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Research on Active Steering Control Strategy of Steering-by-Wire System

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***Abstract* – Based on the software of CarSim and Simulink, the dynamics model of steering-by-wire (SBW) vehicle is established. In the steering control strategy of steering-by-wire (SBW) system, the variable-angle transmission ratio is designed by the fixed-gain method, and the front-active-steering (AFS) control strategy is superimposed to improve the steering stability of steering-by-wire (SBW) vehicle. A new active steering control strategy of steering-by-wire (SBW) vehicle is proposed in this paper. And the active steering strategy is the sliding mode control based on the radial basis function (RBF) neural network to make the adjustment of switching gain, and an additional front wheel angle is superimposed with a two-degree-of-freedom vehicle model as a reference. The simulation results show that the ideal transmission ratio of the steering system designed in this paper can improve the steering stability of the vehicle. The proposed steering control strategy can improve the steering stability of the vehicle. Compared with the traditional sliding mode control, the sliding mode control of the radial basis function (RBF) neural network proposed in this paper can effectively suppress the "chattering" phenomenon, and has stronger robustness and higher control effect.**

***Keywords* – Steering-by-Wire, Variable-Angle Transmission Ratio, Radial Basis Function Neural Network, Sliding Mode Control.**

I. Introduction

Compared with traditional automobiles, the steer-by-wire (SBW) system cancels the mechanical connection between steering wheel and vehicle wheel, which makes the steering angle ratio of the SBW automobile freely designed. When the vehicle is running at low speed, the steering system has a smaller transmission ratio. When the vehicle is running at high speed, the steering system has a larger transmission ratio. Therefore, the contradiction between "light" and "spirit" of the traditional steering system can be effectively solved, thus reducing the driver's driving burden when the vehicle is steering at low speed and improving the steering stability at high speed. Steering by wire system is the future development direction of automobile steering system [1,2].

The variable transmission ratio designed in steering control strategy of steering-by-wire (SBW) system has improved the steering characteristics of vehicle to a certain extent and basically met the control requirements of the steering system. However, in the actual driving process of vehicle, the working conditions are complex and there are many disturbing factors. Only by relying on the variable transmission ratio control that is based on the change of vehicle speed, is it impossible to achieve stable steering of vehicle. Based on the above reasons, the control strategy of active steering is introduced. Active steering control technology has been widely used to improve vehicle driving safety and handling stability. Active steering technology can make full use of the tire lateral force without adjusting driving force or braking force, and carry out superimposed steering intervention more accurately and quickly, so that the vehicle can be stable fastly.

At present, Liu Jun et al, used fuzzy adaptive PI controller to improve the lateral stability of vehicle and roll stability of its body effectively [3]. Tian Jie and Zhang Baozhen have applied sliding mode control method to control the stability of vehicle. The simulation results have verified the robustness and effectiveness of the control method [4,5]. Dong Zhurong proposed active control strategy of rear-wheel-steering based on LQR optimal control theory, which realized ideal steering characteristics well [6]. JI et al, proposed a new robust control including feed forward and feedback links for the AFS system of vehicles. The simulation results showed that the control method can improve vehicle stability, but the method cannot consider the constraint of road adhesion coefficient [7]. Falcone P, have designed the active steering control strategy with the model predictive control method [8].

In this paper, the active steering control strategy of front wheel is added on the basis of variable transmission ratio design of steering-by-wire vehicle, so as to improve the steering stability of SBW vehicle. That is to say, an additional front wheel angle is superimposed with the two-degree-of-freedom vehicle model as a reference. In the active steering strategy, a sliding mode control algorithm based on radial basis function (RBF) neural network is proposed, In order to reduce the chattering of sliding mode variable structure， a real–time adjustment of the switch gain is employed based on RBF neural network.

II. Vehicle Model

A. *Model of Steering by Wire System*

The structure of the steering-by-wire system is shown in Fig. 1. When the driver rotates the steering wheel, according to the signal measured by the steering wheel angle sensor and the speed sensor, the controller calculates the reference front wheel angle, and then sends the control signal to the steering executive motor to make the vehicle steer. At the same time, in order to make the motor output the desired opposite rotary moment of steering wheel and provide the driver with the corresponding "road feeling", the controller converts the information of vehicle driving state into the information of steering wheel opposite rotary moment and the controller transmits it to the motor of steering wheel opposite rotary moment.

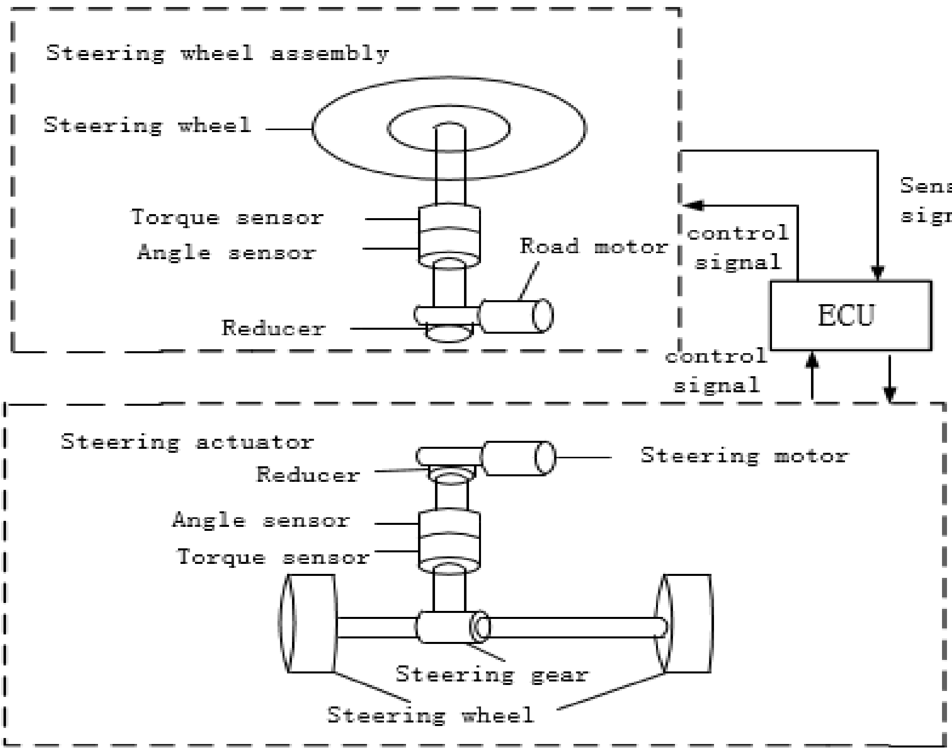

Fig. 1.0 The structure of the steering-by-wire system.

1. *Steering wheel Assembly Model*

$$T_{sw} = J_{sw}\ddot{\delta}_{sw} + B_{sw}\dot{\delta}_{sw} + T_{sen} + T_{fsw} \tag{1}$$

Where T_{sw} is the input moment of steering wheel; J_{sw} is the equivalent moment of inertia of steering wheel; B_{sw} is the viscous damping coefficient of steering wheel; T_{sen} is the torque value of torsion bar sensor; T_{fsw} is the equivalent friction moment of steering wheel.

2. *Steering Execution Motor Model*

$$T_{\mathrm{m}} = J_m\ddot{\theta}_m + B_m\dot{\theta}_m + K_{\mathrm{m}}\left(\theta_m - G_m\frac{x_r}{r_p}\right) + T_{fm} \tag{2}$$

Where T_m is the electromagnetic torque of steering execution motor; J_m is the rotating inertia of steering execution motor, B_m is the viscous damping coefficient of steering motor; K_m is the torsional stiffness of steering execution motor; θm is the angle of steering execution motor; G_m is the reduction ratio of steering execution motor; x_r is the displacement of rack; r_p is the radius of pinion; T_{fm} is equivalent friction moment of steering wheel.

3. *Gear-rack Steering Gear Model*

$$J_{rw}\ddot{\delta}_f + B_{rw}\dot{\delta}_f = K_{kp}\left(\frac{x_r}{G_{rw}} - \delta_f\right) - T_f \tag{4}$$

Where is J_{rw} the rotating inertia of front wheel around main pin; B_{rw} is the viscous damping coefficient of front wheel winding pin; T_f is the turning resistance moment of front wheel.

B. *Vehicle Reference Model*

The simplified linear vehicle model of two-degree-of-freedom is adopted in the vehicle reference model. The state variables of the vehicle are yaw angular velocity ω_r and sideslip angle β of the vehicle mass center. According to the reference [9] (Yu Zhisheng, 2009), two-degree-of-freedom differential equation of vehicle motion can be obtained:

$$\begin{cases} (k_1 + k_2)\frac{v}{u} + \frac{1}{u}(ak_1 - bk_2)\omega_r - k_1\delta_f = mu\omega_d \\ (ak_1 - bk_2)\beta + \frac{1}{u}(a^2k_1 + b^2k_2)\omega_d - ak_1\delta_f = 0 \end{cases} \tag{5}$$

Where k_1、k_2 is the lateral stiffness of front and rear wheels; ω_d is the yaw angular velocity of vehicle in steering; δ_f is the front wheel rotation angle of vehicle; a、b is the distance from front axle and rear axle to vehicle center of mass; u is the vehicle speed along X-axis; v is the vehicle lateral speed; β is the vehicle sideslip angle.

III. Design of the Variable Transmission Ratio

The ideal steering ratio of the SBW system studied in this paper is the total transmission ratio of the vehicle steering system, which is the ratio of the front wheel angle to the steering wheel angle, it can be expressed as follows:

$$i = \delta_{\mathrm{sw}}/\delta_f \tag{6}$$

A. *Design of Steering ratio based on the Constant Yaw-Angular-Velocity Gain*

According to the reference model of two-degree-of-freedom, the relationship between the yaw angular velocity and the front wheel angle can be expressed as follows:

$$\frac{w_r}{\delta_f} = \frac{u/L}{1+\frac{m}{L^2}\left(\frac{a}{k_2}-\frac{b}{k_1}\right)u^2} \tag{7}$$

In automotive system dynamics, the ratio of yaw angular velocity to steering wheel angle of vehicle response is defined as the yaw angular velocity gain or steering sensitivity, which can be expressed as:

$$G_{\text{sw}} = \frac{w_r}{\delta_{sw}} = \frac{u/L}{\left[1+\frac{m}{L^2}\left(\frac{a}{k_2}-\frac{b}{k_1}\right)u^2\right]i} \tag{8}$$

When the transmission ratio is fixed, it can be seen from the above formula that the G_{sw} will change with the vehicle speed, so the driver should always adjust the steering wheel according to the driving demand, which would have increased the driving burden. If the transmission ratio i varies with the vehicle speed, not only the characteristics of the vehicle speed change can be corrected, but also the steering sensitivity G_{sw} can be set. Then there will be a fixed linear relationship between the yaw rate and steering wheel angle, which will greatly reduce the driver's compensation for the change of vehicle steering characteristics [10]. And the gain of fixed yaw angular velocity in this paper is 0.35. Variable transmission ratio of steering by wire is expressed as follows:

$$i = \begin{cases} \frac{u/L}{\left[1+\frac{m}{L^2}\left(\frac{a}{k_2}-\frac{b}{k_1}\right)u^2\right]G_{sw}} & ,v > 30 \\ 7 & ,v \leq 30 \end{cases} \tag{9}$$

IV. Active Steering Control Strategy of Front Wheel

A. *Sliding mode Control Strategy with the Control Target of Yaw Angular Velocity*

The yaw angular velocity is an important parameter to describe the steering motion of a vehicle, and its variation reflects the stability of the vehicle. Therefore, feedback control of yaw angular velocity based on feed-forward control can make the controller perceive the running state of the vehicle in real time. By adjusting the front wheel rotation angle, the steering characteristics of the vehicle can be improved, the ideal transient response of the vehicle can be obtained, and the stability of the vehicle can be improved. The expected yaw angular velocity should be determined first when the yaw-angular-velocity feedback control of SBW vehicle is carried out. Under the normal driving conditions, in order not to change driver's driving habits and improve vehicle steering sensitivity, the steady yaw angular velocity ω_r obtain from the two-degree-freedom vehicle model can be used as the desired yaw angular velocity. But in the extreme driving conditions, in order to ensure the driving stability of vehicles, with the tire adhesion limit, the lateral acceleration must also satisfy the following constraints [11]:

$$|a_y| \leq \mu g \tag{10}$$

$$a_y \approx \frac{u^2}{R} = \omega_r \tag{11}$$

Therefore, the control objective of the sliding controller is:

$$\omega_d = \left\{\left|\frac{u\delta_f}{L(1+Ku^2)}\right|, \left|\frac{\mu g}{u}\right|\right\} sgn(\delta_f) \tag{12}$$

B. *Design of Sliding mode Surface*

Sliding mode variable structure can make the system structure change with time and force the system to stabilize near the sliding mode surface, and then converge to the sliding mode surface by switching function [12]. The control objective of active-front-steering (AFS) system is to make the yaw angular velocity of the vehicle track any change of the current setting value quickly and accurately. The tracking error 'e' is defined as:

$$\mathrm{e} = \omega_r - \omega_d \tag{13}$$

Therefore, the switching function of sliding mode control is defined as:

$$\mathrm{S} = \mathrm{e} + \lambda \int_0^t e\, dt \tag{14}$$

Where ω_r is the vehicle actual yaw angular velocity; ω_d is the ideal yaw angular velocity; λ is the positive weight coefficient.

The derivation of 'S' is obtained as follows:

$$\dot{\mathrm{S}} = \dot{\mathrm{e}} + \lambda \mathrm{e} \tag{15}$$

Let $\dot{S} = 0$, the equivalent control law is obtained as follows:

$$u_{eq} = \delta_0 = \left[\frac{1}{u\mathrm{I}_z}(a^2 k_1 + b^2 k_2)\omega_r + \frac{1}{I_z}(ak_1 - bk_2)\beta_r - \frac{ak_1}{I_z}\delta_f - \dot{\omega}_d + \lambda \mathrm{e}\right]\frac{I_z}{ak_1} \tag{16}$$

The law of switching control law is designed as follows:

$$\mathrm{u}_n = \frac{I_Z}{ak_1} K sgn(S) \tag{17}$$

Thus, the general sliding control law of active steering is as follows:

$$U = \mathrm{u}_{eq} + \mathrm{u}_n \tag{18}$$

Stability Analysis of the system

By Lyapunov formula:

$$\mathrm{V} = \frac{1}{2} S^2 \tag{19}$$

$$\dot{\mathrm{V}} = S \cdot \dot{S} \leq 0 \tag{20}$$

That is, the system tends to be stable.

C. *Switching Gain design based on RBF Neural Network*

The designed RBF neural network has two inputs, six hidden nodes and one output. The structure of RBF neural network is shown in Figure 2.

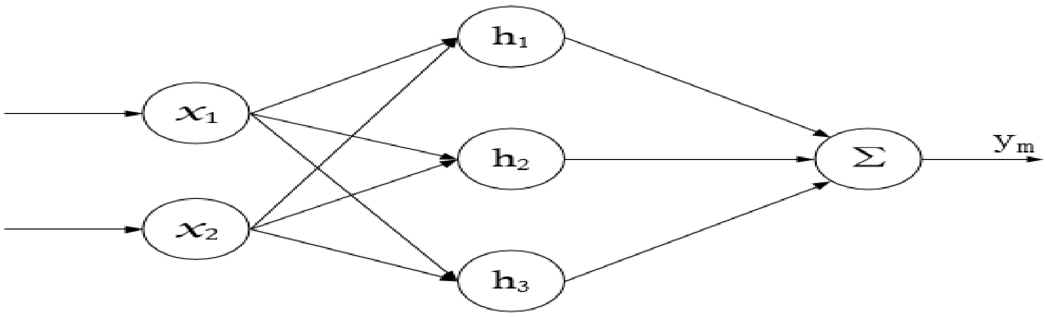

Fig. 2.0 The structure of RBF neural network.

The input of RBF neural network is:

$$\boldsymbol{x} = [\,S\ \dot{S}] \tag{21}$$

The output of RBF neural network is:

$$y_m = \boldsymbol{w}^T\boldsymbol{h} = w_1h_1 + w_2h_2 + w_3h_3 \tag{22}$$

The switching gain regulated by RBF neural network is $K = |y_m|$.

Where $\boldsymbol{w}$ is the weights of RBF Network, $\boldsymbol{w} = [w_1, w_2, w_3]^T$; $\boldsymbol{h}$ is the output of RBF hidden layer, $\boldsymbol{h} = [h_1, h_2, h_3]^T$.

And the output of the neuron is a Gauss basis function, that is:

$$h_j = exp\left(-\frac{\|x-c_j\|}{2b_j}\right),\quad j = 1,2,3 \tag{23}$$

Where, c is the coordinate vector of the Gauss basis function's center point in the jth neuron of the hidden layer, $c = [c_{ij}] = \begin{bmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \end{bmatrix}$; b_j is the width of the Gauss basis function, $b = [b_1,\ b_2,\ b_3]^T$.

The weight adjustment index of RBF neural network can be obtained by gradient descent method.

$$E = \frac{1}{2}e^2 \tag{24}$$

The learning algorithm of network weights is as follows:

$$\Delta w = -\eta_1\frac{\partial E}{\partial w} = -\eta_1 e\frac{\partial e}{\partial w} = -\eta_1 e\frac{\partial \omega_r}{\partial w} = -\eta_1 e\frac{\partial \omega_r}{\partial U}\frac{\partial U}{\partial K}\frac{\partial K}{\partial w} \approx -\eta_1 esgn\left(\frac{\partial \omega_r}{\partial U}\right)\frac{\partial U}{\partial K}\frac{\partial K}{\partial w} \tag{25}$$

The discussion of above formula is as follows:

1) In step response, ω_r is proportional to *u* (*u* is the control output of the system), so, $sgn\left(\frac{\partial \omega_r}{\partial U}\right) = 1$。

2) According to the (16-18) formula, $\frac{\partial U}{\partial K} = sgn(S)$.

3) According to the (22) formula, $\frac{\partial K}{\partial w} = \mathrm{h}(x)sgn\left(w^T h(x)\right)$.

4) So the weight adjustment algorithm is as follows:

$$\Delta w(t) = -\eta_1 esgn(S)h(x)sgn\left(w^T h(x)\right) \tag{26}$$

5) The network weight learning algorithm is as follows:

$$w(t) = w(t-1) + \Delta w(t) + \partial\left(w(t) - w(t-1)\right) \tag{27}$$

V. Construction of Joint Simulation Platform with CarSim and Simulink Software

According to the designed variable transmission ratio and active steering control strategy of steering-by-wire system, CarSim/Simulink joint simulation platform is used to verify it. Using the high precision vehicle dynamics model in CarSim software, the dynamic model of steering-by-wire system is established in Simulink software to realize the design of transmission ratio and active steering control strategy, which is embedded in the CarSim vehicle model closed the traditional steering system to achieve joint simulation [13]. The built joint simulation platform is shown in Figure 3.

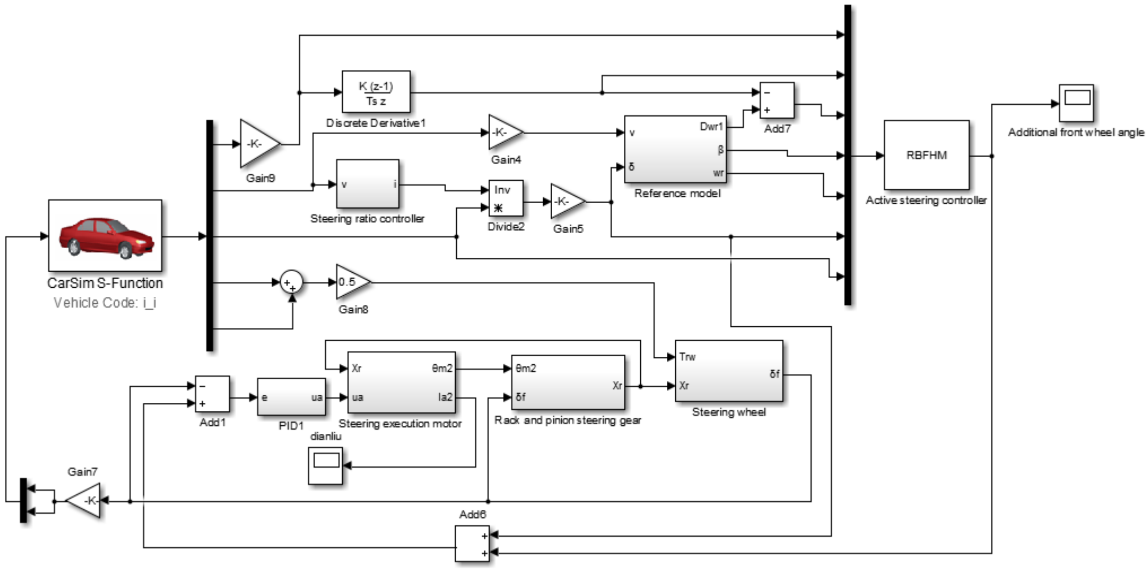

Fig. 3.0 The joint simulation platform.

VI. SIMULATION VERIFICATION

A. *Double Line Shifting Test*

The experimental condition of double-line-shifting was adopted in the experiment. When the vehicle is running at a speed of 30 km/h, the simulation experiment of double lane change is carried out. The experimental result of steering wheel is shown in Figs. 4. As can be seen from the figures, steering angle of steering wheel of steering-by-wire vehicle is obviously smaller than that of traditional vehicle, which reducing driver's driving burden at low speed. The vehicle speed is 60km/h and the ground adhesion coefficient is 0.75. The steering system adopts the fixed transmission ratio of the traditional mode and the variable transmission ratio of SBW system respectively. The experimental results are shown in Figs. 5 and 6. As can be seen from the figures, SBW vehicle adopted variable steering ratio, and its yaw angular velocity and lateral acceleration are less than those of fixed transmission ratio vehicle. It shows that the variable transmission ratio of the steering system designed in this paper can improve the steering handling stability of the vehicle.

B. *Angular Step Test*

The experimental condition of angular step test was adopted in the experiment, the vehicle speed is 80km/h and the steering wheel angle is 0.75. On the basis of variable transmission ratio feedforward control, the active steering control strategy is superimposed. Sliding mode control algorithm and sliding mode control adjusted by RBF neural network are used in active steering control strategy. The experimental results are shown in Figs. 7, 8. As can be seen from the figures, the sliding mode control adjusted by RBF neural network can make the yaw angular velocity and sideslip angle of vehicle response track its ideal value better, and improve the steering stability of SBW system. Compared with the traditional sliding mode control, the sliding mode control of RBF neural network proposed in this paper can effectively suppress the "chattering" phenomenon.

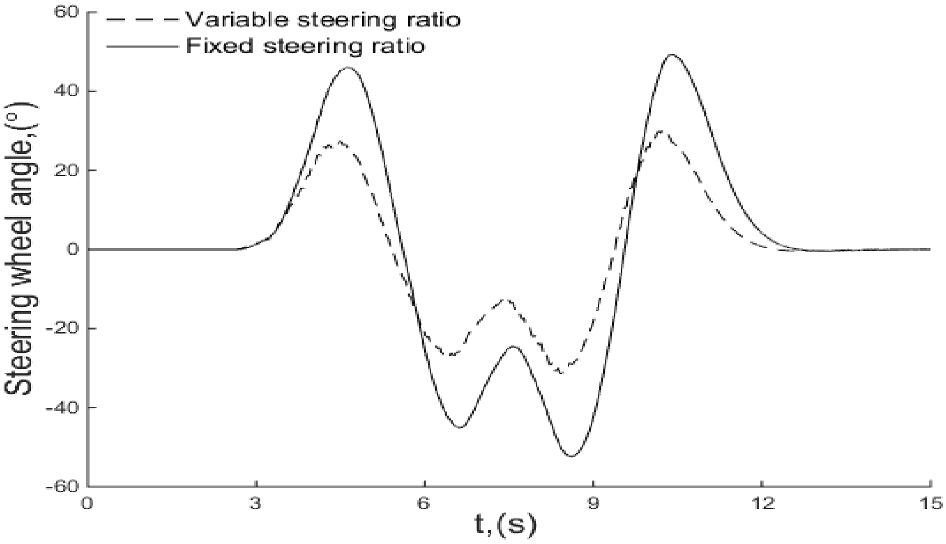

Fig. 4.0 Steering wheel angle at 30km/h.

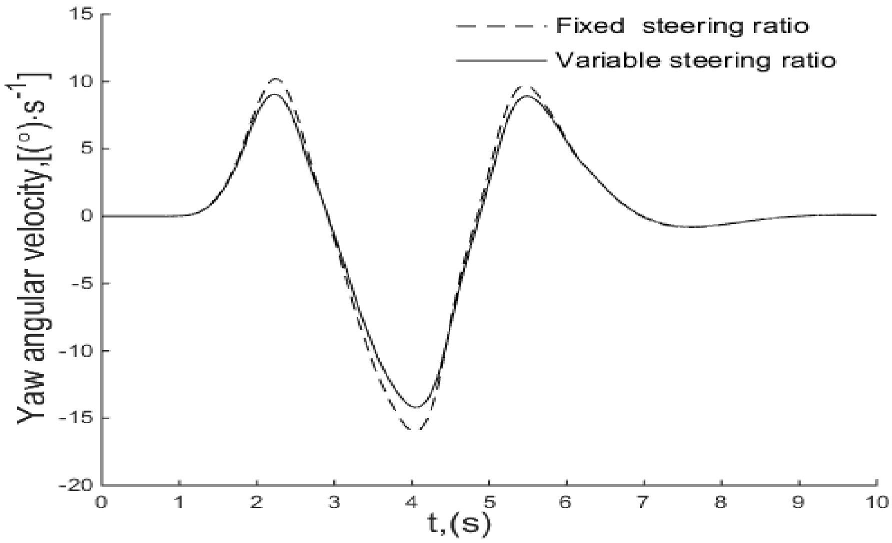

Fig. 5.0 Yaw angular velocity curve at 60km/h.

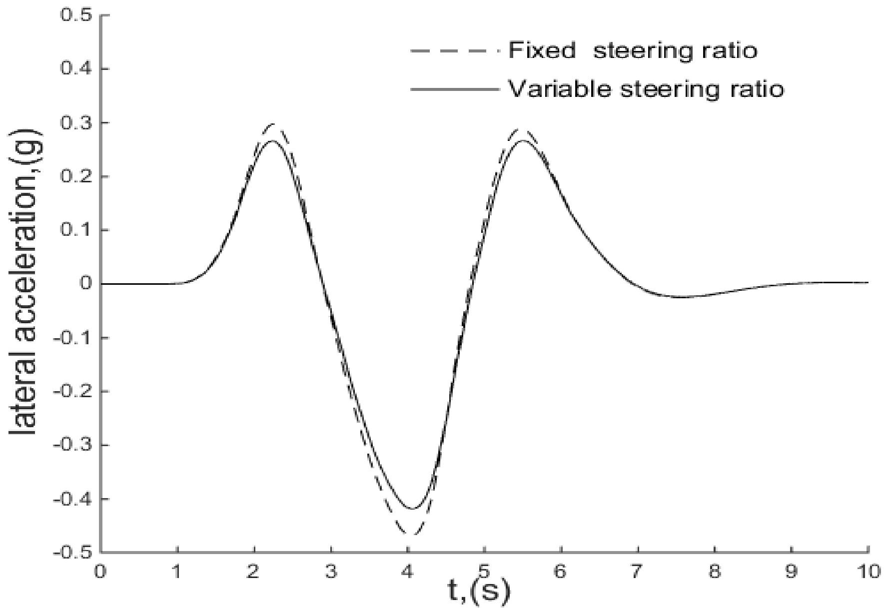

Fig. 6.0 Lateral acceleration curve at 60km/h

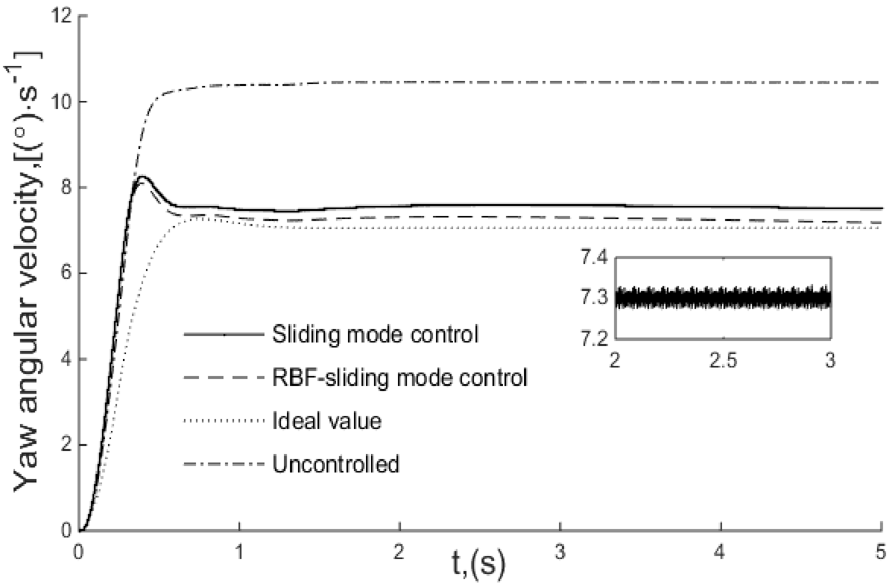

Fig. 7.0 Lateral acceleration curve at 80km/h

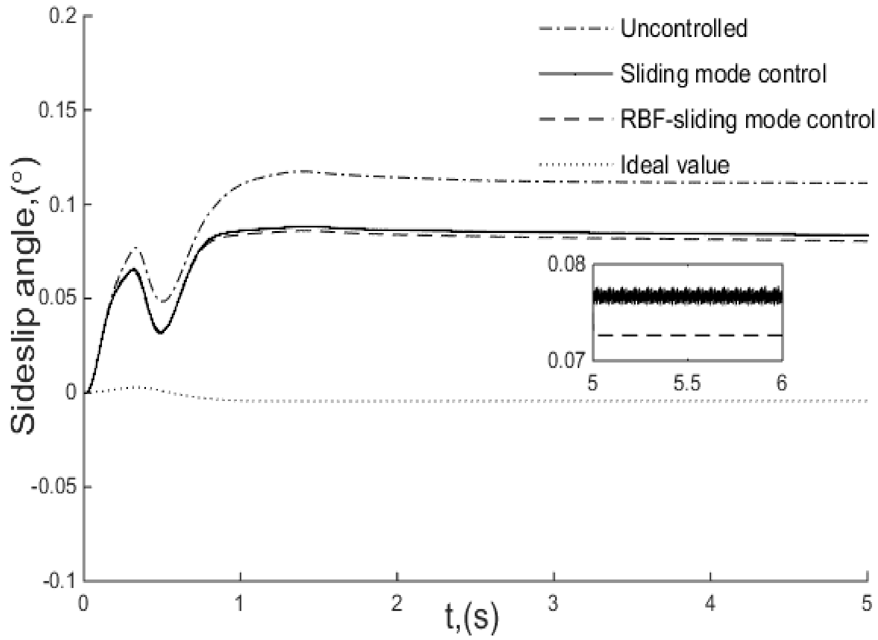

Fig. 8.0 Yaw angular velocity curve at 80km/h.

VII. Conclusion

Verified with the Joint simulation experiments by CarSim and Simulink software, the results show that the ideal transmission ratio of the steering system designed in this paper can improve the steering stability of the vehicle better, and the design method adopted is effective and feasible.

On the basis of variable transmission ratio feed forward control, the active steering control strategy is superimposed. Sliding mode control algorithm and sliding mode control adjusted by RBF neural network are used in active steering control strategy. The simulation results show that the sliding mode control adjusted by RBF neural network can make the yaw angular velocity and sideslip angle of vehicle response track its ideal value better, and improve the steering stability of steering by wire system. Compared with the traditional sliding mode control, the sliding mode control of RBF neural network proposed in this paper can effectively suppress the "chattering" phenomenon.

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