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Control logic for an electric power steering system using assist motor

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Abstract

Electric power steering (EPS) systems have many advantages over traditional hydraulic power steering systems in engine efficiency, space efficiency, and environmental compatibility. This research aims at developing EPS control logic for reduction of steering torque exerted by a driver, realization of various steering feels, and improvement of return-to-center performance. In addition, the torque sensor capable of measuring the steering torque and steering wheel angle is devised, and the hardware-in-the-loop simulation (HILS) system that can implement an actual load torque delivered to the steering column is also developed. With the proposed EPS logic, the driver can turn the steering wheel with the steering torque whose magnitude is determined from a torque map independent of load torques that tend to vary depending on the driving conditions. Experimental studies show that the proposed EPS control logic can improve return-to-center performance of the steering wheel by control of the assist motor.

Keywords: Electric power steering; Steering torque; Torque sensor; Assist motor; Active damping

1. Introduction

A steering system is one of major subsystems for vehicle operation. It rotates the front wheel plane in the desired direction set by the driver's steering input. When the front wheels are steered, a restoring torque which tends to return the wheels to the original position arises. Although this restoring torque provides steering stability, the driver must provide sufficient torque to overcome this torque to steer the vehicle.

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Since considerable steering effort is required for large vehicles particularly at low speeds, power steering was introduced to assist the driver in turning the steering wheel in such driving conditions. Most power steering systems consist of an engine-driven hydraulic pump and a hydraulic actuator [1].

Since the conventional hydraulic power steering (HPS) system is powered from an engine, it not only decreases engine efficiency but also requires complex hydraulic components such as a pump, a drive belt and hoses for its operation. On the other hand, an electric power steering (EPS) system uses an engine-independent motor for power steering, so it eliminates the need for complex hydraulic units. As a result, it improves both engine and space efficiency, and provides power steering even while the engine is not running. Furthermore, it is environmentally friendly because it uses no working fluid. With these advantages over the HPS systems, EPS systems have begun replacing HPS systems in some advanced vehicles and their usage is expected to extend to all types of vehicles in the near future [2].

An EPS system has the following two functions. First, it can reduce steering torque and present various steering feels. The steering torque (or driver torque) is defined as the one which a driver experiences (or a driver applies to the steering column) when turning the steering wheel. When an appropriate assist torque from an EPS system is applied in the same direction as the driver's steering direction, the amount of steering torque required by a driver for steering can be significantly relieved. In addition, adjustment of the characteristics of assist torque allows the driver to experience various steering feels. Second, the EPS system can improve return-to-center performance of a steering wheel when it is steered. While the steering wheel is turned and then released during cornering, it returns to the center position by the so-called self-aligning torque exerted on the tires by the road. Since this torque increases with vehicle speed, at high vehicle speeds the steering wheel may exhibit excessive overshoot and subsequent oscillation. The EPS system can eliminate this phenomenon by providing active damping capability and thus enhance returnability characteristics.

Some research and development on EPS systems have been performed, though detailed information on its control logic has not been released. Commercially, Delphi Automotive and TRW Automotive have already devised EPS system modules and Honda applied its EPS system to the real vehicle model, Acura NSX [3]. The typical control system of many EPS devices is shown in the block diagram of Fig. 1 [4,5]. The target current setting unit determines the reference current i_r to the motor based on the driving conditions, and the controller computes the control signal

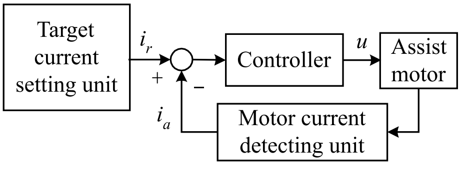

Fig. 1. Block diagram of typical EPS control system.

which minimizes the error between i_r and the actual current i_a. One drawback of this approach is that the steering torque is controlled in an indirect fashion, since the controlled variable is the motor current (i.e., motor torque).

The main objective of this research is to develop control logic for an EPS system. In this research the control logic is constructed so that the steering torque itself is measured and fed back to the controller which generates the control signal minimizing the difference between the reference steering torque and the steering torque. The reference steering torque is determined by the torque map based on the information on vehicle speed and steering wheel. This approach has some advantages in that it can control the driver's steering torque directly and thus present various steering feels.

For measurement of the steering torque and steering wheel angle, the torque sensor composed of two optical encoders is devised. To verify the proposed control logic, a hardware-in-the-loop simulation (HILS) system was constructed in which the load motor attached to a rack-and-pinion system generates various load torques delivered to the steering shaft from the road.

2. Structure and modeling of an EPS system

The main objective of this research is to develop EPS control logic (not to devise EPS hardware). Therefore, the EPS system for this research was made by simply modifying a conventional steering system. Fig. 2 shows the experimental setup for a HILS system, where some components such as vehicle dynamics and restoring

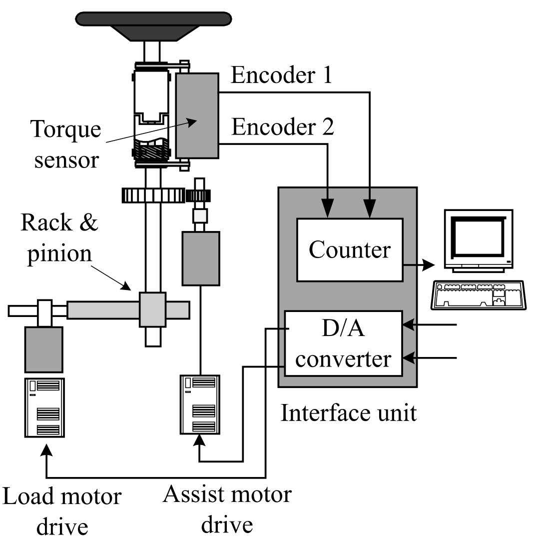

Fig. 2. Experimental setup used to implement EPS control logic.

torque are computed via simulation, whereas the steering system of interest is implemented in real hardware.

The EPS system shown in Fig. 2 adopts a so-called column-type EPS system in which the assist motor connected to the steering shaft through spur gears delivers assist torque to the shaft. And the load motor connected to the rack and pinion mechanism of the steering system provides the emulated load torque including the torque due to the friction between the tire and the road surface. These motors are controlled by motor drives whose input signals are received from the PC where the control logic is implemented. BLDC (brushless DC) motors are employed for both assist and load motors. Note that BLDC motors have the same characteristics as DC motors from the modeling point of view, though they have different structure. The steering torque and steering wheel angle are measured by a torque sensor discussed in the next section.

2.1. Torque sensor

In order to measure the steering torque T_s exerted on the steering shaft by the driver, the torque sensor shown in Fig. 3 was devised in this research. In this sensor, the angular positions θ_{sw} (at the steering wheel) and θ_{ss} (at the steering shaft) at both ends of the torsion bar, which is fitted into the steering column, are measured by the optical encoders 1 and 2, respectively. Since a relatively large displacement $\Delta\theta$ $(=\theta_{sw}-\theta_{ss})$ occurs in the slender torsion bar, and a timing belt and pulley mechanism amplifies this angular displacement, the encoders can measure the angular displacement even for a small torque. As a well-known fact [6], the steering torque T_s acted on the steering column is proportional to the angular displacement as follows:

$$T_s = k_{torsion} \cdot \Delta\theta = k_{torsion} \cdot (\theta_{sw} - \theta_{ss}), \tag{1}$$

where $k_{torsion}$ denotes the torsional stiffness of the torsion bar. Note that the angular position of the steering wheel, which is required for the EPS control logic, can be obtained as θ_{sw} without a separate sensor in the devised torque sensor.

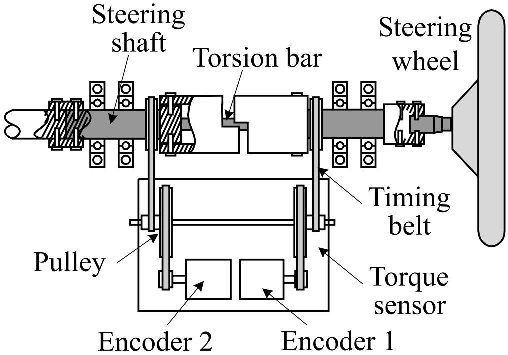

Fig. 3. Structure of a torque sensor.

2.2. System modeling

The mechanical modules of the EPS system shown in Fig. 4 can be divided into a steering column part and an assist motor part. In this figure, T_a and T_l represent the assist torque delivered to the shaft and the load torque, respectively. Note that the load torque mostly depends on the friction between the tire and the road, efficiency of steering gears, and so on. The equation of motion of an assist motor is expressed by

$$J_m\ddot{\theta}_m + B_m\dot{\theta}_m = T_m - \frac{1}{N}T_a, \tag{2}$$

where J_m and b_m represent the moment of inertia and damping coefficient of the assist motor, T_m is the motor torque, and N is the gear ratio with the relation of $\theta_m = N\theta_{ss}$. The electric equation for a BLDC motor, which is identical to that for a DC motor, is written by

$$R_a i_a + K_E\dot{\theta}_m = v_a, \tag{3}$$

where v_a and i_a are the armature voltage and current, and R_a and K_E are the armature resistance and back emf constant, respectively. The motor torque T_m is then given by

$$T_m = K_T i_a, \tag{4}$$

where K_T is the motor torque constant.

In order to implement a HILS system, the road torque exerted on the tire by the road must be computed. For this computation, a so-called Dugoff tire model [7] was employed, where the longitudinal and lateral forces occurring in the tires are expressed by

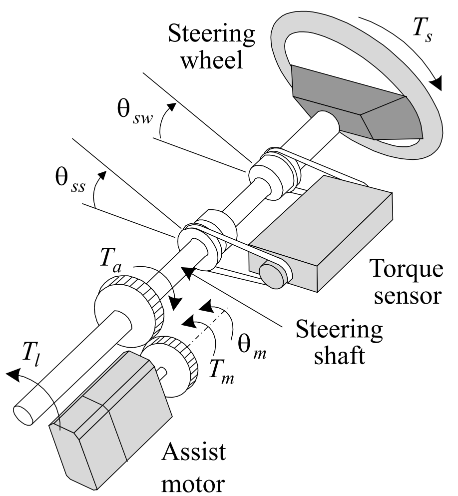

Fig. 4. Configuration and free-body diagram of a steering column.

$$F_x = \frac{AK_x s}{1-s}, \quad F_y = \frac{AK_y \tan \alpha}{1-s}, \tag{5}$$

where K_x and K_y represent the longitudinal and lateral tire stiffness, and A, s, α are the patch area of the tire in contact with the road surface, slip ratio and slip angle, respectively.

The force F_R delivered to the rack from the longitudinal and lateral forces of the tires in Fig. 5 is

$$F_R = F_x \sin \delta + F_y \cos \delta. \tag{6}$$

Since the steering wheel angle θ_{sw} and the steer angle δ has the relation of $\theta_{sw} = n\delta$, where n is the steering ratio, the road torque delivered to the steering shaft becomes

$$T_r = F_R \times r = \left(\frac{AK_x s}{1-s} \sin \frac{\theta_{sw}}{n} + \frac{AK_y \tan \alpha}{1-s} \cos \frac{\theta_{sw}}{n} \right) \times r. \tag{7}$$

Fig. 6 shows the plot of the road torque versus the steering wheel angle, where the load motor generates the road torque computed based on Eq. (7) when the driver's input is sinusoidal with the amplitude of ±180°. Note that the typical values are used for the slip ratio and slip angle in Eq. (7). It is observed in this figure that the road torque varies nearly proportionally to the steering wheel angle. Although the efficiency of the steering system should be taken into account in computing the actual load torque, it is assumed here that the load torque is nearly equal to the road torque.

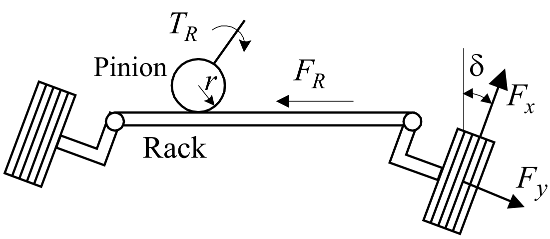

Fig. 5. Simplified model of steering rack and pinion system.

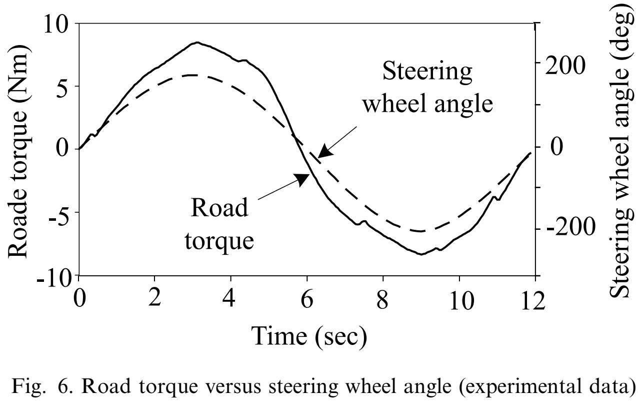

Fig. 6. Road torque versus steering wheel angle (experimental data).

3. EPS control logic

The main functions of the EPS system are reduction in steering torque and improvement of return-to-center performance. These two functions are not required to be activated at the same time, and only one function is needed at a certain instant. In a J-turn maneuver, for example, the assist torque is created to reduce the driver's steering torque on turning the steering wheel, but it is used to return the steering wheel to the original position smoothly without overshoot and subsequent oscillation of the vehicle right after reentering a straight line road. This observation allows two separate EPS control algorithms to be considered for each driving condition.

3.1. Control logic for reduction in steering torque

A proper amount of assist torque should be provided by the assist motor to reduce the driver's steering torque during cornering. Fig. 7 shows the block diagram of the proposed EPS system for generation of such an assist torque. The reference steering torque T_{rs} is first determined by a torque map (discussed below) based on the driving conditions. The assist motor then generates appropriate assist torque so that the steering torque T_s approaches T_{rs}. For example, suppose that T_{rs} is set to 3 Nm for a given load torque of 20 Nm. The driver will experience the steering torque of 3 Nm, provided that the assist torque of 17 Nm is supplied to the steering shaft; without power steering, the driver should apply 20 Nm to turn the steering wheel. Of course, the load torque is not measurable in real driving situations, but the steering torque can be measured by a torque sensor. Therefore, the assist torque is adjusted in such a way that the error between T_{rs} and T_s is minimized. For this purpose, the following PI control scheme is employed in this research.

$$u_1 = K_1(T_{rs} - T_s) + K_2 \int (T_{rs} - T_s)\, dt, \tag{8}$$

where K_1 and K_2 are the PI controller gains. The assist torque T_a generated in this fashion is delivered to the steering shaft in the same direction as the present steering direction.

One of the most important features of the proposed system is the use of a torque map, which determines the reference steering torque T_{rs} based on the information on

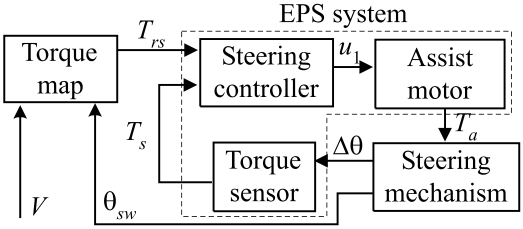

Fig. 7. Block diagram of control logic for reduction in steering torque.

vehicle speed V and steering wheel angle θ_{sw}. It is noted that the vehicle speed plays an important role because the steering torque required by the driver varies with respect to it. For example, at low speed driving (e.g., parking maneuvers), it is desirable that most of steering torque be provided by the power steering system for easy steering. At high-speed driving, on the other hand, more solid (and heavier) steering feel should be created for safe driving. The steering wheel angle is also important because the load torque increases with steering wheel angle as shown in Fig. 6.

Fig. 8 illustrates the outline of the torque map adopted in the experiment. As shown in Fig. 8(a), the reference steering torque at the zero vehicle speed T_0 is set to a relatively small value for steering easiness at low speeds, but it increases with vehicle speed for driving safety at high speeds. Thus, the driver experiences a steering feel which gets stiffer as the vehicle speed increases. However, when the vehicle exceeds the critical speed V_c, the reference torque is saturated to the value of $T_{s,sat}$ to prevent it from further increasing, so steering easiness at high speeds can be ensured to some extent as well. Fig. 8(b) represents the reference torque versus the steering wheel angle, where the reference steering torque is proportional to the steering wheel angle. The three-dimensional form of the proposed torque map, which is stored in ROM in real implementation, is illustrated in Fig. 9. One benefit of using a torque map is that it can be easily altered according to driving situations or the driver's requests.

3.2. Control logic for return-to-center performance

When the steering wheel is turned while driving, the self-aligning torque returns the steering wheel to the center position naturally. This phenomenon offers convenience to the driver while returning the steering wheel to center, but with excessive overshoot, it would have harmful effects on stable driving. A conventional hydraulic power steering system can generate some damping effects by its inertia and friction of the steering system itself, but not actively. On the contrary, in an EPS system, active damping effects can be created by adequate control of the assist motor.

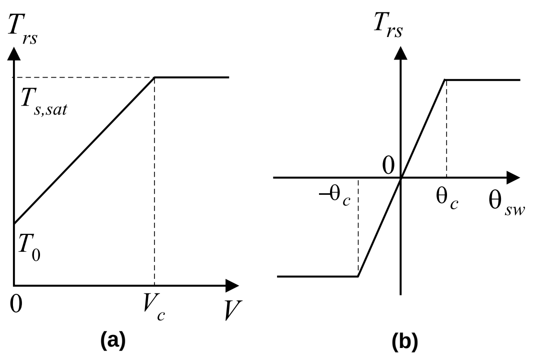

Fig. 8. Determination of reference steering torque depending on (a) vehicle speed and (b) steering wheel angle.

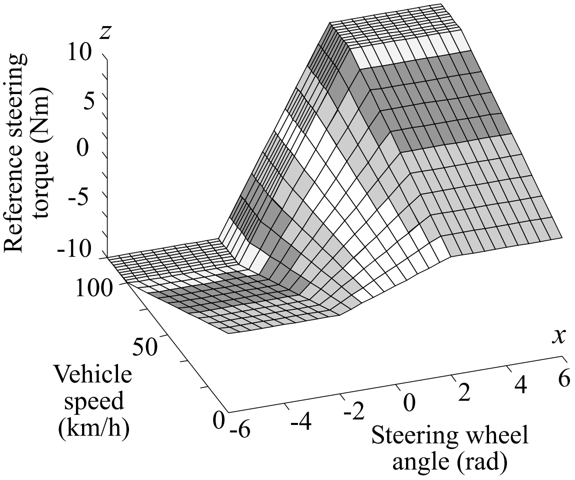

Fig. 9. Three-dimensional plot of proposed torque map.

The control strategy for return-to-center performance can be divided into two algorithms. One is the "return" algorithm used to bring the steering wheel to the center. The main function of this return control is to return the wheel to the center position quickly and accurately, and so it is especially useful when inherent friction prevents the wheel from returning to the exact center position. The other is "active damping" algorithm, which allows the wheel to come back to the center in a nice damped way and avoid oscillations that are usually present at high speeds. It is desirable, therefore, that both return control and active damping control apply in a combined fashion. For this purpose, the following PID controller was employed in this research.

$$u_2 = K_3\theta_{sw} + K_4\int \theta_{sw}\,dt + K_5\dot{\theta}_{sw}, \qquad (9)$$

where K_3, K_4 and K_5 are the controller gains. Note that the PI part of Eq. (9) creates larger restoring assist torque for larger steering wheel angle, and corresponds to return control, and the derivative part is used to create active damping that increases with the angular velocity of a steering wheel. Thus, different return-to-center characteristics can be obtained by adjusting the controller gains.

4. Results and discussions

Various simulations and HILS-based experiments have been performed by applying the proposed EPS control algorithms to a variety of driving conditions. Some typical results are presented below.

Fig. 10 shows the simulation results for the vehicle with the steering wheel angle and vehicle speed held constant. The reference steering torque and load torque are

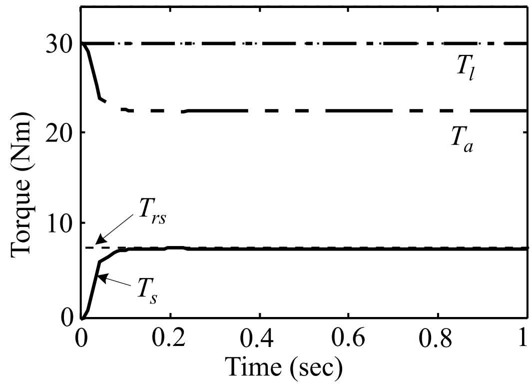

Fig. 10. Time responses of steering torque and assist torque for constant load torque and vehicle speed.

assumed to be constant at 7.5 and 30 Nm. As a result of EPS logic for reduction in steering torque, the assist torque approaches about 22.5 Nm in the steady-state, thus leading to the steering torque of 7.5 Nm. Therefore, the steering torque follows the reference steering torque with accuracy.

Next, the experimental results of dynamic steering are shown in Fig. 11, where the driver is assumed to provide a sinusoidal steering input with the period of 5 s and the amplitude of 180°. The load torque computed from Eq. (7) is delivered to the steering shaft through the rack and pinion mechanism by the load motor. For convenience, the steering torque in the clockwise direction is assumed positive. Without power assist, the driver must provide relatively large and varying steering torque for steering. However, with power assist, the amount of driver's torque is significantly reduced. Furthermore, for differently set reference steering torques, the steering torque also varies, thus resulting in different steering feels. For example, the driver can experience a smooth, luxurious steering feel with the reference steering

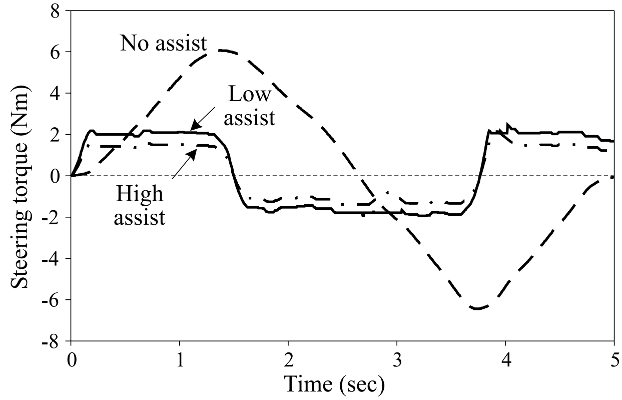

Fig. 11. Steering torque with sinusoidal steering input.

torque set to a lower value, while a solid, sporty steering feel is experienced with a higher value.

Fig. 12 plots the steering torque versus steering wheel angle of an EPS system. The load torque increases nearly proportionally to the steering wheel angle as indicated in Fig. 6. Thus, the steering torque tends to vary significantly depending on the steering wheel angle without power steering, but the steering torque with EPS activated shows little variation for a wide range of the steering wheel angle in Fig. 12.

Next, EPS control logic for return-to-center performance is evaluated below. Fig. 13 shows the experimental results representing return-to-center capability with active damping implemented. The response of the steering wheel without active damping control exhibits overshoot, while with active damping activated no overshoot is observed because of some damping imposed in the opposite direction to the steering wheel rotation. Also, if the gain of the damping controller, which corresponds to the derivative controller of Eq. (7), is adjusted, different returnability characteristics can be obtained. For example, Case A with larger damping yields a more sluggish response than Case B in the figure.

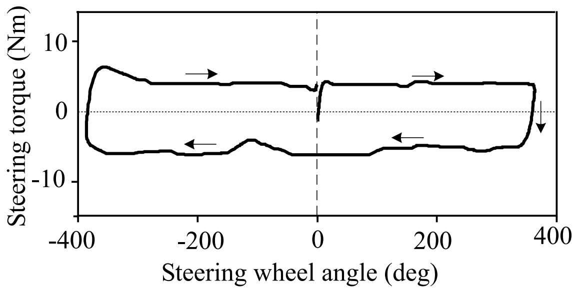

Fig. 12. Plot of steering torque versus steering wheel angle.

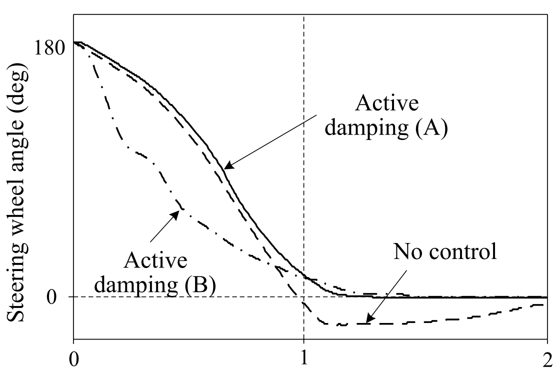

Fig. 13. Responses of steering wheel angle with active damping control activated.

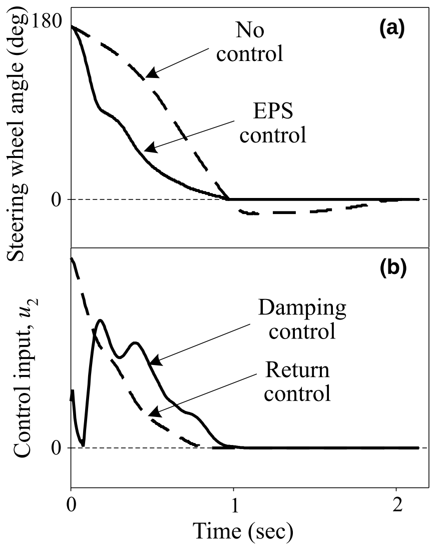

Fig. 14. Responses of steering wheel angle and control inputs with both damping and return control controls activated.

Though the response of the steering wheel shows no overshoot by active damping control, it generates a rather slow return to the center position. In addition, with this added damping, the steering wheel may not return to the center position accurately due to inherent friction. To overcome this problem, the PID control based on Eq. (9) instead of active damping control alone is executed, which yields a restoring force as well as damping force. Fig. 14(a) obtained in this fashion shows a faster response with no overshoot than the damping control alone. Fig. 14(b) illustrates control inputs, where the restoring force input dominant at the beginning is followed by the damping force input thereafter. Therefore, a variety of return-to-center performance can be achieved by various proportions of damping and return control.

5. Conclusions

The EPS control logic for reduction in steering torque, realization of various steering feels, and improvement of return-to-center performance was proposed in this research. In addition, the torque sensor capable of measuring the steering torque and steering wheel angle is devised, and it provides sufficient accuracy of steering torque for the EPS system. The developed HILS system is capable of providing the steering column with a load torque computed based on the driving conditions, and proves that it is very useful for development of EPS control logic.

With the EPS logic for a reduction in steering torque, the driver can turn the steering wheel with a significantly reduced steering torque. It is also shown that the steering torque can follow the reference steering torque determined from a torque map reasonably well, independent of load torques which tend to vary depending on the driving conditions. With the EPS logic for return-to-center performance, a quick response of the steering wheel without overshoot after cornering can be obtained by proper control of the assist motor.

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