Implementation of a Stability Compensator to Improve the Steering Feel for an Electric Power Steering System

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This paper addresses the issue of the steering feel of an Electric Power Steering (EPS) system. An EPS system equips an electric motor to provide assist steering torque and utilizes a torsion bar associated with a sensor to estimate the driver torque as a command to the steering torque control loop. It is well-known that a torsion bar, a reduction gear, and an electric motor in the steering system make up the major system dynamic characteristics. Many unwanted disturbances, such as the torque ripples produced by the electrical and mechanical components in the system, might be measured by the torque sensor and amplified by the electric motor. The unwanted torque response may cause vibration on the steering shaft. In this paper, the authors analyzed the system dynamics, classified the disturbance sources and designed a suitable stability compensator to improve the steering feel. Furthermore, the dynamics of the EPS control system was validated in computer simulation and was implemented with an embedded-DSP in a prototype vehicle as well.

Topics / Steering Control

1. INTRODUCTION

An EPS system has a compact structure compared with conventional power steering systems, and it is an on-demand system which provides right amount steering assist depended on the driver's torque, and only consumes minimum amount of power when it is not needed. Besides, an EPS system has more flexibility to adjust the steering feel by the advantage of the electronic control of the motor. It is easy to adjust the steering system characteristic just by modifying the program of the EPS controller. This is also the reason why many features have been developed for the EPS system. However, vehicles equipped with EPS systems have brought some steering feel issues. The steering shaft may have vibration caused by the unwanted torque ripple and increased by the electric motor. That is a critical issue for EPS systems. Several studies have been devoted to the issues of steering feel to better the steering feel and stability of EPS systems. [1, 2, 3]

The major purpose of this paper is to research and to analyze the steering vibration caused by the electrical and mechanical torque ripples, such as the motor harmonics, the variation of sensors, the contact ripples of gears, the center offset, the shaft unbalance, and so forth. According to the vibration sources, this paper attempts to employ a suitable stability compensator to suppress the vibration effect and hence to improve the steering feel of an EPS system. With the advantage of the auto code-generation tool, the stability compensator is rapidly and easily implemented on the embedded system, and finally the rapid-prototyped controller is carried into the EPS system on the prototype vehicle for validating the result.

2. THE EPS SYSTEM STRUCTURE

An EPS system utilizes an electric motor as an actuator to provide a suitable assist torque when the driver turns the steering wheel. The system structure of an EPS system is shown in Fig. 1. The key components of an EPS system include a steering wheel, a torsion bar and a torque sensor, an electric motor, a reduction gear,

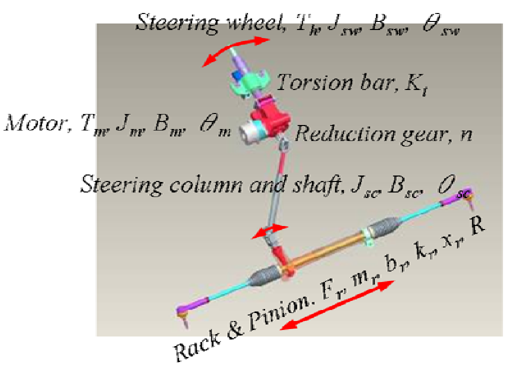

Fig. 1 A Column-EPS structure.

a steering column and shaft, a rack–pinion mechanism, and an electronic control unit (ECU). When the steering wheel is turned, the steering torque is transmitted to the pinion to make the steering column rotate. The torsion bar between the steering wheel and the steering column will be twisted until the steering torque and the reaction force are equalized. The torque sensor detects the twist of the torsion bar and converts the torque into the electrical signal. The ECU receives the torque information from the torque sensor and captures other signals, such as the vehicle speed and the steering wheel angle, to observe the current conditions of the vehicle motion. After calculation, the ECU determines the proper assist current applied to the electric motor. The electric motor's torque is enlarged and transmitted to the column shaft by the reduction gear, and assists the driver turning the steering wheel. Therefore, the driver can turn the steering wheel comfortably and just apply an easier effort to change the direction of the vehicle motion. The dynamic equations of a Column-EPS system are stated as follows:

$$T_h - K_{tb}(\theta_{sw} - \theta_{sc}) - B_{sw}\dot{\theta}_{sw} = J_{sw}\ddot{\theta}_{sw} \tag{1}$$

$$K_{tb}(\theta_{sw} - \theta_{sc}) + K_m(\frac{\theta_m}{n} - \theta_{sc}) + T_f - k_r(\theta_{sc} - \frac{x_r}{r}) - B_{sc}\dot{\theta}_{sc} = J_{sc}\ddot{\theta}_{sc} \tag{2}$$

$$\frac{k_r}{r}(\theta_{sc} - \frac{x_r}{r}) - F_r - b_r\dot{x}_r = m_r\ddot{x}_r \tag{3}$$

$$T_m - \frac{1}{n}K_m(\frac{\theta_m}{n} - \theta_{sc}) - B_m\dot{\theta}_m = J_m\ddot{\theta}_m \tag{4}$$

where T_h is the instructional torque on the steering wheel from the driver; K_{tb} is the stiffness of the torsion bar; J_{sw} and B_{sw} are the inertia and the damping constant of the steering wheel; θ_{sw} and θ_{sc} are the steering wheel angle and the steering column angle respectively. T_f are the friction torque on the steering column and shaft; J_{sc} and B_{sc} are the inertia and damping constant of the steering column and shaft; k_r is the stiffness between the rack and pinion; x_r is the displacement of the rack; r is the stroke ratio; the angle of the pinion is equal to the steering column angle; F_r is the alignment force on the rack from road wheels; m_r and b_r are the mass and the damping constant of the rack; T_m is the electromagnetic drive torque; n is the reduction gear ratio; θ_m is the mechanical motor position of the rotor; K_m is the stiffness between the motor and reduction gear; J_m and B_m are the inertia and damping constant of the motor.

For better assistance performance, a three-phase permanent magnet synchronous machine (PMSM) was adopted as the assist motor. In order to model the dynamics of the PMSM, it can be described in the well-know d-q frame through the rotation reference frame transformation. The architecture of the motor drive is a three-phase inverter bridge composed of six-MOSFETs. The Internal Model Control method was applied to the EPS motor control for obtaining good tracking ability of the current control. [4] The position and current feedback are necessary because the field oriented control method has been employed to generate the space vector pulse width modulation (SVPWM).

Table 1 The Parameters of the Column-EPS system.

Stiffness of the torsion bar	2.5Nm/deg
Motor type	3 Phase PMSM
Pole pairs	3
Resolution of encoder per electrical cycle	48
Reduction gear type	Worm and worm gear
Reduction gear ratio	15.3
Number of teeth of the worm gear	46
Number of teeth of the worm	3
Steering gear type	Rack and pinion
Number of teeth of pinion	7

The motor drive utilized two hall-effect current sensors to measure two of the three phase currents for current feedback and took one hall-effect IC to obtain two quadrature signals for position feedback. In this paper a Column-EPS in vehicle application is chosen and its parameters are shown in Table 1.

3. THE EPS CONTROL STRUCTURE

The primary goals of an EPS system are to reduce the steering torque exerted by the driver and to enhance the steering performance. An EPS system not only improves the steering feel but also increases the driving safety in accordance with vehicle dynamic control. The EPS control is a challenging task, because the behavior of the driver and the driving conditions are not predictable. Moreover, there are many significant events, such as the nonlinear effects caused by the friction and backlash, the road and mechanical disturbance, and the noise of sensors. As a result, the EPS control system need to have a robust control architecture for ensuring the system functions, maintaining the system robustness, and eliminating the unwanted vibrations. Fig. 2 shows that the control architecture of an EPS system. The Column-EPS shown in Fig. 1 can be represented as the block diagrams shown in Fig. 2.

The core control structure of an EPS system can be depicted as three main control loops: the inner loop, the middle loop, and the outer loop. The inner loop dominates the assist torque output provided by the electric motor. It need to deal with many objects, including torque output control of the motor, field weakening control for extending the range of motor speed, and using space vector methodology to

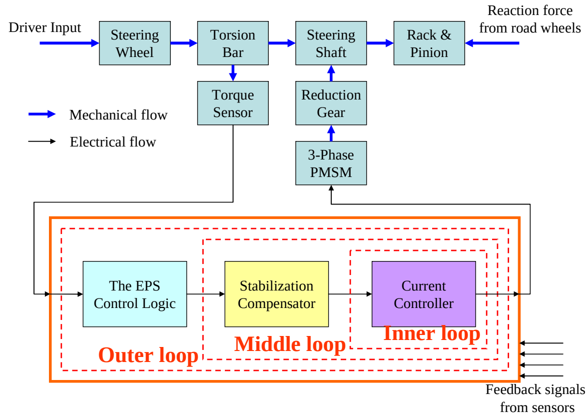

Fig. 2 The control architecture of the EPS system

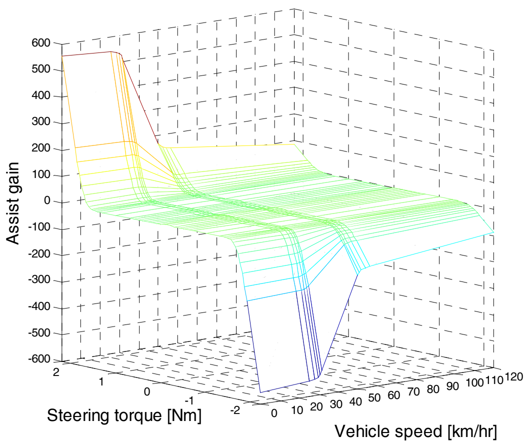

Fig. 3 The boost curve of the EPS system

determine the switching instants of PWM waveform. Another important issue in the development of an EPS system is the ability of the controller to filter out the external disturbance and to provide proper steering feel. Steering feel is effectively defined by the steering wheel torque sensed by the driver from the steering maneuvers and the vehicle response. The steering feel and stability issues are usually handled in the middle loop. Considering the steering functions of an EPS system, the major object of an EPS system is to provide a proper amount of assist torque for various conditions when the vehicle is cornering. For generating a suitable torque output from the motor to assist driver turning the steering wheel, a boost curve map, shown in Fig.3, is needed. The main steering characteristic of an EPS system depends on the setting of the boost curves. Hence this map is a key component in an EPS control system and is usually programmed in the outer loop of the EPS core control structure. In addition, other control logics for improving lateral dynamics and enhancing the steering performance of the vehicle motion, such as active return control, yaw damping control, inertia control, friction compensation, and so forth, are also arranged in the outer loop of the EPS core control structure. [5]

Accordingly, the EPS control structure can be separated into three portions: the inner loop for motor control, the middle loop for system stability, and the outer loop for steering control logics. There are many objects which need to be satisfied; thus designing an EPS controller is a delicate and challenging matter.

4. THE EPS SYSTEM ANALYSIS

The EPS system adopts the torsion bar to estimate the driver torque. The stiffness of torsion bar governs the dynamics of an EPS system. For this reason, a mathematical model of an EPS system is considered, which is essential for system analysis. This paper describes the EPS system as block diagrams, shown in Fig. 4, by using Matlab/Simulink. Referring to the block diagrams, the system dynamics from the driver torque input to the rack force output can be obtained.

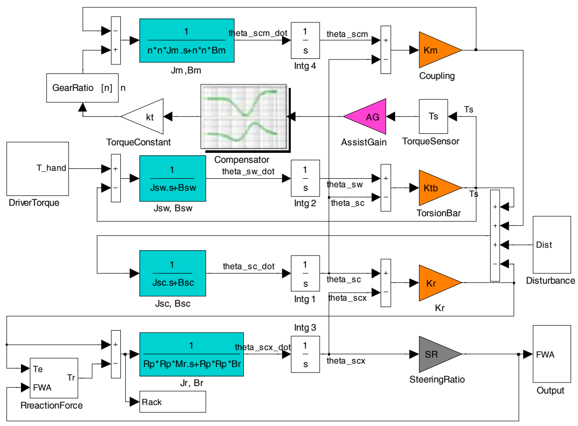

Fig. 4 Simulation block diagram of the EPS system.

The frequency response of the steering system has a peak near 30Hz. That is the natural frequency resulting from the stiffness of the torsion bar. If the torque disturbance carries the oscillation frequency around the natural frequency, the unwanted vibration will be measured through the torque sensor. As a result, the electric motor could enlarge the oscillation effect on the steering shaft. In that situation, the driver will sense the unfavorable steering feel from the steering wheel.

Many components might generate the torque ripple at various steering wheel speeds. The vibration effect may be induced when the frequency of the torque ripple is close to the natural frequency. For example, considering the source of torque ripple caused by the reduction gear, the interaction between the worm and worm gear might have a vibration effect on the steering shaft when the steering wheel is turned at a specific speed. The speed can be expressed as:

$$\dot{\theta}_{sw} = Specific\ Frequency \times \frac{1}{Number\ of\ teeth\ of\ worm\ gear} \times 360^{\circ} \quad (4)$$

These effects are related to the system parameters, the manufacture precision, the motor design, the motor current and position measurement errors, PWM control and more. Table 2 shows the ripple sources and the specific steering wheel angular velocity calculated from the specific frequency (30Hz) and the parameters in Table 1. It is easy to induce the vibration on the steering shaft during normal steering operations.

According to the above analysis, this paper describes the design of a stability compensator to improve the steering feel and to reduce the effect of vibration induced at the system natural frequency. The

Table 2 Ripple sources v.s. specific steering wheel angular speed

Vibration sources	Specific speed [deg/sec]
Encoder resolution	4.9
Motor back-EMF harmonic	39.2
Gain variation of current sensors	117.6
Offset of two current sensors	234.8
Worm gear contact ripple	234.8
Motor shaft unbalance	605
Pinion contact ripple	1542

designed stability compensator has been realized on the embedded-DSP and also validated on a real car. Considering the natural frequency of the EPS system, it is necessary to design a compensator to filter out the specific frequency band from the torque signals and to ensure the system response and stability. As a result, a band-rejected compensator has been taken into account. First, a low pass compensator or lag compensator is employed to filter out the specific frequency from input command. This compensator is designed for stabilizing the system and keeping the system response fast enough to track the driver torque command. Second, the lead compensator with two well-damped complex zeros is adopted for providing good performance over all range of assist gains. [6] Consequently, the final compensator is third order. For hardware implementation, the stability compensator must be transferred to discrete domain and can be expressed as:

$$SC(z) = \frac{B_1 + B_2 z^{-1} + B_3 z^{-2} + B_4 z^{-3}}{A_1 + A_2 z^{-1} + A_3 z^{-2} + A_4 z^{-3}} \qquad (5)$$

The frequency response of the stability compensator is shown in Fig. 5. This compensator was inserted after the EPS control logic block for assist torque (current) command shaping and output the modified signal to the motor current control loop, depicted in Fig. 2.

For verifying the effects of the stability compensator, it was taken into the simulation environment, shown in Fig. 4, to compare the system dynamics with the original one. The results of dynamics simulation with and without the compensator are shown in Fig. 6. The solid-line is the frequency response of the system without the compensator. It can be found that there is a peak point around 30Hz resulting from the stiffness of the torsion bar. The dash-line represents the system with the compensator. The simulation results

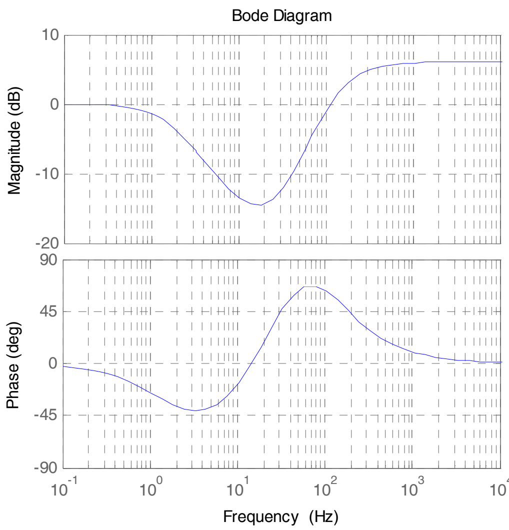

Fig. 5 The frequency response of the stability compensator.

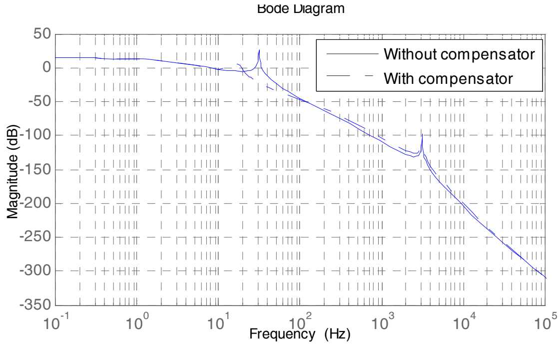

Fig. 6 The frequency response of the EPS system.

show that the system with the compensator can effectively reduce the peak, the under-damping effect, at the specific frequency. The compensator is able to reject in significant degree of the magnitude at the undesired frequency for input signals and is helpful in improving system stability and steering feel.

5. RESULTS

For realizing the stability compensator, this paper utilizes model-to-chip technique to implement the control algorithm on the embedded-DSP. The source code of the EPS control system is coded by using Matlab/Simulink block diagram shown in Fig. 7. [7] This technique can significantly save a lot of development time and tune the parameters of the system quickly.

Fig. 8 and Fig. 9 show the steering torque and steering angle of the EPS system without and with the stability compensator, respectively. There are two distinct experimental results measured from the steering sensor. Fig. 8 reveals a steering torque with an oscillatory waveform (about 30 waves per second). As can be seen, if the EPS control system without a proper stability compensator, it was easy to induce the vibration on the steering shaft. The steering torque and steering angle of the EPS control system with the stability compensator is shown in Fig. 9. The system was stable and had a relatively smooth torque waveform. It means that the stability compensator can effectively alleviate the oscillation and ameliorate the steering feel.

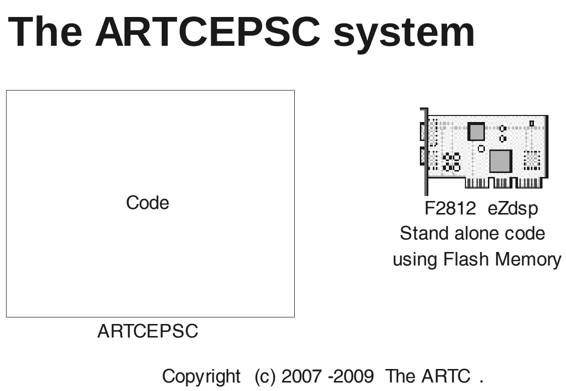

Fig. 7 The source code of the EPS control system.

6. CONCLUSIONS

This paper analyzed the system dynamics and classified the disturbance sources of torque ripple to design a suitable stability compensator for better steering feel. The electrical ripples and mechanical ripples may be measured from the torque sensor and be increased by the electric motor. The vibration makes the driver feel uncomfortable. From the results of the simulation and experiment, it is clear to demonstrate that a stability compensator is beneficial in an EPS application for alleviating the oscillatory response and improving the steering feel. By using the model-to-chip technique, the stability compensator on an embedded system can be implemented in a rapid and easy manner. And the evidence of the compensator's effect was finally shown in the EPS system of a prototype vehicle.

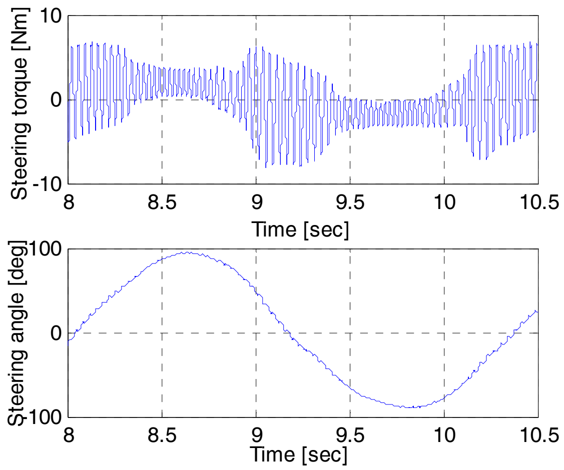

Fig. 8 The steering torque and angle of the EPS system without stability compensator.

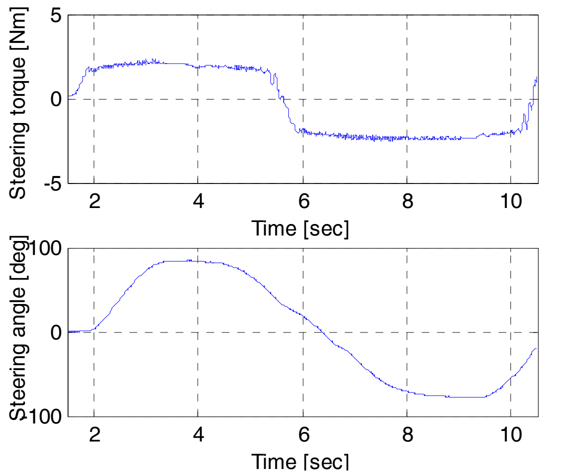

Fig. 9 The steering torque and angle of the EPS system with stability compensator.

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