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On Torque Control of Vehicle Handling and Steering Feel for Avoidance Maneuver with Electric Power Steering

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Abstract: This paper evaluates EPS control strategies for improving vehicle handling and steering feel during high speed avoidance maneuver. Theoretical analysis of frequency response of steering angle and vehicle lateral acceleration relative to steering torque input is performed. Closed-loop simulation studies are also conducted by adopting a driver model to describe the human steering behavior. Based on the study, EPS control strategies of steering torque assistance and damping compensation are investigated. The results show the effectiveness of EPS to improve vehicle responsiveness and stability, to reduce steering effort, and to realize comfortable steering feel for high speed avoidance maneuver.

1. INTRODUCTION

It is common recognized that the steering torque, which is supposed to be the value both as the steering input and as feedback of steering feel, plays an important role in high speed handling. In recent years, the spread applications of electric power steering (EPS) system have added new freedoms to control the steering torque characteristics.

Although the basic function of EPS is to minimize driver's steering effort by provide assistance steering torque with the use of an assist motor, the control to improve vehicle handling and to keep comfortable steering feel are also being intensively researched on. Among the studies, the effectiveness of some algorithms such as inertia compensation, active damp control and active return control have been validated [1] [2] [3]. Meanwhile, there have been some researches on the integrated control to combine EPS with other stability control systems [4]. These studies illustrate the further extension of EPS control functions.

This paper focuses on the evaluation of vehicle handling and steering feel enhanced by EPS control strategies for avoidance maneuver. For an urgent avoidance with high vehicle speed, driver is required for rapid response so as to suffer high level of physical burden and mental strain. In this study, we address the problem in two ways: one is the steering assistance control to reduce driver steering effort and to realize high vehicle responsiveness. The other is damping compensation control to solve damping problems that affect steering stability and steering feel.

In this paper, mathematical models of vehicle lateral motion, steering system and EPS strategies are described. Vehicle high speed cornering characteristics improved by EPS control are analyzed according to the frequency response of steering angle and vehicle lateral acceleration relative to steering torque input. The avoidance simulations are carried out by adopting a driver model to describe the human steering behavior. Based on the simulation results, vehicle handling and steering feel performances are evaluated to verify the effectiveness of the control strategies.

2. MATHEMATICAL MODEL

The overall driver-vehicle-controller system in this study is mathematically modelled as the diagram of Fig.1.

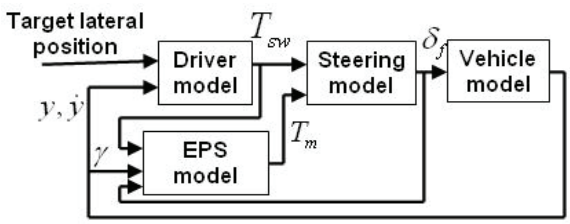


Fig.1 Diagram of mathematical model

2.1 *Equations of Vehicle Lateral Motions*

In order to simplify the dynamics for analysis, the two-degree-of-freedom (2-DOF) two–wheel vehicle model is employed in the study (Fig.2).

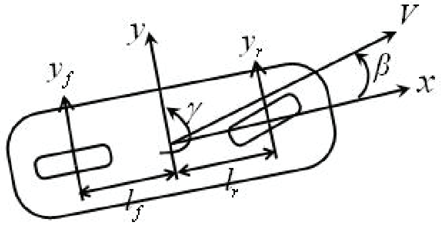


Fig.2 2-DOF two-wheel vehicle model

The governing equation of vehicle lateral motion is:

$$mV(\dot{\beta} + \gamma) = 2Y_f + 2Y_r \quad (1)$$

where, V denotes the vehicle velocity, β the body side slip angle, γ the yaw rate, m the vehicle mass, Y_f the front tire lateral force, Y_r the rear tire lateral force.

The governing equation of vehicle yaw motion is:

$$I_z\dot{\gamma} = 2l_f Y_f - 2l_r Y_r \tag{2}$$

where, I_z denotes the vehicle moment inertia, l_f and l_r are the distances from front and rear axles to mass center.

Tire lateral forces are calculated as:

$$Y_f = -C_f\left(\beta + \frac{l_f}{V}\gamma - \delta_f\right) \tag{3}$$

$$Y_r = -C_r\left(\beta - \frac{l_r}{V}\gamma\right) \tag{4}$$

where, C_f and C_r are the front and rear tire cornering stiffness.

According to the vehicle kinematics, vehicle lateral acceleration a_y is:

$$a_y = V(\dot{\beta} + \gamma) \tag{5}$$

2.2 Equations of Steering System dynamics

Shown as Fig.2, for frequency response characteristics analysis, this paper adopts a linearized model of steering system equipped with EPS.

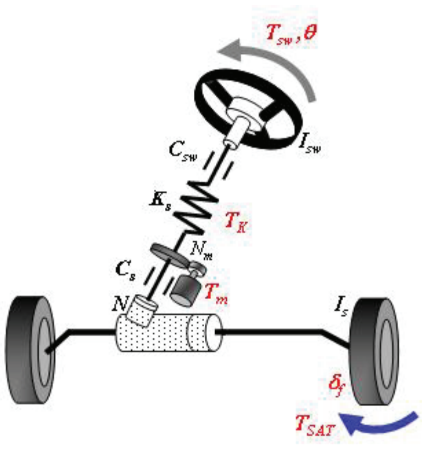


Fig. 3 Model of steering mechanism with EPS

The governing equation of steering wheel rotation around column axis is:

$$I_{sw}\ddot{\theta} + C_{sw}\dot{\theta} + K_s(\theta - N\delta_f) = T_{sw} \tag{6}$$

where, T_{sw} denotes the steering wheel torque, θ the steering wheel angle, δ_f the front wheel angle, N the steering gear ratio. I_{sw}, C_{sw} and K_s are the inertia, the damping and the stiffness coefficient of steering column.

The governing equation of front tires rotation around kingpin axis is:

$$I_s\ddot{\delta}_f + N^2C_s\dot{\delta}_f - NK_s(\theta - N\delta_f) = T_{SAT} + NN_mT_m \tag{7}$$

where T_{SAT} denotes the self-aligning torque of front tires, T_m the assist motor torque, N_m the reduction gear ratio of assist motor, C_s the damping of steering shaft, I_s the inertia of front tires along kingpin.

The self aligning moment is concerned with vehicle motions, and is calculated as:

$$T_{SAT} = 2\xi C_f\left(\beta + \frac{l_f}{V}\gamma - \delta_f\right) \tag{8}$$

where, ξ denotes the length of the tire trail.

2.3 Driver Steering Model

The driver model is a preview tracking model, which describes the driver behaviour to follow the target path [5]. The steering torque applied by driver to the steering wheel is proportional to the desired lateral acceleration (Fig. 4).

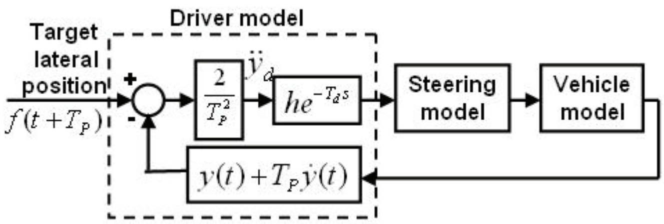


Fig. 4 Diagram of driver steering model

Vehicle desired lateral acceleration is calculated by predicting the tracking error of vehicle at preview point based on feedback of lateral position and lateral velocity:

$$\ddot{y}_d(t) = \frac{2}{T_P^2}[f(t+T_P) - y(t) - T_P\dot{y}(t)] \tag{9}$$

where, $\ddot{y}_d(t)$ denotes the desired lateral acceleration, T_P the driver preview time, $f(t+T_P)$ the target lateral position at the preview point, $y(t)$ vehicle lateral position, $\dot{y}(t)$ vehicle lateral velocity.

The steering torque applied by driver to the steering wheel is proportional to the desired lateral acceleration:

$$T_{sw} = he^{-T_d s}\ddot{y}_d(t) \tag{10}$$

where, T_{sw} denotes steering torque, h the steering torque gain. T_d is the driver reaction time.

2.4 EPS Control Strategies

This study investigates the algorithms of EPS as follows:

- Assistance control, based on steering torque input value
- Damping compensation, based on the response of steering angle and vehicle state variables.

The control block of EPS is shown as Fig. 5.

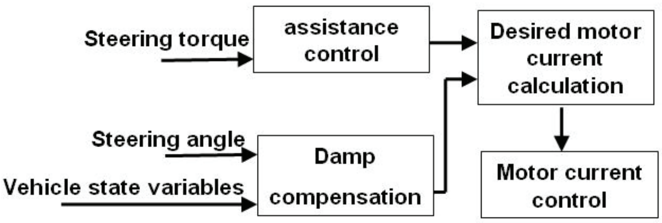


Fig. 5 Control block diagram of EPS system

The assistance control is based on steering torque sensor signal which represents the driver's steering input. The basic assistance torque value is proportional to the input steering torque, which can be described as:

$$T_m = k_{AT} T_K \tag{11}$$

where k_{AT} denotes the assistance coefficient, T_K the torque sensor value. According to Fig. 3 and equation (6):

$$T_K = K_s(\theta - N\delta_f) \tag{12}$$

For emergency maneuver situations, extra assistance is needed to achieve higher vehicle response. So assistance torque value proportional to the steering torque derivative value is also applied, which can be described as:

$$T_m = k_{ATd} \dot{T}_K \tag{13}$$

where k_{ATd} denotes the assistance coefficient

Assistance torque value of (11) and (13) are called as proportional and derivative control respectively.

The aim of damping compensation control is to solve damping problem that affects steering stability and steering feel in high speed maneuver situations. The compensation steering torque value is a negative feedback of steering output variables. Combined with other stability control systems, more vehicle state variables are available for this feedback control purpose [2] [4]. In this study, steering angle and vehicle yaw rate are chosen as the feedback variables for damping compensation control. The compensation torque value is described as:

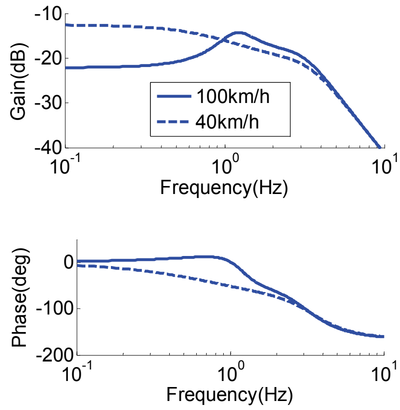
$$T_m = k_{d1}\dot{\theta} + k_{d2}\dot{\gamma} \tag{14}$$

where k_{d1} and k_{d2} denote the coefficient of damping control.

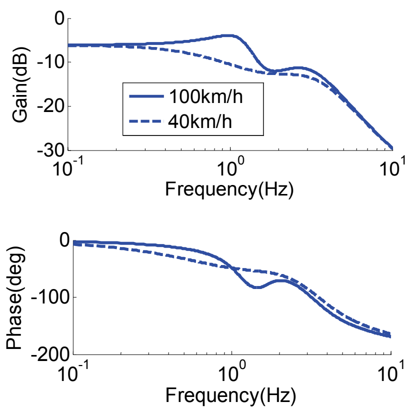
3. FREQUENCY RESPONSE ANALYSIS

To evaluate the effectiveness of EPS control to improve the vehicle handling, lateral acceleration response to steering torque input is analyzed for it represents the vehicle response and also is an important feedback of driver steering.

The steering feel analysis is generally hard to conduct for it depends greatly on subjective factors of individual driver. Still, some objective evaluation methods have been proposed for it. Since the touch sense on steering wheel is the primary source for diver steering feel, the relationship between steering wheel angle and torque is selected for steering feel analysis in this study.



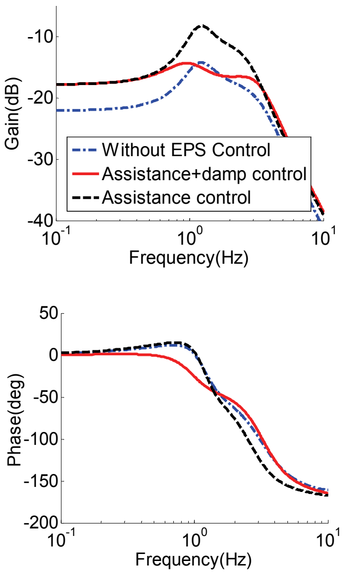
a) θ / T_{sw}



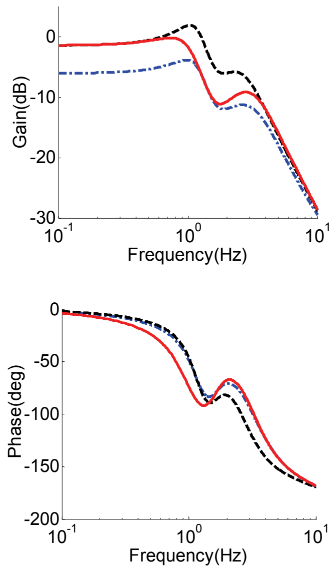
b) a_y / T_{sw}

Fig.6 Frequency response at high and low speed without EPS

Frequency responses without EPS control are shown as Fig.6. According to the results, the gain responses at high frequency region are low, which means the higher steering effort for driver in urgent steering situations. It also shows that at high speed, both the responses are characterized by poor damping in comparison with that at low speed. The amplitude of gain responses clearly increase around resonant frequency. Meanwhile, the phase response sign of steering angle changes around resonant frequency and there is a large steering angle phase lead problem in the lower frequency range. This means the unnatural sensitive vehicle response and light touch sense on steering wheel, so that the driver may have difficulty in handling steering wheel and vehicle smoothly at high speed.

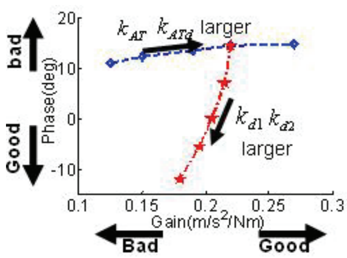


a) θ / T_{sw}

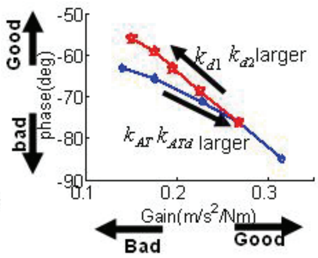


b) a_y / T_{sw}

Fig.7 Frequency response with EPS control ($V=100$km/h)



a) 0.8Hz



b) 2Hz

Fig.8 Influence of control parameters on frequency response

Fig. 7 is the comparison of frequency response with and without EPS strategies at high speed ($V=100$km/h). Fig.8 shows the influence of control parameters on the frequency response. The results show the effectiveness on the increasing of gain response with EPS assistance control, which can reduce driver steering effort and make rapid maneuver response. However, steering torque assistance also further deteriorates the damping characteristics at high speed. The damping compensation control can solve problem well. Steering angle phase lead in lower frequency is also restrained so that steering feel can be improved. Higher responsiveness and comfortable steering feel can be realized by the balance of assistant and damping control parameters.

4. CLOSED-LOOP SIMULATIONS OF AVOIDANCE MANEUVER

In the simulations, the vehicle makes obstacle avoidances with the velocity of 100km/h to make the vehicle move to the adjacent lane with lateral displacement of 3.5m. Parameters used in the simulations are as table 1.

Table 1 Simulation parameters

Symbol	Unit	Value	Symbol	Unit	Value
m	Kg	1020	N_m	-	13.67
I_z	kgm^2	1800	I_s	kgm^2	1.17
l_f	M	1.0	ξ	m	0.0579
l_r	M	1.6	T_P	sec	0.7
C_f	N/rad	31096	h	Nms^2/m	1.4
C_r	N/rad	35407	T_d	sec	0.1
N	-	18	k_{AT}	-	0.073
I_{sw}	kgm^2	0.022	k_{ATd}	-	0.017
C_{sw}	Nmsec/rad	0.1661	k_{d1}	-	-0.037
K_s	Nm/rad	134.07	k_{d2}	-	-0.351
C_s	Nmsec/rad	0.6960	V	km/h	100

4.1 Transient response characteristics

The transient response results (Fig.9) show that for an urgent avoidance maneuver, driver's steering effort may get large up to his physical limit without EPS assistance. So the effectiveness of EPS assistance on the reduction of driver steering effort is evident. Moreover, lateral trajectory results also show the transient response of path tracking can also be improved with EPS control. For the EPS assistance with and without damping compensation, the trajectory results are almost same in this simulation condition. But the time history curves of steering wheel torque and angle characteristics are quite different. With damping compensation, the steering wheel torque and angle shows mild and less fluctuation during the maneuver process. Therefore, it can be expected that steering operation will be relative more comfortable with such active damping control combined with basic EPS assistance function.

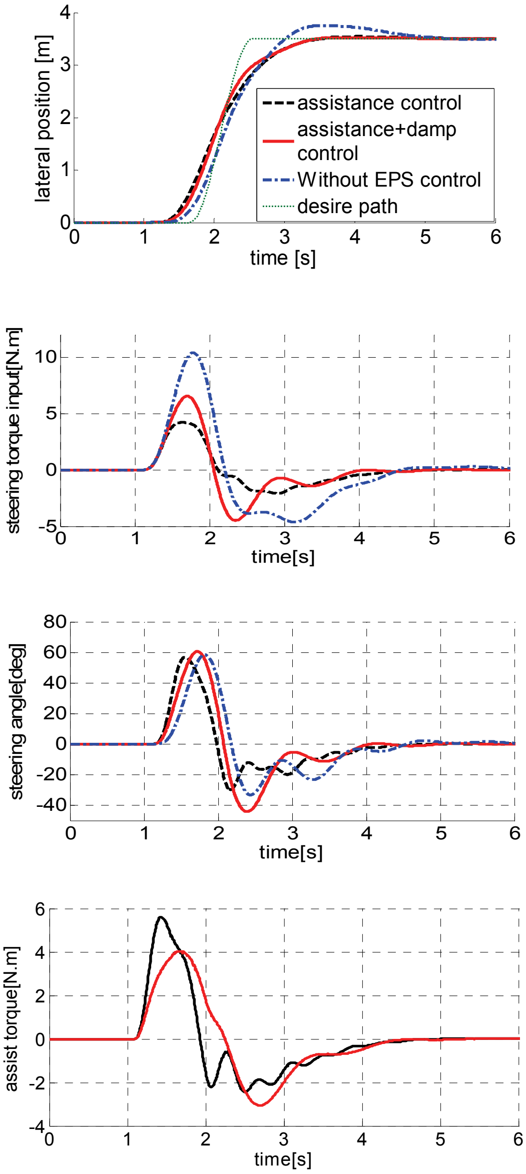


Fig.9 Simulation results of avoidance maneuver

4.2 Driver's workload characteristics

Fig.10 is the lissajou's figure of steering torque with respect to steering wheel angle of the simulation results. Great different characteristics among different control strategies are shown. So there may be the possibility to do a further evaluation of steering feel based on the relationship between steering wheel torque and angle. According to paper [6], the driver's subjective feeling can be investigated from the viewpoint of energy consumption, which is the steering workload performed by the driver obtained in integral form as follows:

$$W_S = \int_0^\infty \frac{dW_S}{dt}dt = \int_0^\infty T_{sw} \cdot \dot{\theta} \tag{15}$$

where the product of the steering torque T_{sw} and the steering speed $\dot{\theta}$ is the steering power performed by the driver.

If the driver operates the steering wheel voluntarily, it is natural for him to perform positive steering work effectively, but if he operates the steering wheel against unnatural fluctuation of the vehicle, unnecessary negative steering work will be performed. Therefore, the ratio of the total negative steering workload to the total positive steering workload can be used to assess driver's steering feel.

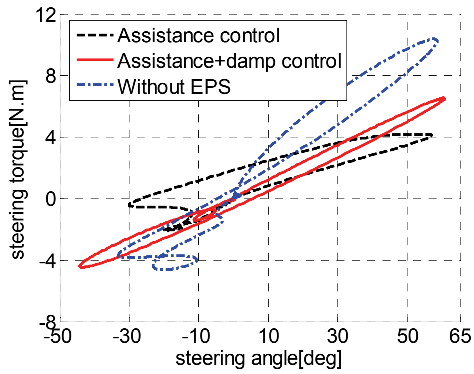


Fig. 10 Lissajou's figure of steering torque with respect to steering wheel angle

The amounts of the negative and positive steering workload are respectively defined as follows:

$$W_{SN} = -\int_0^\infty \frac{dW_S}{dt}dt \;\; [when \; \frac{dW_S}{dt} = negative] \tag{16}$$

$$W_{SP} = \int_0^\infty \frac{dW_S}{dt}dt \;\; [when \; \frac{dW_S}{dt} = positive] \tag{17}$$

The ratio of the total negative steering workload to the total positive steering workload is calculated as

$$R_S = \frac{W_{SN}}{W_{SP}} \tag{18}$$

The negative and positive steering workloads as well as the ratio R_S are calculated from the simulation results. The results are shown in Fig.11.

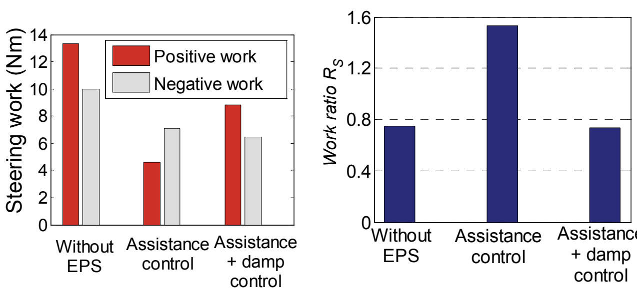


Fig.11 Steering workload of avoidance maneuver

Without EPS control, both the positive and negative steering workloads are large so that driver's steering effort is hard. For the case of only assistance control is exerted, although the total steering workload is the least, the negative workload ratio is large which means the existing of much unnatural steering operation. With damping compensation combined with assistance control, the amount and ratio of negative work ratio can be reduced even less then that without EPS control. It means the more natural operation of driver handling and more comfort steering feel.

4.3 Close-loop stability analysis

The driver characteristics, i.e. steering gain h and preview time T_P, also strongly influence the avoidance performance, so the closed-loop driver-vehicle system stability is also considered in the study. The closed-loop handling performance is evaluated by the integral of the lateral position deviation from target path with the weighting of time as follows:

$$D_c = \int_0^{t_{sim}} t \cdot | f(t) - y(t) | \, dt$$

D_c values are calculated for simulations with different values of steering gain h and preview time T_P. Although the increasing of h and shortening of T_P can make higher response of avoidance maneuver, there exist limits of the possible values of those parameters to make stable vehicle motion. Exceeding such limits can cause divergent responses of lateral position and D_c is beyond the tolerance value.

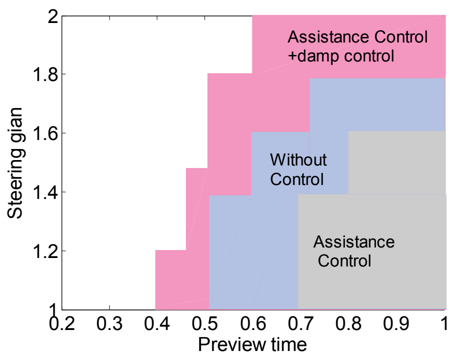


Fig.12 Limits of possible values of driver model parameters

According to simulation results, the Limits of possible values of h and T_P for convergent maneuver are shown in Fig.12. It shows that the EPS assistance control with damping compensation can also improve close-loop stability by enlarging limits of possible values of driver model parameters.

5 CONCLUSIONS

The high speed avoidance handling and steering feel performances with different EPS control strategies are analyzed by theoretical analysis and computer simulations. The results are summarized as follows:

The steering efforts can be largely reduced with EPS assistance, which can also improve the handling response of avoidance maneuver.

The steering workload characteristics are analyzed according to the relationship between steering wheel angle and torque steering. Based on steering workload calculation, EPS with damping compensation control strategies can effectively reduce negative steering workload which means drive can operate the vehicle more naturally. Therefore the more comfort steering feel can be obtained.

The damping compensation control can also assist driver to improve vehicle stability by enlarging the limits of possible values of driver's steering gain h and preview time T_P.

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