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Adaptive electronic differential control of vehicle by torque balance

Hong Tian[1] · Weiguo Zhu[2] · Sharon Wang[3]

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Abstract

Current adaptive torque balancing control of electric wheel-driven vehicle has shortcomings in electronic differential control of drive motor by using rotation speed mode. In order to solve this problem, an adaptive electronic differential control method of electric wheel-driven vehicle is proposed in this paper by torque balance. Firstly, by starting from the kinematics and dynamics of vehicle steering, the speed and force of each drived wheel in the steering are analyzed to explain the auxiliary role of electronic differential control to adaptive torque balancing, as well as influence of steering radius in vehicle. Then, electronic differential distribution by torque of wheel is used to control the abnormal jump interference and calculate the optimal combination of parameters in electronic differential control system. Finally, based on the optimal combination of these parameters, an adaptive electronic differential control of electric wheel-driven vehicle by torque balance is realized with fuzzy control in active and the reactive power. Experimental results show that the proposed method suppresses the abnormal jump interference factors of electronic differential control, as well as realizes the differential functions in control system. It has far-reaching significance by provideing a basic guarantee to realize adaptive electronic differential control system in electronic wheel-driven vehicle.

Keywords Fuzzy control · Electric wheel-driven vehicle · Torque balance · Differential speed control · Electronic differential auxiliary steering

1 Introduction

With the development of computer intelligent control technology, electric wheel-driven vehicle usually uses distributed two-wheels or four-wheels driven motor. It has the advantages of short driving chain, high efficiency, compact structure, high space utilization, independent and accurate control of the torque of each driven wheel, the recovery of braking energy, and good mobility by compared with the internal-combustion engine and the electric centralized-driven vehicle. Researchers are interested in the technical problems of the power, stability and reliability of electric wheel vehicle today [1]. The main technologies such as hub motor and its control, electronic differential method, torque coordination control, vehicle driving force control, and differential auxiliary steering technology have further space for research and solution. On the basis of these technologies, the anti-lock braking system (ABS), traction control system (TCS) and vehicle stability control (VSC) system have greater potential for development [2]. At present, research directions are mainly divided into (a) electronic differential technology based on rotation speed control and (b) electronic differential technology based on torque control [3, 4].

(1) Control based on rotation speed directly controls the rotation speed of two-side driven wheels to realize electronic differential control [5]. At present, the main control method is based on the acceleration pedal and feedback signal of each wheel's speed. Combined with the steering wheel rotation angle and the speed relation of each driving wheel, the control instruction is sent to the driving motor through comprehensive analysis and calculation by the differential control of two-side driven wheels [6]. However, this method is mostly based on the Ackerman steering model, which ignores the characteristics of nonlinear system, which causes errors between the model and the actual vehicle. In order to solve this problem, some nonlinear systems, such as neural

✉ Weiguo Zhu
zwg2007@hyit.edu.cn

✉ Sharon Wang
shuihuawang@ieee.org; s.wang6@lroro.ac.uk

1 Department of Electrical Engineering, Baotou Iron & Steel Vocational Technical College, Baotou 014010, China

2 Jiangsu Key Lab of Advanced Manufacturing Technology, Huiyin Institute of Technology, Huai'an 223003, China

3 School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough LE11 3TU, UK

network and fuzzy control algorithm are adopted to reduce the problem of poor accuracy in traditional models. However, because of the dynamic and time-varying characteristics of the electric vehicle in the turning process, it is difficult to ensure the accuracy of the mathematical model and it also makes the control complexity [7, 8].

(2) The electronic differential technology based on torque control includes direct yaw moment control and slip rate control. The yaw moment control is a control method based on vehicle stability and safety. Taking yaw angular velocity and side-slip angle as reference, a reasonable control algorithm is used to allocate the torque of driving wheel, which does not only realize differential control, but also improve vehicle handling stability and safety [9].

Based on the theoretical analysis of permanent magnet motor and traditional mechanical differential steering mode, two permanent magnet motors are proposed as the adaptive torque balance control scheme of the driving motor [10, 11]. The solution of high stable electronic differential system is designed to solve problems generated by current electronic differential speed scheme. Relationship between the wheel speed-steering angle and the speed-power distribution is calculated and analyzed. Some control methods of coordination work for the wheels are put forward by the simulation model and experiment to determine the control strategy of the electronic differential speed.

Based on the rear wheel independent driven electric vehicle, the development of electronic differential steering control is researched, and test of electronic differential control is carried out. Experimental results show that the control strategy is well implemented in the test vehicle, and it provides the foundation for further control strategy research.

Following content of this paper is organized as follows. Section 2 analyzes principle of electronic differential auxiliary steering. Section 3 provides and analyzes experimental results. Section 4 concludes the whole paper.

2 Principle of electronic differential auxiliary steering

2.1 Principle of electronic differential steering

Differential refers to that the internal and lateral wheels of the vehicle need to realize the speed difference to ensure the stable turning of the vehicle and avoid the rotation and drag of the wheels because of the situation of turning or unequal to the road during the driving [12, 13]. When the vehicle is steered, the wheels on both sides are on the arc track. And the driving path of the outside wheel is larger than the inner one [14, 15]. Therefore, the speed of the outer wheel must be larger than the inner wheel speed at the same time. Based on the principle of electronic differential and the application of hub motor in control, the design of electronic differential system with auxiliary steering function is possible. Because the hub motor can be controlled separately, different from the traditional mechanical differential system, the electronic differential system does not need conventional parts such as clutch, transmission, deceleration, and mechanical differential. Because the driving of two sides driven wheels is independent, electric wheel vehicle lack the constraint of traditional vehicle differential system. If the electronic differential is designed based on the speed control strategy, transmission constraint is needed to be imposed on the two independent driving wheels [16, 17]. An expectation is $n_1 = f(n_2)$, which denotes that the instability of wheel slip is avoided, this constraint is made to be matched with the road constraint. However, this control method is difficult to avoid and solve the complex and changeable problems of nonlinearity in vehicle system and road constraints, as well as hard to make the two constraints match accurately. Therefore, the rationality and accuracy of control strategy need to be discussed. Usually, the electrical differential control method is based on torque and slip rate control, which adds more consideration to both stability and control.

2.2 Kinematics and dynamics analysis of electric wheel-driven vehicle steering

In this section, the kinematics and dynamics of the vehicle steering process are analyzed. Through a series of formulas, the force situation of the steering wheel and the driving wheel is analyzed. Combined with the electronic differential steering principle, the necessity of the electronic differential control in the steering process of the vehicle and the auxiliary effect on the steering are explained in theory.

When the vehicle is running in a straight line on the road with uniform speed, the steering wheel moves parallel to the vehicle's running direction under the action of longitudinal horizontal thrust E_n. At this time, the thrust E_n of the steering wheel is balanced with the rolling resistance E_{nf} of the tire, that is, $E_n = E_{nf}$. When the vehicle is steered, the longitudinal horizontal thrust E_n' of the steering wheel can be decomposed into E_x and E_y, due to the steering angle δ of the steering wheel. The force E_x is used to overcome the rolling resistance E_{nf}' along the $x-x$ direction of the steering wheel, and the force E_y generates the road resistance E_y' along the $y-y$ direction.

In the steering, the following conditions need to be satisfied: The force E_x overcomes the rolling resistance E_{nf}' and E_y is less than the adhesion force between the pavement and the tire in the $y-y$ direction, which is to ensure no lateral slide in the $y-y$ direction and only rolling in the $x-x$ direction. Generally speaking, the adhesion force in the $y-y$ direction is much larger than the rolling resistance E_{nf}'. Therefore, there is no lateral slide in the $y-y$ direction. When the steering wheel moves steadily along the $x-x$ direction, the force E_x is balanced with the rolling resistance $E_{nf^{`}}$ of the tire. The rolling resistance $E_{nf^{`}}$ of the steering wheel moving along the $x-x$ direction and is considered equal to the rolling resistance E_{nf} when it moves before steering, that is, $E_{nf}=E_{nf^{`}}$. Then we have Eq. 1,

$$E_{n^{`}}=\frac{E_x}{\cos\delta}=\frac{E_n}{\cos\delta} \tag{1}$$

where δ is the steering angle, and $E_n<E_{n^{`}}$. It needs more longitudinal horizontal thrust $E_{n^{`}}$ than the horizontal thrust E_n required before steering when the vehicle is steered, so that the steering wheel will maintain stable rolling along the $x-x$ direction. The larger the deflection angle of the steering wheel, the greater the required longitudinal horizontal thrust is.

2.3 Force analysis on wheel speed of each drive wheel

In the process of vehicle steering, the motion state of every point on the vehicle body can be synthesized by linear motion and rotational motion. Due to the friction between the wheel and the ground, the turning resistance moment $N_{\mu f}$ of the steering wheel and the steering resistance moment $M_{\mu d}$ of the driving wheel are present in the steering process, as well as pass through the tires to the vehicle.

During the steering process, the vertical planes of the steering wheel and the driving wheel are subjected to the force E_{fy} and E_{dy}, respectively. Under the premise that the driving force E_D cannot balance the steering resistance moment, the steering torque is formed and its equilibrium is formed, which is expressed as Eq. 2.

$$E_D=E_{fy}\cdot\sin\alpha \tag{2}$$

The moment balance is taken in the midpoint of the rear drive wheel, then Eq. 3 is defined.

$$E_{fy}\cdot L\cdot\cos\alpha=N_{\mu f}+N_{\mu d} \tag{3}$$

Equation 3 can be simplified as Eq. 4.

$$E_{fy}=\frac{N_{\mu f}+N_{\mu d}}{L\cdot\cos\alpha} \tag{4}$$

The moment balance analysis of the steering center O is carried out. Then it is calculated by Eq. 5.

$$E_D\cdot R=N_{\mu f}+N_{\mu d}+E_{fd}+R^{'}\cdot E_{ff}\frac{R}{\cos\alpha} \tag{5}$$

Equation 5 can be simplified as Eq. 6.

$$E_D=E_{fd}+\frac{N_{\mu f}+N_{\mu d}}{R}+\frac{E_{ff}^{'}}{\cos\alpha} \tag{6}$$

When the vehicle runs in a straight line, that is, the deflection angle of the steering wheel is $\alpha=0$, the rolling resistance $E_{ff}^{'}$ of the steering wheel and the rolling resistance E_{fd} of the driving wheel have the driving force E_D, which is defined as Eq. 7.

$$E_D=E_{fd}+E_{ff} \tag{7}$$

Compared with Eqs. 6 and 7, it is known that the driving force of the driving wheel needs to be increased to overcome the steering resistance moment and drive the steering wheel to roll forward when the vehicle is running from straight line to steering.

2.4 Electronic differential abnormal jump interference suppression

First, the voltage control model of electronic differential system is used to eliminate the abnormal jump interference of electronic differential. The optimal combination parameters of electronic differential control are calculated. The steps of operation are as follows.

Assume the parameter that can describe the abnormal jump error of electronic differential is H, the signal error of electronic differential abnormal jump controlled by using this parameter is $i(t)$, abnormal jump rate of electronic differential is Hx and the expression is $ix(t)$, the variable control coefficient of the electron differential is K. Then the control model of electronic differential is expressed as Eqs. 8 and 9,

$$H=Ki(t) \tag{8}$$

$$Hc=Kix(t) \tag{9}$$

where $Kix(t)$ is coefficient of electron differential. Under the condition of abnormal jump of the electronic differential, the expression of the control rate of the electronic differential signal is calculated by Eq. 10.

$$Q=\beta H+(1-\beta)Hx \tag{10}$$

where β is the abnormal jump amplitude coefficient of electron differential, which is set to 1 in normal condition. In order to reduce the computational complexity, the Eq. 10 can be transformed as Eq. 11.

$$\beta=\beta_o+K_\beta|H||H|\max \tag{11}$$

where β_o is the abnormal jump adjustment coefficient of electronic differential in the case of $|H|=0$. When $0\le\beta\le0.5$ and $0\le\beta\le1$, K_β is a constant and $0\le K_\beta\le(1-\beta_o)$.

In Eq. 11, With the exception of the electronic differential jump, the electronic differential jump control error can be effectively calculated. The relationship between the control error i and u is unstable under the electronic differential jump.

A large number of electronic differential control data acquisition processes are determined by their data types as a starting point. When the system fixes judgment module according to the different file identifier suffixes, the system data processing module will initiate a transmission message tampering protection protocol to greatly improve the safe running time of the data after completing a large number of electronic differential control data types. When the data security time reaches the system operation requirement, the judgment module determines the specific collection method of each data according to the type of the protection protocol of the vehicle network data packet. If the car network data message tampering protection protocol, under the protection of TCP/IP network protocol, it can satisfy a large number of electronic differential control data base collection process, then the system will repair the security hole caused by the data by itself. The main reason why the system runs safely and can be greatly improved. The specific large amount of electronic differential control data acquisition process is shown in Fig. 1.

According to the obtained electronic differential control data, the electronic differential jump control parameters Δk_q, Δk_l, and Δk_f are analyzed. The obtained values of these parameters are normalized to the interval (−1, 1) under the environment of IoTs. The possible electronic differential jump control parameters in the electronic differential abnormal jump region with transformation are i', ix', Δk_q, Δk_l, and Δk_f is restricted by Eq. 12.

$$i', ix', \Delta k_q, \Delta k_l, \Delta k_f = \{-5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5\} \quad (12)$$

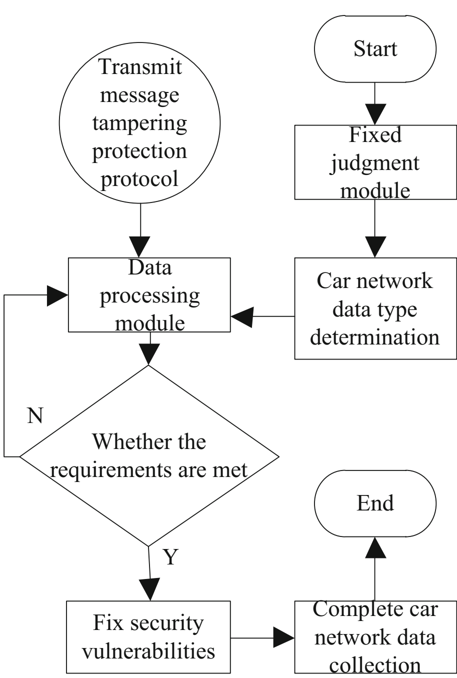

Fig. 1 Flow chart of data acquisition for vehicle

The fuzzy subset of these electronic differential abnormal jump control parameters changes is given by Eq. 13.

$$i', ix', \Delta k_q, \Delta k_l, \Delta k_f = \{NB, NM, NS, O, PS, PM, PB\} \quad (13)$$

According to Eq. 13, the electronic differential fuzzy standard table of the changed Δk_q, Δk_l, and Δk_f is set up. i', ix', Δk_q, Δk_l, and Δk_f obey normal distribution. In order to remove the influence of these changes, the abnormal jump of electronic differential is needed to be confirmed. The electronic differential control rule is set by designing the membership of the fuzzy variable of the electronic differential under the environment of IoTs. After the completion of the electronic differential control table, the degree of electronic abnormal jump can be quantified by looking up the table. The rule expression is given by Eq. 14.

$$\begin{cases} k_q' = \Delta k_q\left\{i', ix'\right\} \\ k_l' = \Delta k_l\left\{i', ix'\right\} \\ k_f' = \Delta k_f\left\{i', ix'\right\} \end{cases} \quad (14)$$

The variation rule of electronic differential control parameters i', ix', Δk_q, Δk_l, and Δk_f can be obtained by analyzing the abnormal jump of electronic differential. Then, the correlation control of these electronic differential control parameters is optimized to eliminate the abnormal jump interference of electronic differential.

In order to quantify the effect of electronic differential control parameters under the environment of IoTs, quantify the correlation between the parameters of the electronic differential control is needed to be quantified, which is expressed as Eq. 15,

$$J = \int_0^t t|i(t)|dt = \min \quad (15)$$

where J is the quantized results of precision of control signal, which is obtained through response time of the electronic differential control signal, control process, and electronic difference signal to noise ratio. In order to achieve electronic differential energy saving, the parameters of electronic differential control i', ix', Δk_q, Δk_l, and Δk_f are needed to be optimized. According to the optimal rule of the elimination of the abnormal jump interference factors of electronic differential under the environment of IoTs, the optimum parameters of the electronic differential control are arranged and adjusted to obtain the best value of the energy saving parameters. The optimal combination of electronic differential control parameters is given by Eq. 16.

$$\begin{cases} 0 \le \beta_o \le 0.5 \\ 0 \le K_\beta \le (1-\beta_o) \end{cases} \quad (16)$$

2.5 Adaptive torque balance electronic differential control for electric wheel-driven vehicle

According to the optimal combination of electronic differential control parameters, the adaptive torque balance electronic differential control of the electric wheel-driven vehicle is realized by using the fuzzy control of the active power and the reactive power of the electronic differential.

The resistance R and the reactance $X$of the electronic differential line are controlled and set as Eq.17.

$$R + jX = Z\frac{N_{CT}}{N_{PT}} \tag{17}$$

where Z is the equivalent impedance of controller to electronic differential load center, N_{CT} is the change ratio in the controller, N_{PT} is the change ratio of the electronic differential.

On the premise of not using the electronic differential adjustment equipment, the calculation of the power flow under the maximum load of the electron differential is carried out, and the equivalent impedance value of the output of fuzzy controller to the electronic differential PCC is obtained under the environment of IoTs, which is expressed as Eq. 18.

$$Z = \frac{V_{regulator} - V_{load}}{F_{line}} \tag{18}$$

where $V_{regulator}$ is the phasor of the electronic differential of the controller output, V_{load} is the phasor of the controller in the electronic differential load center, F_{line} is the phasor of the output of the controller.

Then the equivalent impedance between the controller output and the electronic differential bus is calculated and expressed as Eq. 19.

$$Z = \frac{V_1 - V_3}{F_1} = \frac{F_1Z_1 + F_2Z_2}{F_1} = Z_1 + \frac{F_2Z_2}{F_1} \tag{19}$$

where the number 3 represents the electronic differential load center, V is the electronic value of the controller output, V_3 is the differential of the electronic differential load center, and F_1 is the electronic differential of the controller output.

According to Eq. 19, analysis is carried out for the following 3 cases.

(1) If the system under the controller is not connected to the electronic distributed power DG, the direction of power flow of the controller is from the controller to the electronic differential load center. According to Eq. 19, it can be known that, the change of electronic differential load influences the change of F_2/F_1. When the load of electronic differential is changing, the equivalent impedance Z_{13} of the controller is also changing.

(2) (2) If the electronic differential bus 2 is connected to the electronic distributed power DG, when the electronic distributed power DG is high permeability, it is possible that DG at the electronic differential bus 2 can supply the power supply to the upstream power grid at the same time that the downstream load of the electronic differential is satisfied. F_1 and F_2 are almost reverse. It makes that the equivalent impedance of the actual controller is much smaller than the equivalent impedance of the electronic differential maximum load, resulting in the failure of the electronic compensation circuit.

(3) If the electronic differential bus 1 is connected to the electronic distributed power DG, when the electronic distributed power DG is high permeability, the electronic differential bus 2 may become the power point of the controller feeder. F_1 and F_2 are almost reverse. Like the case 2, the control performance of the electronic compensation circuit is also invalid.

From the above 3 cases, when the electronic differential power supply DG with high permeability connected to electronic distribution network under the fuzzy controller causes the reverse power flow under the environment of IoTs, the controller can control the voltage amplitude of the electronic differential load center accurately. The purpose of the adaptive torque balance electronic differential control of electric drive wheel vehicle is achieved.

3 Experimental results and analysis

The electronic differential control platform is set up, and the electronic differential control experiment is carried out with the bench. Each driven wheel is powered by a 72 V power battery pack. The signal is input through an electronic throttle. The rotational speed of the left and right motor is adjusted to 200 r/min. At time t = 3 s, the steering signal is input to the steering wheel, and the steering angle is from 0°to 60°in 1 s. The electronic throttle signal and steering wheel corner signal are replaced by two knobs. The analog amount of the electronic throttle signal is 0~5 V. The simulation of steering wheel angle signal is −5~5 V. The main parameters of the controller are shown in Table 1.

The car accelerates straight to 20 km/s and runs at constant speed. At time t = 3 s, the experimenter left the steering wheel at 60°in 1 s, as shown in Fig. 2. Keep the electronic throttle opening unchanged and make steady steering. Finally, the curves of wheel torque and speed change with time are obtained. The speed and torque of the driving wheel can be displayed by the torque power meter. The test results of wheel speed and torque change with time are shown in Figs. 3 and 4, respectively.

Table 1 Parameters of the controller

Name	Value	Unit
Rated voltage	24	V
Rated current	2.5	A
Rated torque	100	Nm
Slip power	8	kw

From the above figures, it can be seen that there is a certain error in the process of driver steering wheel, and it is difficult to achieve precise control of steering wheel angle under the environment of IoTs. But it follows the target steering wheel angle. There is a certain error between the torque and speed of the left and right driving wheels and the simulation results when the vehicle speed is stable near 20 km/h. But the variation of their values is basically the same, achieving the basic functions of differential speed and differential torque. The real vehicle test provides foundation for further research on the auxiliary steering and vehicle stability control based on the electronic differential control.

4 Conclusions

The Internet of Vehicles is the specific application of the Internet of Things in urban transportation, while the automobile is the terminal carrier of the Internet of Vehicles technology. It consists of a network of vehicles that collect and process various dynamic data through wireless communication to realize information interaction between cars, between cars and buildings, and between cars and other public facilities, so that cars can be integrated into cities. In the network, the owner can communicate with the information center without interruption through wireless communication, realizing a series of functions such as real-time navigation, fault diagnosis, safe driving, entertainment communication, etc., and making the car more humanized under the support of the Internet of Vehicles technology.

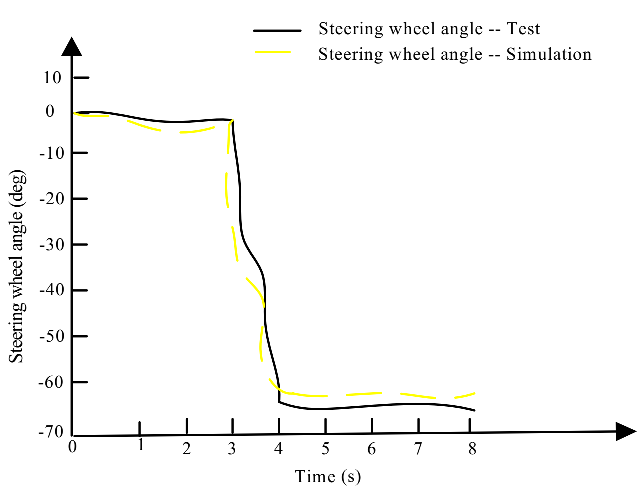

Fig. 2 Steering wheel angle

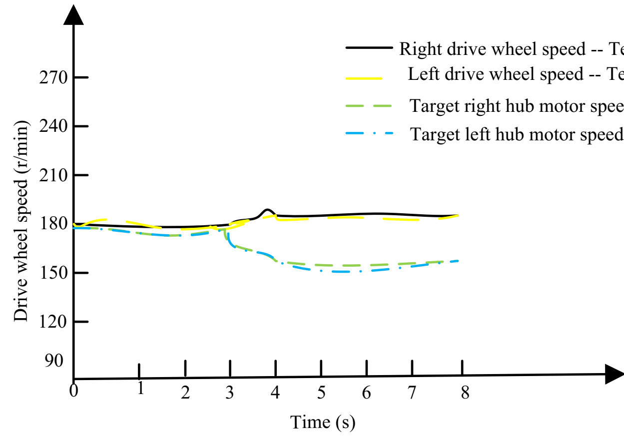

Fig. 3 Left and right wheel speed

Based on the rear wheel independent driven electric vehicle, a control strategy is well implemented in the test vehicle with the development of electronic differential steering control. This proposed method provides the foundation for further control strategy research.

The dynamics and kinematics of electric wheeled vehicle are analyzed by the principle of electronic differential speed under the environment of IoTs. From the test, it is found that the proposed method can suppress the abnormal jump interference of electronic differential control and achieve the basic functions of differential speed and differential torque. The control effect of the torque and speed of the driving wheel is better. It will lay a theoretical foundation for further research on the effect of electronic differential on vehicle steering and driving.

The further researches are as follows.

(1) Multi-objective integrated control is applied to the steering process of electric wheels, so as to achieve

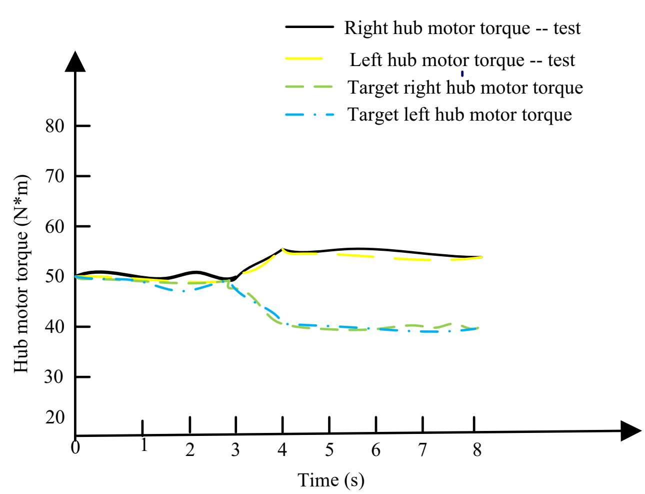

Fig. 4 Left and right hub motor speed

hierarchical control for low speed steady state steering and high speed steering.

(2) A simpler and faster response model is built. The torque of driving wheel is controlled to realize the differential function of low speed steering. The steering characteristics and excessive steering and insufficient steering are modified to improve steering path following ability and driving stability.

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