU.

Parameter	Value	Unit
Processor clock	4	MHz
Data bus	8	Bit
Memory	8	K
PWM resolution	8	Bit
D/A, A/D resolution	8	Bit
Motor driver	FET H-bridge	Type
Power	12 V	
Disconnected wiring detecting (Motor, Clutch)		
Diagnosis code generating		

tion of the steering wheel and converting the measurements to an 8 bit analog-digital value, pulse width modulation output, error detection, and power blockage during malfunction and conversion to manual mode. Each function was developed and tested using the HILS system and evaluated in the real vehicle test.

4.1. Organization of the Electronic Control Unit

The ECU regulates vehicle speed, the torque sensor, and the motor of the steering device with the rpm input (Kim and Song, 2002). The input and output functions of the EPS ECU are presented in Table 12, and its specifications are shown in Table 13.

4.2. Design of the Electronic Control Unit

Figure 14 shows a block diagram of the EPS ECU.

4.2.1. Power system

The ECU is induced with ground and 12 V batteries. The induced current is stabilized through noise eliminating coils, while the varistor prevents high-capacity noise that can occur during driving or the input of a surge current from the motor. The varistor is an electronic component with significant nonlinear current-voltage characteristics and is used to absorb part of the surge current. The connected varistor conducts excessive current to prevent malfunctions and damage. It is generally used in the power input of a vehicle.

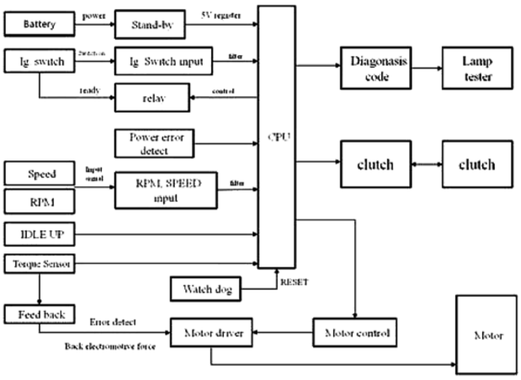


Figure 14. Schematic diagram of the EPS ECU.

Table 14. Specification of EPS ECU power.

Voltage	Function
12V-battery	Vehicle battery power
12V-relay	Clutch supply power
8V	OP-supply power
24V	Motor driver power
5V	TTL level power
5V stand-by	Error code register power

The types of power used in the ECU are shown in Table 14. The 12 V vehicle battery is always connected to the power, and it consumes less than 1 mA of current when it is induced. After the input of the ignition switch, the ECU processor checks the motor for disconnection. If there are no problems, the relay is operated to induce the 12 V relay power. The constantly supplied main power is used to operate the EPS system motor. The 12 V relay power is used when there is a problem in the ECU to block the power to the clutch and to drive the EPS system manually.

The control system is made up of sensor inputs and circuits, uses OP supply power, and is induced with an 8-V current. The rest of the power supply includes a regulator with watchdog functions to induce a 5-V TTL-level power. In the case of the 5-V TTL-level power, the relay has to work to provide power. When the relay does not work, the power is not induced and it senses a malfunction. When the 5V TTL level power is blocked, the 5-V stand-by power connected to the CPU is induced at below 5% error of the 5 V TTL level power in order to maintain the content of the stand-by RAM. The content of the first 8 bytes of the stand-by RAM is maintained in case the power is blocked

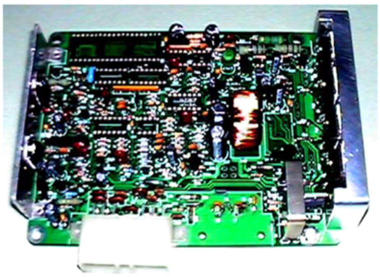


Figure 15. Developed EPS ECU.

by the 5V stand-by power. The ECU stores the error code that occurred just before the power outage in the stand-by RAM. When the ECU stops operating due to a malfunction, these functions monitor the errors, re-enters the ignition switch, and checks the errors before resetting. Error codes are created for the fix driver protection and steering maintenance.

The operation of the ignition switch is connected to the ECU for the ECU to automatically operate when the ignition is turned on. However, in the test vehicle, the switch is attached on the outside so that it can operate during testing.

The motor control of the EPS system was stepped up by a DC-DC converter with FET voltage to create 24 V current and used a FET gate power. The input of the boosting voltage circuit induced a power voltage of 12 V. To verify that the DC-DC converter is operating normally, the transistor is connected to the output control to monitor the output of the boosted 24 V power on the CPU to prevent malfunctions.

Figure 15 shows the EPS with the actual designed electric control device and shows the developed EPS ECU.

5. HILS SYSTEM SIMULATION RESULTS

The simulation parameters of the HILS system were adjusted with the steering force values from the manual steering experiment and are compared with the results of the real vehicle test in Figure 16.

In estimating the vehicle parameters of the HILS system, the electronic steering device operates at 0~45 km/h; therefore, the parameters of interest were tuned for that range. At 60 km/h, the HILS system had a tendency not to influence the actual vehicle. If the parameters are estimated and tuned for the HILS system to be applied at speeds above 60 km/h, the system does not follow appropriately in the range of interest. This is thought to be due to the complex operation of the vehicle at high speeds and because proper testing at high speeds was not done.

The precise parameters of the vehicle model (17 DOF) were not measured. The results were obtained with the general vehicle model parameters mentioned in other papers. The differences occurred because the state of the tires and the state of the road were not exactly applied. However, in this paper, use of the HILS for the development of the EPS system and through actual vehicle testing demonstrates the overall direction of system development. Matches with the simulation model were not proven, but similar tendencies were confirmed. That is, the model parameters have to be adapted each time depending on the

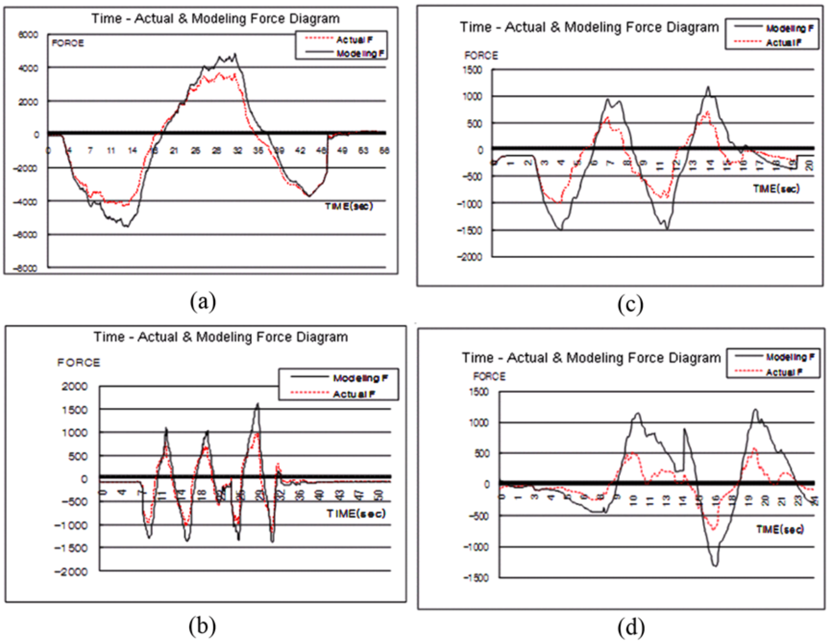


Figure 16. Comparison of steering force in the HILS system and the real vehicle at (a) 0 km/h, (b) 20 km/h, (c) 40 km/h and (d) 60 km/h.

vehicle models that use the EPS system.

However, the results of the HILS system show that the steering force measured in the actual vehicle and the tire lateral force produced in the HILS system were consistent. Therefore, this system can be used in the development and testing of electronic steering devices.

6. CONCLUSION

In this study, a HILS system is applied in the development process of an electronic steering device to facilitate easy repetitive simulations and to demonstrate the credibility of actual vehicle testing. Compared with using a hydraulic steering device, developing an electronic steering device using HILS reduces time and expenses.

To construct the HILS system, mechanical hardware from the steering wheel to the pinion and rack and a 17-degree-of-freedom vehicle model were used to reproduce the lateral force of the tires with the input of velocity and steering angle. The results of the reproduced lateral forces of the tires were controlled through the hydraulic system of the HILS and compared with results of tire lateral force from actual vehicle testing.

An electronic steering device was developed to aid the driver by applying an electronic control device to the existing product. The electronic steering device operates the motor using velocity and steering input. To ensure safe operation when applied in an actual vehicle, a self-diagnosis function is included in case of a malfunction. Improvements on the precision of steering torque and the feeling of steering were accomplished through the control of the electronics controlling device.

The developed electronic steering device was installed in the HILS system and applied with a control algorithm, which was determined in advance, to produce the targeted steering torque and to measure the steering feel. In addition, malfunction situations that are difficult to confirm in actual vehicle testing were tested, and malfunction detection was verified. The developed electronic steering device of the ECU was subsequently installed in an actual vehicle to evaluate and analyze its performance.

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