Study on Wire-Controlled Differential Steering of Hub-Driven Four-Wheel Electric Vehicle

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Keywords: Hub-Driven, Electronic Differential, Wire-Controlled Steering, Motor Rotational Speed, Ackermann Steering Model.

Abstract: In order to research the differential steering control method of the hub-driven electric vehicle, an Ackermann differential steering model applicable to low-speed driving of four-wheel electric vehicles is established. A permanent magnet synchronous motor model is established using a double closed-loop control of rotational speed loop and current loop combined with SVPWM algorithm. At the same time, four motor controllers are used to control the rotational speed of four driving motors respectively, achieving differential steering. The differential steering control system is built and simulated in the MATLAB/Simulink environment. The simulation results show that the adopted Ackermann differential steering control system can meet the requirements of low-speed differential steering of four-wheel electric vehicles. Meanwhile, the PI rotational speed control system can achieve adaptive tracking of the given speed, effectively improving the safety and stability of the vehicle during rotational speed change.

1 INTRODUCTION

In recent years, hub-driven electric vehicles have received widespread attention. The technological advantage of hub-driven lies in the elimination of components such as mechanical differential clutches, transmissions, and drive shafts, which improves the space utilization rate and transmission efficiency, as well as the layout structure, chassis integrated control, and execution flexibility (Li- Du, Peng).

In the research of hub-driven electric vehicles, the steering system is one of the research hotspots. One of the problems that need to be solved for electric vehicles driven by hub motors is the synchronization and coordination of each wheel, namely the differential steering problem (L. Jian-Termous). The main approach to the solution is to coordinate the rotational speed of each driving motor through the vehicle controller, or to realize it through a special motor (Yuan, 2022). This paper, based on the low-speed characteristics of four-wheel electric vehicles during steering, analyzes the vehicle steering dynamics, establishes the Ackermann differential steering model, and analyzes the mathematical model of the vehicle drive motor to construct a double closed-loop control system of the drive motor. The differential model is combined with the motor system, and the motor rotational speed is coordinated and controlled, and it is verified and analyzed on the Simulink simulation platform.

2 DIFFERENTIAL STEERING MODEL

2.1 Design of Differential Steering Model

For low-speed vehicles, the differential strategy adopted is the electronic differential analysis model proposed by Ackermann-Jeantand. The assumptions of this model are: (1) the vehicle body is rigid; (2) the wheels are pure rolling motion, and the tire slip and slide running state are not considered; (3) the lateral deformation and lateral force of the tire are proportional, and the tire material and structural nonlinearity and the impact of the centrifugal force causing changes in the tire’s vertical load are not considered. The designed differential steering model is as shown in Fig. 1.

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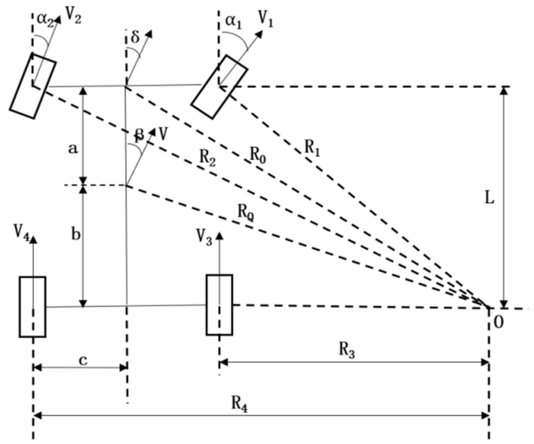

Figure 1: Differential Steering Model.

According to the Ackermann-Jeantand steering model in Fig. 1, taking a right turn as an example, we know from geometric relationships:

$$R_Q = \sqrt{b^2 + (L/\tan\delta)^2} \quad (1)$$

$$R_1 = \sqrt{L^2 + (L/\tan\delta - c)^2} \quad (2)$$

$$R_2 = \sqrt{L^2 + (L/\tan\delta + c)^2} \quad (3)$$

$$R_3 = L/\tan\delta - c \quad (4)$$

$$R_4 = L/\tan\delta + c \quad (5)$$

From which we can get:

$$\tan\alpha_1 = L/(L/\tan\delta - c) \quad (6)$$

Then we have:

$$\tan\delta = L\tan\alpha_1/(L + c\tan\alpha_1) \quad (7)$$

According to the Instantaneous Center of Rotation (ICR) theorem, we know:

$$\frac{V}{R_Q} = \frac{V_1}{R_1} = \frac{V_2}{R_2} = \frac{V_3}{R_3} = \frac{V_4}{R_4} \quad (8)$$

The longitudinal speeds of each wheel can be obtained as:

$$V_1 = \frac{V\sqrt{L^2 + (L/\tan\delta - c)^2}}{\sqrt{b^2 + (L/\tan\delta)^2}} \quad (9)$$

$$V_2 = \frac{V\sqrt{L^2 + (L/\tan\delta + c)^2}}{\sqrt{b^2 + (L/\tan\delta)^2}} \quad (10)$$

$$V_3 = \frac{V(L/\tan\delta - c)}{\sqrt{b^2 + (L/\tan\delta)^2}} \quad (11)$$

$$V_4 = \frac{V(L/\tan\delta + c)}{\sqrt{b^2 + (L/\tan\delta)^2}} \quad (12)$$

Where V is the speed of the omnidirectional electric chassis centroid, V_1~V_4 are the longitudinal motion speeds of each wheel respectively, L is the wheelbase from the front axle and rear axle, c is half of the track, a and b are the distances from the front axle and rear axle to the vehicle centroid respectively, R_1~R_4 are the steering radii of each wheel around the rotation center O respectively, R_Q is the steering radius of the centroid around the rotation center O, α_1 and α_2 are the steering angles of the right front wheel and left front wheel respectively, and δ is the vehicle's Ackermann steering angle.

2.2 Differential Steering Simulation Model

The wheel speed is generally calculated from the wheel rotational speed collected by the speed sensor. The conversion formula from wheel speed to wheel rotational speed is:

$$v = \frac{\pi n r}{30} \quad (13)$$

Where v is the wheel speed, n is the wheel rotational speed, and r is the radius of the tire.

According to the established mathematical model of the electric vehicle's differential steering, a differential steering system simulation model is built in the MATLAB/Simulink environment. As shown in Fig. 2, the vehicle speed and the right front wheel steering angle serve as inputs, with the speeds of all four wheels as the output.

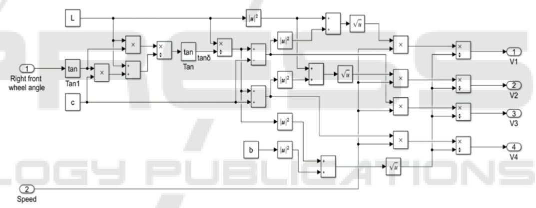

Figure 2: Ackermann Steering System Simulation Model.

3 PMSM MODEL BASED ON PI ROTATIONAL SPEED CONTROL

Due to the excellent startup performance of the Permanent Magnet Synchronous Motor (PMSM), along with its good reliability, high security, and high efficiency during rated operation, it can well meet the requirements of vehicle drive motors. In addition, such motors also have features such as light weight, small size, and low rotor heating rate. Therefore, PMSM is selected as the subject for control analysis.

3.1 PMSM Mathematical Model

Since the stator induced electromotive force of the PMSM is a sine wave, the use of coordinate transformation theory is a relatively effective analysis method. The motor in the actual operation process will inevitably be affected by the actual environment, causing changes in the motor's resistance and inductance. To simplify the analysis process, the following assumptions are made: (1) The motor air gap magnetic field is uniform and sinusoidal, the winding resistance and inductance values are constant; (2) Saturation effects of the magnetic circuit are ignored; (3) Magnetic hysteresis and eddy current losses are not considered; (4) The influence of the stator slots is neglected.

The three-phase voltage equation of the PMSM model under the three-phase stator ABC coordinate system is:

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} r & 0 & 0 \\ 0 & r & 0 \\ 0 & 0 & r \end{bmatrix} \begin{bmatrix} i_A \\ i_B \\ i_C \end{bmatrix} + \frac{\mathrm{d}}{\mathrm{dx}} \begin{bmatrix} \psi_A \\ \psi_B \\ \psi_C \end{bmatrix} \tag{14}$$

The mathematical model of the Permanent Magnet Synchronous Motor established under the synchronous rotating coordinate system is:

$$\begin{cases} u_d = ri_d + \frac{d\psi_d}{dt} - \omega\psi_q \\ u_q = ri_q + \frac{d\psi_q}{dt} + \omega\psi_d \end{cases} \tag{15}$$

When the motor's salient pole effect is not considered, the magnetic linkage equation is:

$$\begin{cases} \psi_d = L_d i_d + \psi_f \\ \psi_q = L_q i_q \end{cases} \tag{16}$$

Using the principle of equal amplitude transformation, the electromagnetic torque of the Permanent Magnet Synchronous Motor is obtained:

$$T_e = \frac{3}{2} n_p \left(\psi_f i_q + \left(L_d - L_q \right) i_d i_q \right) \tag{17}$$

The mechanical motion equation of the motor is:

$$\begin{cases} T_e - T_L = B\omega_m + J\frac{d\omega_m}{dt} \\ \omega_m = \frac{\omega}{n_p} \end{cases} \tag{18}$$

Where u_d and u_q are the voltages of the d and q axes; id and i_q are the currents of the d and q axes; n_p is the number of pole pairs; ψ_d and ψ_q are the direct-axis and quadrature-axis components of the stator magnetic linkage; ψ_f is the magnetic linkage; L_d and L_q are the direct-axis and quadrature-axis inductances; r is the phase resistance of the stator; T_L is the load torque of the motor; ω_m and ω are the mechanical and electrical angular speeds of the motor; B and J are the damping coefficient and moment of inertia.

3.2 Motor Simulation Model

According to the PMSM mathematical model, a motor control system is established using the rotational speed loop PI controller and current loop PI controller dual-loop control combined with the Space Vector Pulse Width Modulation (SVPWM) algorithm. Fig. 3 is the overall structure diagram of the motor control system, mainly including the rotational speed control module, current control module, voltage inverter module, SVPWM algorithm module, and so on. A motor system simulation model is built in the MATLAB/Simulink environment.

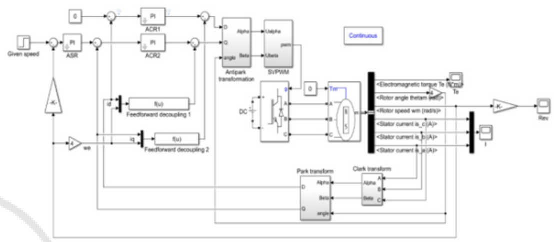

Figure 3: Motor Simulation Model.

4 DIFFERENTIAL CONTROL METHOD BASED ON MOTOR ROTATIONAL SPEED

According to the differential model, motor model, and speed- rotational speed conversion model, a differential steering control system is established. The collected vehicle speed and steering angle are used as variable inputs to the differential steering model. Through the model calculation, the wheel speeds of the four wheels are obtained and converted into desired rotational speed via the speed-rotational speed conversion model. Then we have to calculate difference between the desired speed and the actual rotational speed of the motor and then input the value to the PI controller to control the operation of each hub motor and drive the vehicle to steer. The schematic diagram of the differential steering system is shown in Fig. 4.

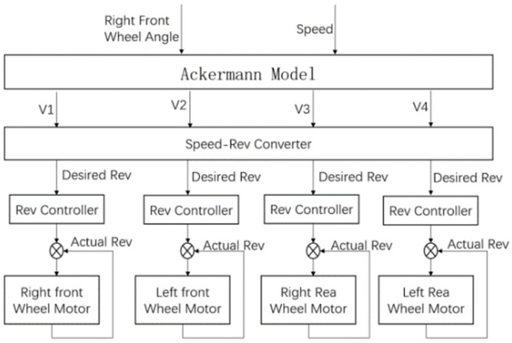

Figure 4: Differential Steering Control System.

5 SIMULATION RESULTS ANALYSIS

The design parameters of the sample vehicle are as shown in Table 1.

Table 1: Three Scheme comparing.

Parameter Name	Wheelbase(m)	Tread width(m)	Tire radius(m)
Parameter Value	2.35	1.52	0.6

Motor parameters are as shown in Table 2.

Table 2: Three Scheme comparing.

Parameter Name	Inductance （H）	Resistance （Ω）	Rotor Flux Linkage （Wb）	Moment of Inertia （kg·m²）	Number of Pole Pairs	Damping Coefficient （N·m·s）
Parameter Value	0.000835	0.11	0.1119	0.0016	4	0.0002024

5.1 Motor Performance Test

To verify whether the hub motor parameters can meet various performance requirements, the established motor system simulation model is tested as follows: the initial load torque is set to zero, the motor is started without load, the load is suddenly added at 0.2s, and the load is removed at 0.4s; the initial rotational speed is set to n=1000r/min, and at 0.6s, it is accelerated to n=1100r/min.

Simulation results show that when the motor gradually accelerates from zero to the reference rotational speed of 1000r/min, although there is an overshoot, the response speed of the motor system is fast, and the stability is relatively strong. It is evident that the use of PI control rotational speed has strong anti-interference capability and rapid adjustment speed. Fig. 5 shows the rotational speed change curve, Fig. 6 shows the electromagnetic torque change curve.

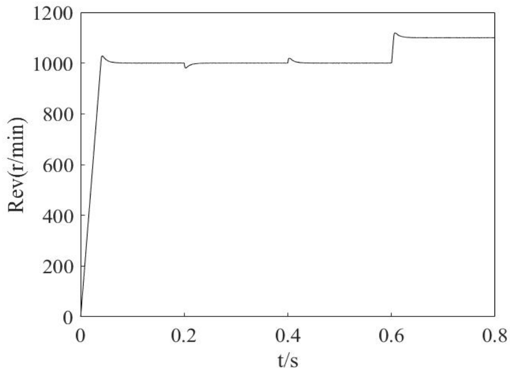

Figure 5: Rotational Speed Change Curve.

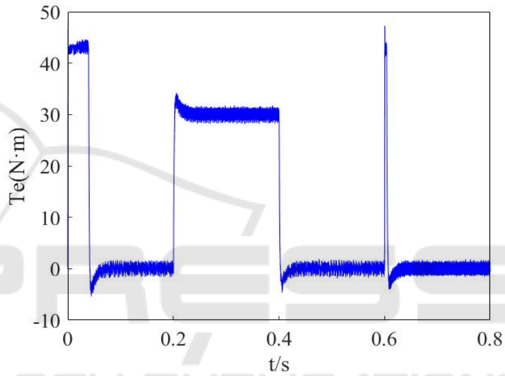

Figure 6: Electromagnetic Torque Change Curve.

5.2 Differential Performance Test

Taking the right front wheel as an example, the steering angle is set to 10°, the vehicle speed v=10m/s, and a comparative test is carried out with and without PI control. The simulation result is shown in Fig. 7. The result shows that the right front wheel with PI control has reduced the overshoot, effectively weakening the overshoot phenomenon. When a disturbance is added at t=0.3s, the right front wheel's rotational speed response time is short with PI control, significantly enhancing the robustness of the differential steering control system.

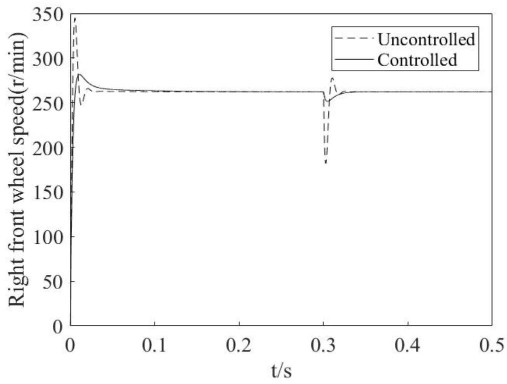

Figure 7: Comparison of control curves for the right front wheel.

Given a lower driving speed of v=15m/s, the right front wheel's steering angle changes uniformly from [0, 50]. The wheel rotational speeds are shown in Fig. 8. Through simulation analysis, when the vehicle is turning, the rotational speed of the outer wheels is higher than the inner wheels, which is consistent with the actual situation, verifying the correctness of the differential steering control system. As the steering angle changes continuously, the vehicle controls the hub motors of each wheel to achieve differential steering through the differential steering system and always maintains the condition that the rotational speed of the outer wheel is higher than the inner wheel, verifying the feasibility of the differential steering system controlling the vehicle's steering movement.

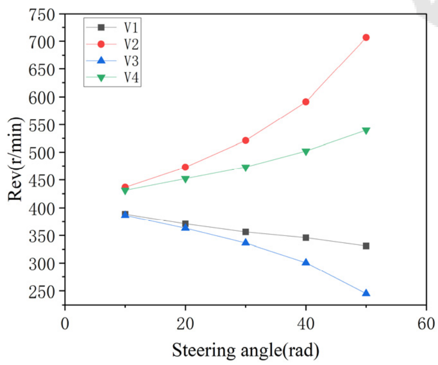

Figure 8: Curve of speed change of each wheel.

6 CONCLUSION

Hub-driven electric vehicles have shown many advantages in economy and vehicle control and are one of the future development directions of cars. Differential steering technology is one of its essential performance indicators, and the quality of the differential steering system affects the stability and smoothness of vehicle travel. Therefore, continuous exploration of differential steering is essential.

This paper takes the hub-driven four-wheel electric vehicle as the research object, establishes a differential steering control system suitable for low-speed steering, and verifies and analyzes this system in the Simulink simulation platform. The results show that the constructed permanent magnet synchronous motor system has strong robustness. The established steering control system can fully meet the differential requirements, enhancing the stability and security of the vehicle when steering. This system is simple and practical and has some reference value for future research on differential steering systems.

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