An Electric Power Steering Control by Fuzzy logic in HILS system

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Abstract

This paper discusses a DC motor equipped electric power steering (EPS) system and demonstrates its advantages over a typical hydraulic power steering (HPS) system. The tire-road interaction torque at the steering tires is calculated using the 2 d.o.f. bicycle model, which is verified with the J-turn test of a real vehicle. By using hardware-in-the-loop simulation(HILS), the control responses of the vehicle are obtained. In previous EPS systems, the assisting torque for the measured driving torque is developed as a boost curve similar to that of the HPS system. To improve steering stiffness and returnability of the steering system, assisting torque map is determined by fuzzy logic.

1 Introduction

Recently the automotive industry has focused on improving vehicle performance, safety and convenience for drivers. Steering assist systems play an important role in each area. The conventional HPS system, which is made up of an engine-driven hydraulic pump and a hydraulic actuator, decreases engine efficiency but requires complex hydraulic components. To cope with the deficiencies of HPS, an EPS system has been vigorously researched. Since the EPS system uses an engine-independent motor without complex hydraulic units, the weight and volume of steering systems can be reduced. Thus, EPS systems achieve better fuel and space economy and maintains the feel of the steering even during quick changes in driving conditions through software. Moreover no harm is done the environment because no hydraulic fluid is used [1].

To improve steering stiffness and returnability of the steering system, steering feel should be set up. Adams, F. J. [2] researched the feel of power steering and Norman, K. D. [3] introduced on center handling performance. Gary P. Bertollini and Robert M. Hogan [4] drew up a preference curve as a function of vehicle speed based on the effort needed for steering by various drivers using VTI driving simulators. Rakan C. C. and Le Yi Wang [5] used boost curves of assist torque for a given vehicle speed. Based on these objective indices, Camuffo, et al [6] tuned an EPS to have the steering feel of an HPS. Generally EPS systems are controlled by comparing the measured steering torque with the reference steering torque. Using a steer-by-wire EPS, Tong Jin Park, et al [7] utilized the steering wheel motor to alter the steering feel according to vehicle speed and controlled the front wheel motor by PID Control to minimize the error between steering angle and wheel angle. With steering wheel angle and torque sensors attached to a steering column, Anthony W. Burton [1] calculated assistance torque by summing the high gain related to steering torque and the low gain related to steering position. To improve returnability, M. Kurishige, et al [8] developed a control strategy based on an estimation of alignment torque generated by tires and road surfaces without sensors. Since steering torque assistance and returnability are not active at the same time, Kim and Song [9] separated the two control algorithms where the reference steering torque was determined by the torque map based on vehicle speed and steering wheel position.

In this paper, the 2 d.o.f. bicycle model will be used to calculate the tire road interaction torque. Although the steering of a vehicle affects its rolling motion, a description of the rolling system is beyond the scope of this dissertation since an EPS does not control the active driving angle but the assisting torque. In previous EPS systems [5], assisting torque for the measured driving torque was making a chart as a boost curve like the HPS of Adams's research [2]. In the research of Kim and Song [9], the reference steering torque depended on vehicle speed and steering wheel angle by encoder. The evaluated assisting torque map by fuzzy logic will be simulated in HILS system [10]. The fuzzy logic is useful for nonlinear system and decision making for controllers.

The organization of the paper is as follows: Chapter 2 describes a vehicle system and a hydraulic servo system and verifies the mathematical models for the vehicle system. Chapter 3 presents HILS system for EPS. In chapter 4, the assisting torque map is proposed by fuzzy logic. The control results in HILS are discussed in chapter 5. Finally, the main conclusions are given in chapter 6.

2 Tire-road Interaction Torque

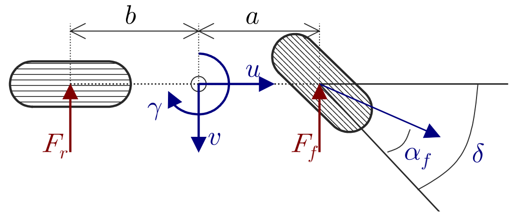

Fig. 1. Coordinate of the single-track model

To find the tire-road interaction torque, τ_t, the kingpin torque [11] is obtained as

$$\tau_k = \tau_V + \tau_L + \tau_A \quad , \tag{1}$$

where τ_V and τ_L are the vertical torque and the lateral torque, respectively. And the third term, τ_A, is aligning torque. Because of the kingpin offset angle, d, and a lateral inclination angle, λ, the vertical force, F_z, on the tire produces the vertical torque, τ_V. When the kingpin offset angle and the lateral inclination angle are small, the vertical torque generated by the vertical force can be approximated by

$$\tau_V = -F_z\, d \sin\lambda \cdot \sin\delta, \tag{2}$$

where δ is the steering angle. Since the lateral force, F_y, acting at the tire center produces a torque through the longitudinal offset resulting from the caster angle, the lateral torque generated by the lateral force is given by

$$\tau_L = F_y\, r_t \tan\nu, \tag{3}$$

where r_t is a tire radius and ν is a caster angle. The lateral force, F_y, is developed by a tire at a point behind the tire center. So the aligning torque is written as

$$\tau_A = p_t F_y \cos\sqrt{\lambda^2 + \nu^2}\ , \tag{4}$$

where p_t is the pneumatic trail distance. Considering the length from kingpin to rack-bar, the rack-bar force is written by

$$F_r = \frac{\tau_k}{\{l_0 \cos(\theta_0 - \delta) + l_0 \cos(\theta_0 + \delta)\}} \quad , \tag{5}$$

where l_0 is the length of the tie-rod and θ_0 is the tie-rod angle.
The ground reactions on the tire are described by

$$\tau_t = F_r \cdot r_p, \tag{6}$$

where r_p is the radius of the pinion. Additionally the friction torque, τ_f, is defined as follows:

$$\tau_f = C_{fric} \cdot \mathrm{sign}(\dot{\theta})\,. \tag{7}$$

where C_{fric} is the friction gain. Although the steering system has more complex frictions, these are ignored here. The classical single-track model [12] is obtained by lumping the two front wheels into one wheel in the centerline of the vehicle, the same is done with the two rear wheels as shown in figure 1. For the lateral direction and the yaw axis, the vehicle kinetics at the center of gravity (C.G.) are describes as

$$m\, a_y = 2(F_f + F_r)\,, \qquad I_{zz}\dot{\gamma} = 2a(F_f - F_r)\,, \tag{8}$$

where a_y and γ are the lateral acceleration and the yaw rate, m and I_{zz} are the vehicle total mass and the yaw moment of inertia, F_f and F_r are the lateral forces at the front and the rear tire, and a is the distance from the vehicle C.G. to front axle. Since tires can be modeled as linear within $|a_y| \leq$ 0.3 g, the lateral forces at the front and the rear tires are obtained as

$$F_f = C_f \cdot \alpha_f, \qquad F_r = C_r \cdot \alpha_r, \tag{9}$$

where C_f and C_r are the front and the rear cornering stiffnesses. Usually to verify the steering performance, a J-turn test is fulfilled. For the verification, the steering wheel angle, θ, is stepped up to 34° within 0.2 sec when the longitudinal velocity, u, is 22 m/s. Figure 2 shows the J-turn results for the single-track model and the actual vehicle. The lateral acceleration, a_y, and the yaw rate, γ, settled to around 3.4 ㎨ and 8.3 deg/s. The integrals of time muliplied by the absolute magnitude of the error (ITAE) for the lateral acceleration and the yaw rate are 0.29 ㎨ and 0.42 deg/s, where the nonlinearity of the tire may be the main factor for the errors. As a result, the single-track model has characteristics almost similar to the actual vehicle's. A hydraulic servo system is used for realization of the lateral force in HILS system. In this paper, there are several assumption. A velocity difference between going and returning is regarded as disturbance, servo valve is symmetric, supplied-pressure and falling-pressure at the valve orifice are constant, returned-pressure is zero, and there is no loss of friction at the pipe.

3 HILS System for an Electric Power Steering

For the design, implementation and testing of control systems, some actuators are real, and the process and the sensors are simulated. The reason is that actuators and the control hardware very often form one integrated subsystem, also actuators are difficult to model precisely and to simulate in real time. By using this HILS, the effects of faults and failures of actual sensors and computers on the overall system can be tested in spite of extreme and dangerous operating conditions. The expenditure of developing cost and time can be cut down since experiments are reproducible and frequently repeatable [13]. Especially, HILS systems are useful for the active or semi-active vehicles. By using HILS, the control responses of the vehicle for the various conditions of speed, steering angles, and disturbances are obtained precisely, safely, cheaply, and rapidly. The tire-road force related to the vehicle dynamics is calculated by software and is exerted on rack-bar by hydraulic actuator, where steering torque is measured by torque sensor attached on the steering column. Steering system organized by steering wheel, steering column, and rack-bar is embodied in hardware. In figure 2, ECU makes the EPS motor generate a proper torque which is dependent on vehicle speed, u, and measured driving torque, τ_s. A hydraulic actuator controlled by a servo-valve realizes lateral force, which is calculated steering wheel angle by potentiometer and vehicle speed by dial. By Visual

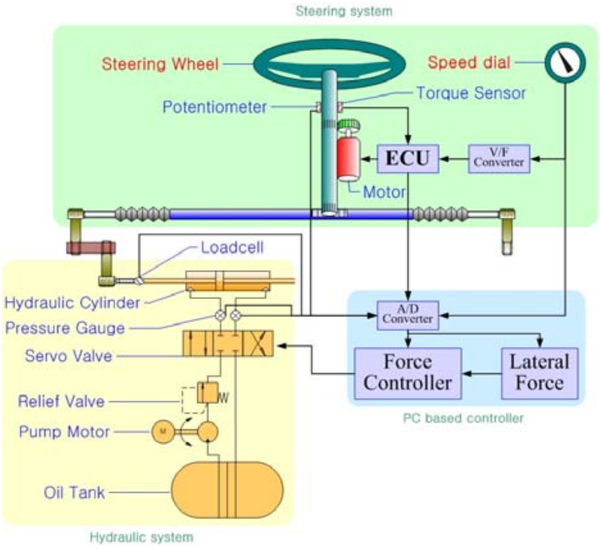

Fig. 2. Constitution of HILS system

C++ under MS window 98, the 2 d.o.f. vehicle dynamics yields lateral force, yaw rate, and lateral acceleration. To control the hydraulic actuator precisely, LMI based H_∞ controller is used and the force is measured by loadcell. And also the output of sensors are displayed by indicators and an emergency button is setup for the malfunction. The EPS (C-EPS of KOYO SEIKO Co.) mounted on a column axis provides an assist force to a column shaft via a worm gear. The optimal value of a current required for a motor is calculated by ECU (Electronic Control Unit), based on a electric signal from a torque sensor and a signal from a vehicle speed sensor. The torque sensor sends the signal depending on a torsional angle of a torsion bar mounted in the inner part of a column axis, which is proportional to a steering force. This EPS system adopts a brushless DC motor which has a lot of advantages versus a brushed motor. By non-contact electronic switching of brushless motor, the life cycle is lengthened, and the absence of brushed and commutator enables the motor to be downsized and reduces the noise of it. In addition, lower inertia of the brushless motor gives good steering feel because there is no permanent magnets as the rotor [16]. Commonly, it is not necessary to measure a steering wheel angle, since an EPS system is related with a steering torque. However, lateral force in the HILS system is determined by the vehicle speed and the steering wheel angle, which is measured by a potentiometer(Model 534, Vishey Co.). The resolution of measured angle is doubled by 2:1 gear between the potentiometer and the steering column. Vehicle speed has influence on the lateral force at tire and the EPS system. By dial-gauge equipped potentiometer, vehicle speed is set up in the HILS system. The realized speed as analog voltage is adopted by DAQ and used for the calculation of the lateral force. However, ECU (Electronic Control Unit) in vehicles recognizes the speed by accumulating the pulse of speed. So the speed as voltage type should be converted to the pulse type. The output range of frequency is tuned by 104 ㎌ condenser, where the maximum frequence is 200 Hz for the maximum speed of vehicle, $u_{\max}=83$ ㎧. The servo-valve is a proportional valve, direct operated, which provides both directional and non-compensated flow control according to the electronic reference signals. This operates in association with electronic drivers, which supplies the proportional valves with correct current signal to align valve regulation to the reference signal supplied to the electronic driver. This valve has a 4-way spool, sliding into a 5-chambers and directly operated by solenoids. In order to make the accurate lateral force, axile force on rack bar should be measured and controlled. Sensors and actuators in the HILS system need the sources of electricity. Because they are operated by DC, transformer with bridge circuit converts AC into DC. To stabilize the supplied voltage, linear voltage regulators and condensers are used, where the suppling states are checked by LED. The sensor signals are acquired by PIC-MIO-16X-4 of National Instrument Co.

4 Steering Feel and Assisting Torque Map

Vehicle dynamics and steering systems behave strongly nonlinear which causes difficulties in developing a classical controller system. Fuzzy logic however facilitates such system designs and improves tuning abilities [10]. A Fuzzy logic controller is used to give a desired assisting torque. The longitudinal speed of a vehicle, u, and the measured torque, τ_m, are applied to a Fuzzy controller. The membership functions are composed of the triangular and the trapezoidal functions. Table 1 shows the rule base for the Fuzzy controller. By the Mamdani's fuzzy implication and the max-min composition, the control surface is made up as shown in figure 3.

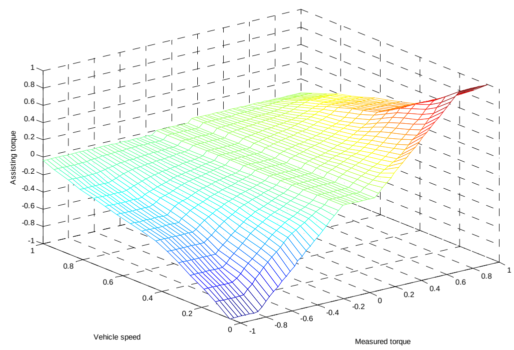

Fig. 3. Normalized control surface

Table 1. Fuzzy rule-base for EPS controller

u \ τ_m	NB	NM	NS	ZE	PS	PM	PB
ZERO	NX	NB	NM	ZE	PM	PB	PX
LOW	NB	NM	NS	ZE	PS	PM	PB
MID	NM	NS	NS	ZE	PS	PS	PM
HIGH	NS	NS	NS	ZE	PS	PS	PS

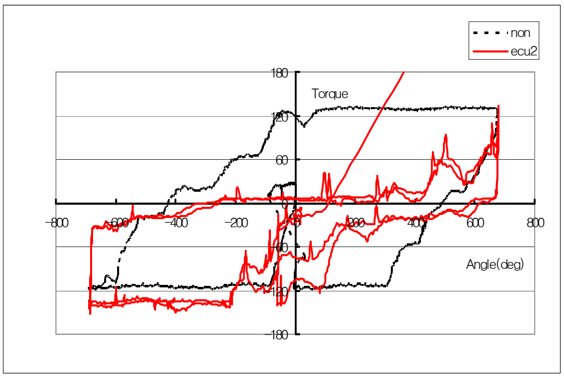

Fig. 4. Plot of steering angle vs. steering torque (u = 0 m/s)

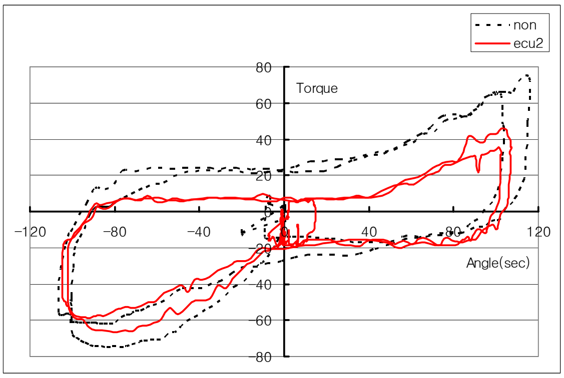

Fig. 5. Plot of steering angle vs. steering torque (u = 11.1 m/s)

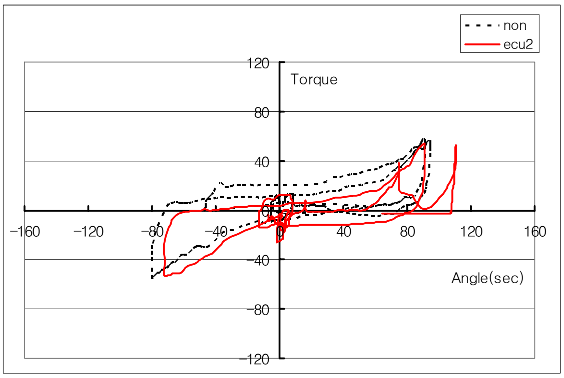

Fig. 6. Plot of steering angle vs. steering torque (u = 16.6 m/s)

5 Experimental Results

Figures 4-6 show the plots of steering wheel angles versus steering torques. When a vehicle is stopped as shown in figure 1, the EPS system helps a driver to park. As the speed of vehicle is increased, the assisting torque by the EPS system is decreased.

6 Conclusions

In this paper, the vehicle model utilized 2 d.o.f. bicycle model and was verified by the J-turn test of a real vehicle. We introduced a cubic curve as a torque map. To improve steering stiffness and returnability of the steering system, assisting torque map was drawn by fuzzy logic. This proposed torque map waw simulated in HILS system with a real steering system. By using this map, the EPS system was improved sufficiently.

Acknowledgements

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