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Robust steering-assist torque control of electric-power-assisted-steering systems for target steering wheel torque tracking☆

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ABSTRACT

This paper describes robust steering assist torque control of electric-power-assisted-steering (EPAS) systems for a target steering wheel torque tracking. The steering assist torque control algorithm has been developed to overcome the major disadvantage of the conventional method of time-consuming tuning to achieve the desired steering feel. A reference steering wheel torque map was designed by post-processing data obtained from target performance vehicle tests with a highly-rated steering feel for both sinusoidal and transition steering inputs. Adaptive sliding-mode control was adopted to ensure robustness against uncertainty in the steering system, and the equivalent moment of inertia damping coefficient and effective compliance were adapted to improve tracking performance. Effective compliance played a role in compensating the error between the nominal rack force and the actual rack force. The performance of the proposed controller was evaluated by conducting computer simulations and a hardware-in-the-loop simulation (HILS) under various steering conditions. Optimal steering wheel torque tracking performances were successfully achieved by the proposed EPAS control algorithm.

1. Introduction

Over the past decade, steering torque feedback and steering feel performance have been vigorously researched to improve on-center handling, and quantification of vehicle steering feel and responsiveness. Bertollini et al. [1] showed that drivers' preferences f0or steering wheel feel change with vehicle speed, and Green demonstrated that a steering effort that changes with vehicle speed is preferred by drivers [2]. Several techniques have been proposed to determine steering feel according to the hysteresis curve [3]. In addition, numerous studies have attempted to combine subjective and objective criteria. The correlation of subjective and objective methods has been investigated to identify physical parameters that are associated with each other [4]. Recently, Jang et al. [5] presented a correlation of subjective and objective measures of on-center handling performance of a vehicle by utilizing an interaction formula obtained from a statistical model that relates driver ratings and key physical parameters. This paper presented the three most influential, large parameters with a statistical correlation through a steering torque and lateral acceleration curve. In this case, the absolute value of the steering torque is defined by the 'looseness' at 0 g of lateral acceleration. In addition, the torque gradient at that part is the 'steering stiffness', and the instantaneous minimum rate in the range of 0.1 g of lateral acceleration is defined by the 'sharpness on center.' More recently, a study was also performed about the factors that strongly affect steering torque feedback [6]. Despite the substantial amount of extant research on measuring factors that affect steering feel, time-consuming tuning tasks are still required to be applied to real vehicles to utilize these findings. Therefore, developing a common electric-power-assisted-steering (EPAS) system presents challenges in implementing the steering feel that the developer desires.

Oh et al. [7] described the design of a controller for a steer-by-wire system using a reference torque map. The reference torque map utilized the steering wheel angle and vehicle speed information. Kim et al. [8] presented a control logic with PID control, which comprises a return and active damping function to reduce steering torque effort for an EPAS system. In this research, improvement of return-to-center performance was proposed employing a reference steering map defined from vehicle speed and steering wheel angle. Oh et al. and Kim et al. [7,8] proposed a reference torque map to implement or improve steering wheel torque. However, it is difficult to consider the damping or friction component because the steering angular velocity is not considered in the map. Actually, the steering wheel torque feel

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possesses a hysteresis affected by friction and damping components. Kim et al. [8] additionally considered active damping control to avoid oscillation of steering wheel angle. However, the active damping control can act as a hindrance in implementing the desired steering wheel torque.

In the early 1950s, sliding mode control (SMC) was first proposed, and it was successfully implemented to tackle system uncertainties and external disturbances with good robustness [9–11]. In general, an SMC requires an appropriate control law, such that the sliding mode is reached in a finite amount of time. However, no simple SMC, regardless of whether such uncertainty or disturbance is bounded, nor adaptive sliding mode control (ASMC), has been proposed [12,13]. Moreover, integral augmented sliding mode control has been introduced to improve the control performance of a system [14,15].

This paper proposes a novel EPAS assist motor torque control to overcome the conventional time-consuming tuning method for EPAS development by introducing a reference steering wheel torque surface defined by steering angle, angular velocity, and vehicle speed. The proposed algorithm offers expandability to implement various steering wheel torque conditions and different vehicle speeds according to the user's preferences through modifying the reference map. An adaptive sliding mode control algorithm was also proposed for robustness against uncertainties of the steering system parameter to adapt external tire forces. The performance of the proposed algorithm has been investigated via computer simulation and hardware-in-the-loop-simulation (HILS) to efficiently evaluate real-time performance.

2. Dynamic model of electric power assisted steering system

A column type electric-power-assisted-steering (CEPAS) model is utilized to design the steering assist torque control law. CEPAS is one of the steering system types that is assisted by electric motor power on the column. Zhang et al. presented a mathematical model and characteristic curves of an EPAS system [19]. The steering system comprises a steering wheel, upper column, lower column, electric motor, and steering rack, as shown in Fig. 1.

Yih et al. [17] represented the dynamics of the steering system utilizing a simple second-order model to modify the vehicle handling characteristics via steer-by-wire. Yih proposed that the frequency response of the system can be approximated by using the empirical transfer function estimate (ETFE), i.e., the ratio between the output and input discrete Fourier transform (DFT). Yih assumed that the transfer function could represent the steering system, including the total moment of inertia, the effective viscous damping coefficient, the Coulomb

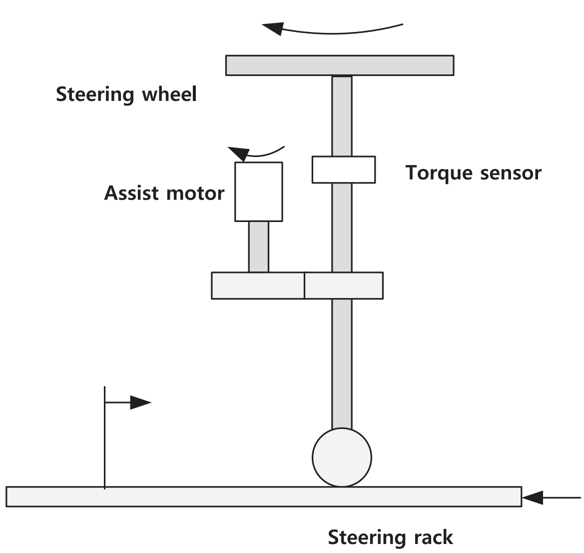

Fig. 1. Schematic of a column-type electric power assisted steering system.

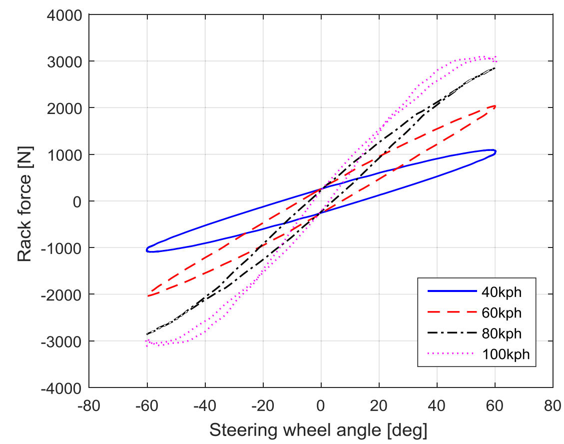

Fig. 2. Comparison of different vehicle speeds and rack force.

friction, and the disturbance from the tire force and aligning moment.

Therefore, the simple second-order model is proposed as follows:

$$J_{eq}\ddot{\theta}_{sw} + B_{eq}\dot{\theta}_{sw} = T_{sw} + T_m - K_{eff}\theta_{sw} - R_{rp}F_r \tag{1}$$

where J_{eq} and B_{eq} are the system equivalent moment of inertia and damping coefficient, respectively; T_{sw}, T_m, K_{eff}, and F_r are steering torque, assist torque, effective compliance, and rack force, respectively; and R_{rp} is the gear ratio between the rack and the end of the steering column. Most of the disturbance in steering systems is the rack force, F_r, from tire forces. Hence, rack force information is critical to implement the controller for steering systems. Gillespie [16] reported that the steering system could be represented by effective compliance in the low-frequency range. The following experiments were conducted to identify the characteristics of rack force. Fig. 2 shows the rack forces under different vehicle speeds on 0.85 road friction with weave tests at 0.2 Hz and 60° open-loop command using Carsim software E-Class Sedan. As can be seen in Fig. 2, the rack force increases linearly as the steering wheel angle increases. In addition, the rate of the rack force corresponding to the steering wheel angle increases as the vehicle speed increases. As a result, the rack force has linearity until the tire forces are saturated. Therefore, the rack force was assumed to be linear using effective compliance, K_{eff}, and selected as an adaption parameter. Effective compliance plays a role in compensating for the error between the nominal rack force and the actual rack force.

3. Target steering wheel torque tracking control

The electric-power-assisted-steering systems (EPAS) algorithm function consists of three parts, as shown in Fig. 3. The assist torque control uses the sensor information of EPAS and vehicle chassis. The target steering wheel torque map is designed by the steering angle, steering angular velocity, and longitudinal velocity of the vehicle. The nominal rack force is calculated using the linear tire model with the vehicle sensor information, and steering states with a Kalman filter are estimated to implement the adaptive sliding mode control (ASMC). Finally, the ASMC controller is used for the target steering wheel torque tracking. The ASMC calculates the assist torque input of the EPAS of the steering system at every time-step.

3.1. Target steering torque map generation

The steering characteristics are measured by conducting various tests. Sinusoidal and transition tests constitute typical test scenarios for steering characteristics. The sinusoidal test, which is also known as a weave test, measures the characteristics of the steering system, such as the degree of hysteresis and the assist torque. The transition test is carried out under constant steering angular velocity to measure the