Front wheel angle control of steering by wire system based on fuzzy adaptive PID algorithm

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Abstract: - Steer by wire system can be free to design steering force transmission characteristics and angular displacement transfer characteristics, which can realize the coordination of portability, the driver steering road feel and handling stability. The dynamics models of steer by wire and vehicle system are established. Control strategy of front wheel angle based on fuzzy adaptive PID control is put forward, and simulation in different working conditions and road test are conducted. The simulation results show that front wheel angle control based on fuzzy adaptive PID can make the system achieve good control stability in different conditions and different road test. The results of this study can provide certain theoretical basis for research and application of steer by wire system.

Key-Words: - vehicle; steering by wire; fuzzy adaptive PID; front wheel angle; control

1 Introduction

The mechanical connection between the steering wheel and front wheels of automotive steer-by-wire system (SBW) has been cancelled, which gets rid of the limitation of traditional steering system completely. Thus, it can design the force and displacement transmission characteristics freely, and resolve the contradiction between the portability and steering feel of the steering system [1]. In addition, the steer-by-wire system can realize active intervention control, which can improve the vehicle handling stability, and bring more development space for the design of steering characteristics [2].

The front steering angle of SBW system is mainly controlled by the steering angle motor, which can make it obtain more direct and accurate control [3-4]. Meanwhile, because of the influence of the vehicle structure on the transmission characteristics, the vehicle system has the hysteresis and nonlinearity in itself. When driving in the complex environment, the vehicle is expected to not only have a real-time and accurate operation according to the intention of the driver, but also can automatically revert to the safe state in case of danger [5-6]. Therefore, it is necessary to control the front steering angle reasonably.

At present, research on the control of the front steering angle mainly focus on improving the vehicle handling stability [7-12]. However, they neither have a comprehensive analysis of the control effects under different road test, nor consider the driver factors in the whole closed loop system. Therefore, it is unable to analyze the influence of the SBW system on the vehicle dynamic characteristics comprehensively.

In this paper, the dynamic model of the vehicle, driver model and SBW system, which include the steering wheel subsystem model and the front wheel system subsystem model, are established. Considering the yaw rate gain and sideslip angle gain, the control strategy of the front wheel angle based on fuzzy adaptive PID is conducted, and the simulation analysis in different working
conditions and road test are carried out.

2 Dynamic model

2.1 Dynamic model of the vehicle

Assuming that the vehicle has only two DOF of the lateral and yaw motions, and the actual vehicle model is simplified to a two wheels model with only the front and rear wheels, then the two DOF vehicle model is obtained shown in figure 1.

![Figure 1 Two DOF vehicle model](image1)

The two DOF vehicle differential equations can be expressed as:

\[
\begin{align*}
(k_1 + k_2)\beta + \frac{1}{u}(ak_1 - bk_2)\omega - k_1\delta_f &= m(\dot{v} + u\dot{\omega}) \\
(ak_1 - bk_2)\beta + \frac{1}{u}(a^2k_1 + b^2k_2)\omega - ak_1\delta_f &= I_z\dot{\omega} 
\end{align*}
\]

(1)

where \( m \) is the vehicle total mass, kg; \( I_z \) is vehicle moment of inertia around Z axis, kg·m²; \( \alpha_1, \alpha_2 \) are the front and rear wheel side slip angle respectively, rad; \( k_1, k_2 \) are the front and rear tire cornering stiffness respectively, N·rad⁻¹; \( \delta_f \) is the front wheel angle of the vehicle, rad; \( a, b \) are the distance of front and rear axle to center of mass respectively, m; \( u \) is the velocity of the vehicle along the x axis, that is, the forward speed of vehicle, m·s⁻¹; \( v \) is the lateral speed of vehicle, m·s⁻¹; \( \omega \) is the yaw rate at steering, rad /s; \( \beta \) is sideslip angle, rad.

2.2 Steering wheel subsystem model

The direct connection preserved by the traditional vehicle between the steering system and the front wheels has been disconnected. Thus, the steering wheel subsystem model can be independent relatively, compared with the previous model. The simplified model of the steering wheel subsystem is shown in Figure 2.

![Figure 2 Steering wheel model](image2)

Then, the differential equations of steering wheel subsystem can be given as:

\[
J_s\dot{\theta}_h + C_s\dot{\theta}_h = T_h - T_{sm}G_{sm}
\]

(2)

where \( J_s \) is the moment of inertia that the steering wheel subsystem equivalent to steering column kg·m²; \( \theta_h \) is the steering wheel angle, rad; \( C_s \) is the damping coefficient that the steering wheel subsystem equivalent to steering column, N·m/(rad/s); \( T_h \) is the steering wheel torque, N·m; \( T_{sm} \) is the force motor torque, N·m; \( G_{sm} \) is the transmission ratio of the force motor reducer.

2.3 Front wheel subsystem model

Ignoring the stiffness coefficient of the parts, and taking the moment of inertia and damping coefficient of the steering motor shaft equivalent to the steering wheel shaft, then the simplified front wheel subsystem model can be obtained as shown in figure 3.

![Figure 3 Front wheel system model](image3)

Based on figure 3, the differential equations of front wheel subsystem can be depicted as:

\[
J_f\dot{\theta}_f + C_f\dot{\theta}_f = T_{fm}G_{fm}G_s - T_a
\]

(3)

where \( J_f \) is the moment of inertia that the steering wheel subsystem equivalent to the front wheel steering pin, kg·m²; \( C_f \) is the damping coefficient that the steering wheel subsystem equivalent to the front wheel steering pin, N·m/(rad/s); \( T_{fm} \) is the steering motor torque of the front wheel, N·m; \( T_a \) is the front wheel aligning torque, N·m; \( \theta_f \) is the front wheel angle, rad; \( G_s \) is the transmission ratio of the rack and pinion redirector; \( G_{fm} \) is the transmission ratio of the front wheel steering
motor reducer.

2.4 Driver model

The driver model which describes the manipulation behavior of the driver is used [13], as shown in figure 4.

The driver model can be depicted as follows:

\[ G_{NM} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \] (4)

\[ G_{p1} = \frac{K_1 s}{s + 1/T_1}, \quad G_{p2} = \frac{K_2}{s + 1/T_2} \] (5)

\[ G_L = \frac{1}{T_3 s + 1}, \quad G_c = \frac{1 + m T_m s}{T_3 s + 1} \] (6)

where \( G_{NM} \) is the transfer function of the driver's arm neuromuscular system; \( G_{p1} \) and \( G_{p2} \) is the feedback transfer function of the driver body and muscle movement respectively; \( G_L \) is the delay transfer function of the driver's brain information process; \( G_c \) is the lead compensation transfer function of the driving behavior in the low frequency.

3 Control strategy of the front wheel angle

3.1 Control structure

Figure 5 shows the block diagram of the front wheel steering angle control. The input of the driver model is the difference between the expected and actual lateral velocity, and the output is the steering wheel torque. \( T_m \) is the torque of feedback motor; \( K_c(v) \) is the aligning torque coefficient related to the speed; \( K_t \) is the feedback torque gain; \( \delta_h \) is the steering wheel angle; \( \delta^* \) is the expected front wheel steering angle; \( \delta \) is the actual front wheel steering angle.

The difference between the expected and actual front wheel steering angle is input to the fuzzy controller, and the modified one is obtained. Next, it is output to the two DOF vehicle model to get the actual lateral velocity, which is then feedback to the driver model, so as to realize the closed-loop control of the driver-vehicle system.

3.2 Control method

In this paper, the fuzzy adaptive PID control method is adopted, whose control law is based on the PID control. Its general form can be expressed as:

\[ u(t) = K_p e(t) + K_i \int_0^t e(t) dt + K_d \frac{de(t)}{dt} \] (7)

In the actual control process, it is often used the summation and difference quotient instead of integral and differential respectively, and the discretization equation can be given as:

\[ u(k) = K_p e(k) + K_i \sum_{i=0}^{k-1} e(i) + K_d [e(k) - e(k-1)] \] (8)

Figure 6 shows the designed two-dimensional fuzzy control structure with double input and three outputs. The input of the fuzzy controller is the deviation \( e \) and deviation change rate \( ec \) between the expected and the actual front wheel angle. The output is the deviation of the proportional, integral and differential coefficient respectively, which can be expressed as \( \Delta kp \), \( \Delta ki \), and \( \Delta kd \).
In the steering process, by constantly testing $e$ and $ec$, the fuzzy controller can adjust the three parameters of the proportion, differential and integral coefficient $kp$, $kp$, $kp$, to meet the different requirements of $e$ and $ec$. It can make the vehicle has a good response, and achieve the vehicle steering stability.

The same membership functions are used for the input and output fuzzy sets, with the beginning, middle and end part as the one of Z, triangle and S type respectively.

Considering the influence of the deviation change rate $ec$, the fuzzy control rules of the three parameters are established as shown in table 1 to table 3.

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The fuzzy control rule surfaces of the three parameters for the controller are shown in figure 7 to figure 9.
3.3 Simulation analysis

The simulation model of the controller and the vehicle are established with Matlab/Simulink software, which are shown in figure 10 and figure 11. The simulations are carried out with the PID control and fuzzy adaptive PID control respectively. Table 4 shows the main simulation parameters.

Setting the initial speed of the vehicle as 30km/h, 60km/h and 90km/h, the simulation analyses are conducted in the steering transient response test, double lane change test and serpentine road test. It can be seen from figure 12 to figure 14 that the yaw rate and the sideslip angle are all increased with the increase of the speed, and the maximum values are all in a reasonable range, in the steering transient response test, double lane change test and serpentine road test. Thus, they meet the requirement of the vehicle handling stability. Moreover, compared with the traditional PID control, the response time of the system is improved in a certain extent, and the steady-state or peak value of the yaw rate and the sideslip angle are all reduced, with fuzzy adaptive PID control. Therefore, the system has better control effect with fuzzy adaptive PID control. It can further improve the vehicle driving stability, and reduce the driver's manipulating burden.

Table 4 Main simulation parameters

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<td>$C_y$ (N·m/(rad/s))</td>
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<td>$b$/m</td>
<td>1.585</td>
<td>$C_z$ (N·m/(rad/s))</td>
<td>0.03</td>
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| $k_1$/(N/rad) | -62618 | $G_s$ | 20   |
| $k_2$/(N/rad) | -110185| $G_{fm}$ | 25 |
| $\xi$        | 0.459  | $T_1(s)$ | 2.5 |
| $\nu_0$      | 9.2    | $T_2(s)$ | 0.225 |
| $K_1$        | 0.088  | $T_3(s)$ | 0.3  |
| $K_2$        | 1.6    | $T_c(s)$ | 0.0109 |
| $\alpha$     | 2.3    |           |       |
4 Conclusions

In this paper, the vehicle dynamic model, driver model and SBW system are established. Then, the control strategy of the front wheel angle based on fuzzy adaptive PID is studied, and the simulation analysis in different working conditions and road test are conducted. The simulation results show that the control strategy based on fuzzy adaptive PID control can ensure the vehicle has good handling stability under different conditions. The simulation results show that the control strategy based on fuzzy adaptive PID control can ensure the vehicle has good handling stability under different conditions. The results of this paper can provide certain theoretical basis for the research and application of the SBW system.
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References:


