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Research Article

Research on Friction Compensation Control for Electric Power Steering System

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A novel friction compensation control method is proposed to compensate both the dynamic and static friction torque of steering system. The change of EPS assist torque under fixed amplitude friction compensation torque can cause the diver's steering feeling fuzzy. That is due to the fact that the friction torque felt by driver varies with EPS assist gain. Therefore, a further modified friction compensation control method is proposed based on EPS assist gain to make the driver have similar friction feeling. Finally, computer simulation and vehicle test are performed to verify the effectiveness of adaptation method in the proposed controller. Test results indicate that the proposed controller improved the driver's steering performance.

1. Introduction

As a combination of electronic technology and steering system, EPS sticks to the development topics of modern automobile and has received much attention since the 1990s [1]. EPS, with assist torque determined by the steering torque and vehicle speed, can lighten the burden of the driver's manipulation and improve the driver's steering performance and driving comfort [2, 3]. Its development is continuing to satisfy increasing demands on the safety of vehicles.

The increased friction loss torque with motor and reduction mechanism added to steering system makes adverse effects on the vehicle steering performance [4, 5]. Most of friction compensation control models are represented through the sign function or saturation function of motor angular velocity, which can effectively reduce the frictional loss torque of steering system [6]. However, it can not compensate the static friction loss torque in the relative motion tendency of steering system.

In this paper, a novel friction compensation control method is proposed to compensate both the dynamic and static friction torque for steering system. As for the fuzzy feedback of the driver's road feeling caused by the compensated friction torque with fixed value, variable friction compensation control method is presented to guarantee the identical friction feeling under different EPS assist gains. Finally the performance of the proposed control strategy is verified through a modified EPS vehicle.

2. EPS System Dynamic Model

As shown in Figure 1, the driver's steering torque is detected through the torque sensor placed between the steering wheel and assist motor. The actual current of assist motor is detected through a current sensor. The desired assist torque is determined based on the steering torque and vehicle speed. From the desired assist torque, the EPS controller distributes the actuator input optimally based on the current status of subject vehicle. The assist torque and the driver's steering torque are applied to conquer the resistance torque of steering system.

The dynamic equations about the steering system are presented as follows [7, 8]:

$$T_s + T_a - T_r = J \cdot \ddot{\theta}_p + B \cdot \dot{\theta}_p + T_{\text{friction}}, \quad (1)$$

$$T_s = K_s \cdot \left(\theta_{\text{sw}} - \theta_p\right), \quad (2)$$

$$T_a = K \cdot G \cdot T_s, \quad (3)$$

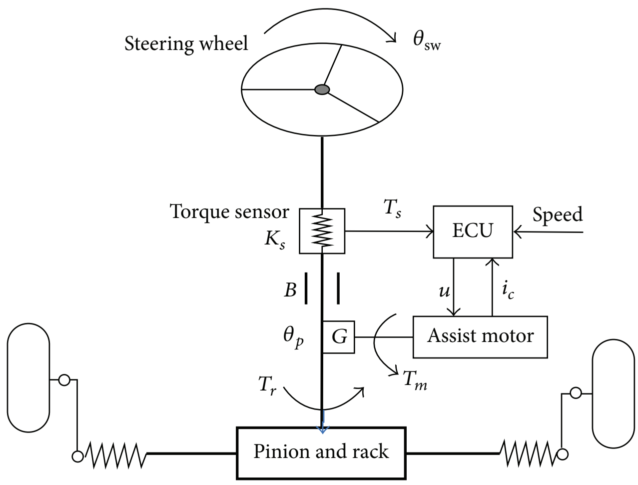


Figure 1: Scheme of EPS system.

$$u = R_c \cdot i_c + K_c \cdot \dot{\theta}_m + L_c \cdot \frac{di_c}{dt}, \quad (4)$$

$$\dot{\theta}_m = G \cdot \dot{\theta}_p, \quad (5)$$

where T_s is the torque from torque sensor. T_a is the torque generated by motor. T_r denotes the torque from road wheels. J, B, and T_{friction} are moment of inertia, damping coefficient, and friction for steering system. θ_p represents the angle of rotation of steering pinion position. θ_{sw} denotes the angle of rotation of steering wheel. K_s is the stiffness coefficient for torque sensor. K is the assist gain for EPS. G is the reduction ratio of motor. u is the motor armature voltage. R_c is the electric resistance of motor. i_c is the motor armature current. K_c is the motor EMF coefficient. θ_m denotes the angle of rotation of motor. L_c is the electric inductance of motor.

3. Coordinated Dynamic and Static Friction Control

As shown in Figure 2, system friction is mainly represented by the sign function and saturation function of angular velocity [9].

In Figure 2(a), the friction compensation control method can apply compensation torque with fixed amplitude based on the sign function of the rotation velocity. The output limit of sgn(·) is ±1.

In Figure 2(b), the friction compensation torque is applied based on the saturation function of the rotation velocity. Parameter lambda is the coefficient about angular velocity for saturation function.

The friction compensation control method mentioned above can apply control torque to compensate the dynamic friction of system. However, it loses control effect on the static friction of system. So a novel friction compensation control method is given in (6) to compensate both the dynamic and static friction torque of steering system:

$$T_{\text{fc}} = \chi \text{sat}\left[V_{\dot{\theta}c} + \gamma\left(1 - \left|V_{\dot{\theta}c}\right|\right)\right] T_{\text{friction}}, \quad (6)$$

where T_{fc} represents the applied friction compensation torque. χ denotes the adjustment coefficient of friction compensation torque. $V_{\dot{\theta}c}$ is saturation function of the rotation velocity of motor. γ is the adjustment coefficient of saturation function.

If the motor angular velocity is large enough to make the expression $V_{\dot{\theta}c}$ saturate, the applied friction compensation torque is $\chi\text{sgn}(\dot{\theta}_c)T_{\text{friction}}$ to compensate the dynamic friction torque of steering system. If the motor angular velocity is zero, the output of $V_{\dot{\theta}c}$ is zero and the applied friction compensation torque is $\chi\text{sat}(\gamma)T_{\text{friction}}$ to compensate the static friction torque of steering system. In the other case, the applied friction compensation torque represents the conversion process of dynamic and static friction of steering system.

In order to obtain the change regulation of the proposed friction compensation torque, the open loop current is applied to EPS motor to make the steering wheel in sinusoidal rotation under the condition that the road wheels of ground vehicle are out of ground. Figure 3 shows the real-time simulation results of the proposed friction control method. The friction compensation torque as shown in the fixed line in Figure 3 changes smoothly when the steering wheel switches between rotation state and halt state. So the proposed friction compensation control method will be a good candidate for the friction of steering system.

4. Variable Friction Compensation Control

4.1. The Analysis of Friction Compensation Control with Fixed Amplitude. The moment of inertia and damping of steering system have great influence on the dynamic steering characteristics, and both of them need the driver's subjective evaluation to calibrate. Therefore, the moment of inertia and damping of steering system will not be considered in this paper. The dynamic equation of steering system can be expressed as follows:

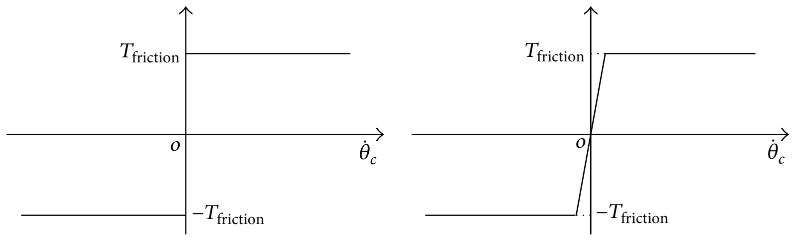
$$T_s + T_a + T_{\text{fc}} = T_r + T_{\text{friction}}. \quad (7)$$

Combined with (3) and (7), the following equation can be derived:

$$T_s = \frac{T_r}{1 + K \cdot G} + \frac{T_{\text{friction}} - T_{\text{fc}}}{1 + K \cdot G}. \quad (8)$$

From (8), it can be found that the driver's steering torque contains the steering reaction torque and the friction torque after friction compensation control. When EPS assist gain increases, the driver's steering torque caused by the reaction torque from road wheels will decrease to coordinate the steering torque and road feeling. However, the decrease of friction loss torque felt by the driver will cause the road feeling fuzzy [10].

To further explain the fuzzy phenomenon of road feeling, a 2 m/s^2 0.2 Hz slalom is performed at a constant speed of 100 km/h on a $\mu = 0.85$ road. The adjustment coefficient of friction compensation torque χ is preliminary set as 0.8. The steering torque relative to steering wheel angle and lateral acceleration is shown in Figures 4 and 5, respectively.



(a) $T_{fc} = \text{sgn}(\dot{\theta}_c)T_{friction}$ (b) $T_{fc} = \text{sat}(\lambda\dot{\theta}_c)T_{friction}$

Figure 2: Friction compensation control of sign function and saturation function.

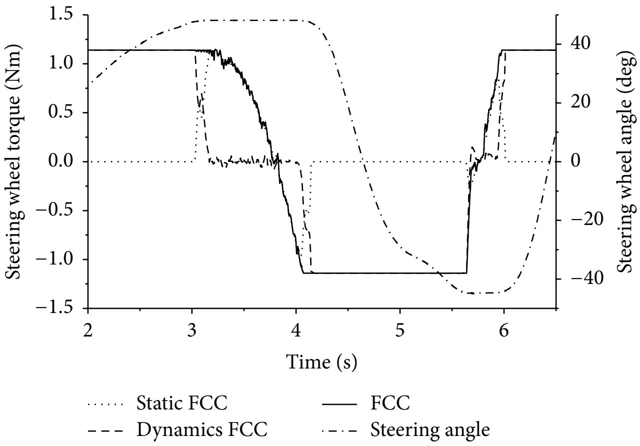


Figure 3: The conversion process of dynamic and static friction.

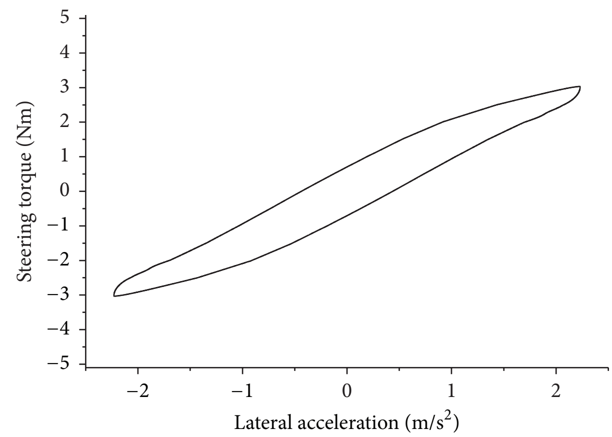


Figure 5: The steering torque according to lateral acceleration.

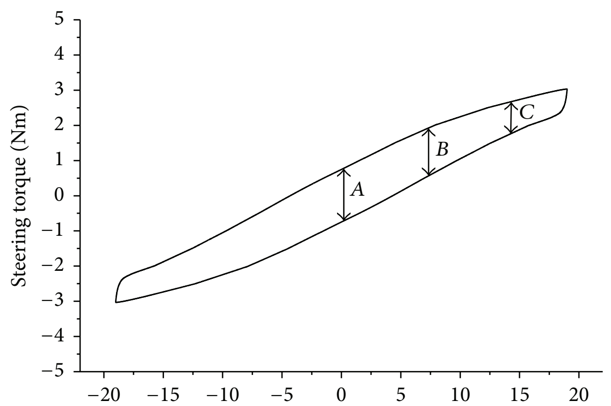


Figure 4: The steering torque according to steering wheel angle.

It can be seen that the longitudinal space of steering torque changes obviously at different steering wheel angle and lateral acceleration after applying the friction compensation control method shown in (3). As shown in Figure 4, the longitudinal spaces as A, B, and C decrease gradually with the increase of steering wheel angle. It also means that the friction torque felt by the driver decreases gradually. In addition, the road feeling in steering process is weaker than that of return process and the driver will get different friction torque of steering system at different steering wheel angle.

As the friction compensation torque increases the torsion of the steering torque is represented by the increase in the steering wheel angle. For example, when the driver turns the steering wheel in an anticlockwise direction, defined as the positive direction, the driver's steering torque at the positive change rate will be lower than that at the negative change rate for the same steering wheel angle. This will reflect the driver's road feeling and also make the driver feel that there exists external interferential force in steering operation [11].

4.2. Variable Friction Compensation Control. In order to make the absolute value of the friction loss equal for both operation directions, the friction compensation torque should be adjusted according to EPS assist torque.

The desired friction loss determined by the driver's subjective evaluation is defined as follows:

$$T_{prefer} = \frac{T_{friction} - T_{fc}}{1 + G \cdot K}. \quad (9)$$

Combining (3) and (9), the friction compensation control torque can be expressed as follows:

$$\begin{aligned} T_{fc} &= T_{friction} - (1 + KG)\, T_{prefer} \\ &= T_{friction} - \frac{T_a + T_s}{T_s} T_{prefer} \\ &= \left(T_{friction} - T_{prefer}\right) - \frac{T_a}{T_s} T_{prefer}. \end{aligned} \quad (10)$$

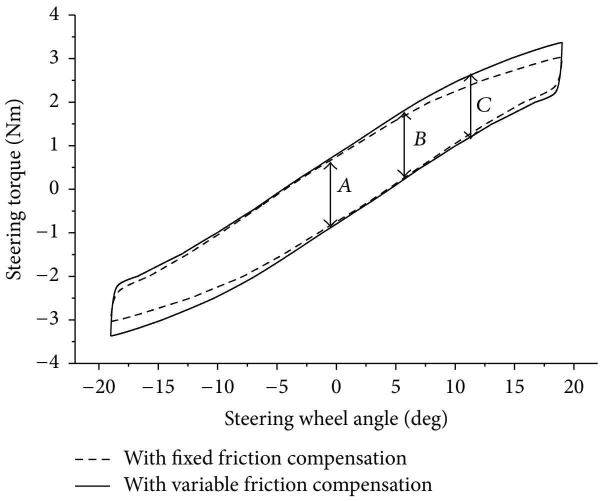


Figure 6: The steering torque according to steering wheel angle.

From (10), the expression in brackets is the friction loss torque that needs to be compensated. And the rest expression is to eliminate the effect on the driver's fuzzy friction feeling caused by EPS assist torque.

Ignoring the saturation function, the amplitude adjustment coefficient in (6) can be expressed as follows:

$$\chi = 1 - \frac{T_{\text{prefer}}}{T_{\text{friction}}} - \frac{T_a}{T_s}\frac{T_{\text{prefer}}}{T_{\text{friction}}}, \tag{11}$$

where the expression T_a/T_s is calculated in real time according to the torque from torque sensor and motor. In order to keep the expression T_a/T_s validity when the driver's steering torque is nearly zero, the following expression is given:

$$\frac{T_a}{T_s} = \begin{cases} \left.\dfrac{T_a}{T_s}\right|_{T_s=0.5}, & |T_s| < 0.5\,\text{Nm} \\ \dfrac{T_a}{T_s}, & |T_s| \geq 0.5\,\text{Nm}. \end{cases} \tag{12}$$

In this section, the effect of the variable friction compensation control on the steering feeling is studied. The $2\,\text{m/s}^2$ 0.2 Hz slalom is performed for a vehicle speed of 100 km/h on a $\mu = 0.85$ road. The driver's steering torque according to steering wheel angle and lateral acceleration under fixed and variable friction compensation control are shown in Figures 6 and 7, respectively.

As shown in Figure 6, the longitudinal space of steering torque, such as A, B, and C, is basically the same with the increase of steering wheel angle according to that with fixed amplitude friction compensation control. It means that the driver's friction feeling is similar at different steering wheel angle when the driver turns the steering wheel in both directions slowly. So the proposed variable friction compensation control method can reduce the effect of EPS assist torque on the driver's friction loss torque.

Table 1: Measurement equipment and parameters.

Number	Parameters	Equipment	Range
1	Steering wheel angle	Steering robot	±1080°
2	Steering torque	Steering robot	±50 Nm
3	Vehicle speed	Speedometer	0–50 m/s
4	Lateral acceleration	Gyroscope	$\pm 9.8\,\text{m/s}^2$

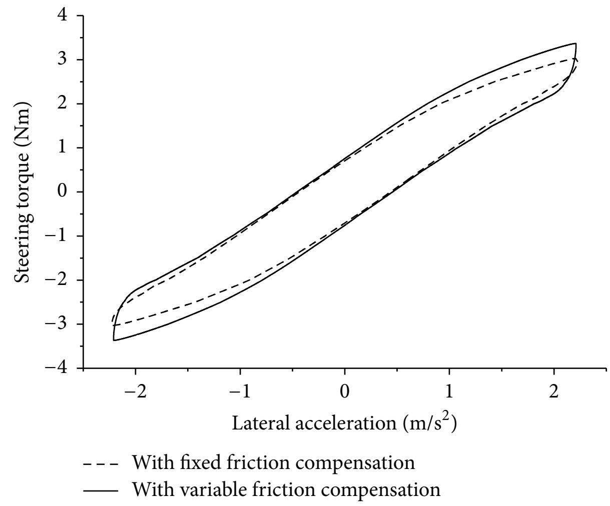


Figure 7: The steering torque according to lateral acceleration.

Figure 8: Test vehicle with EPS.

5. Vehicle Test Verification

This section presents experimental results obtained from a test vehicle shown in Figure 8. The main objective of the experiments is to verify the validity of the proposed variable friction compensation control method. The vehicle velocity is held at 100 km/h and the desired steering input angle is given by $45^\circ \sin(2\pi f t)$, where f is fixed at 0.2 Hz. The measuring equipment and parameters are in Table 1.

The resulting plots of these experiments are given in Figures 9 and 10. Shown in each figure is the driver's steering torque according to steering wheel angle and lateral acceleration.

It is noted in Figures 9 and 10 that the longitudinal distance of steering torque is basic consistency, which means that the friction loss torque felt by the driver is basically the

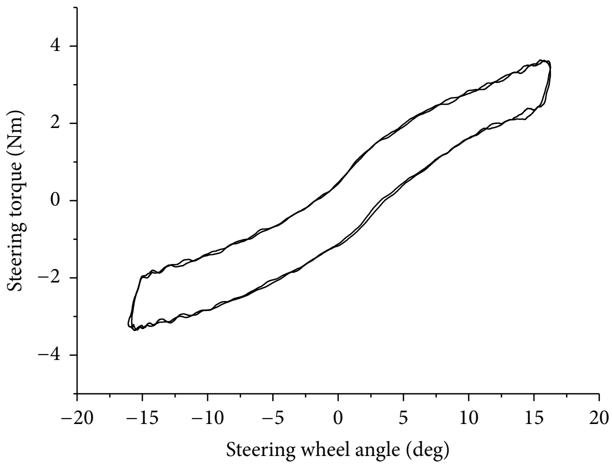


Figure 9: The steering torque according to steering wheel angle.

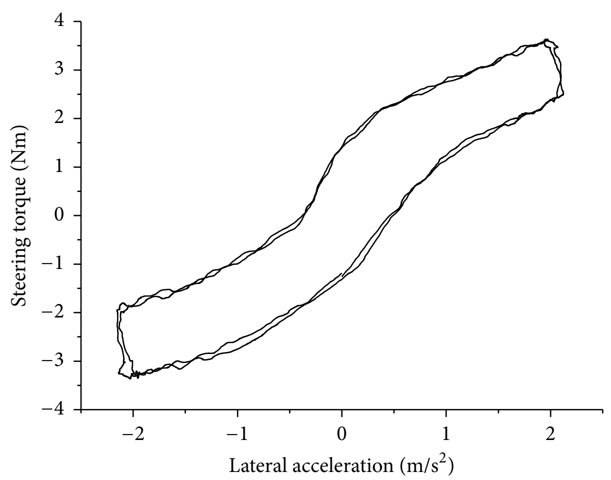


Figure 10: The steering torque according to lateral acceleration.

same at different steering wheel angle and lateral acceleration. The variable friction compensation control method can make the driver get the same friction feeling in steering operation. So the driver's steering feeling is only influenced by EPS assist torque, which makes the calibration for road feeling easier.

6. Conclusions

(1) A novel friction compensation control method is proposed to compensate both the dynamic and static friction torque of steering system. The applied friction compensation torque can transit smoothly between the rotation and static conversion of steering operation.

(2) According to the fuzzy friction feeling caused by EPS assist torque, the variable friction compensation control is proposed to adjust the friction compensation torque based on EPS assist torque.

(3) The experimental results obtained from computer simulation and test vehicle are implemented. The results verify that the variable friction compensation control can make the driver have similar friction feeling at different steering angle.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

Acknowledgments

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