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Electronic Differential Speed Steering Control for Four In-wheel Motors Independent Drive Vehicle*

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***Abstract* - Study all-wheel steering control strategy of electronic differential speed for four in-wheel motors independent drive vehicle. According to kinematics of steering, a dynamics model of three degrees-of-freedom steering is established, and a control system of electronic differential speed for four in-wheel motors independent drive is proposed. A comprehensive control strategy of speed and torque based on Neural Networks PID electronic differential is proposed to calculate object speed of four wheels. Four PID controllers are used to achieve torque distribution on four in-wheel motors, to realize electronic differential speed steering. The simulation results with different reference steering angle and velocity indicate that the strategy can improve the steering maneuvering and stability of vehicle in a low speed.**

Index Terms - In-wheel motor, Independent drive, All wheel steering, Electronic differential.

Gearbox, retarder, differential and steering mechanism are canceled from the four in-wheel motors independent drive vehicle. So it has flexible layout and efficient transmission system. Using four in-wheel motors independently to drive four driving wheels, while electronic differential speed controls the speed and torque of the four driving wheels, then steering of the vehicle is achieved. The strategy of electronic differential speed control is a technological difficulty of vehicle steering. Most researches on electronic differential speed control are combined with the Ackerman model of steering kinematics, and coordinate the control for speed or torque of the four in-wheel motors[1]. If speed control alone is used in steering, the degree of freedom of the vehicle would decrease and the maneuvering would become worse[2]; If torque control alone is used in steering, the stability would become worse[3]. In order to raise vehicle maneuvering in low speed and stability in high speed, in this paper, based on the Ackerman model of steering kinematics and the three DOF model of kinematics, and combined with driving motors' controlling characteristic. Research on the electronic differential speed steering control strategy for four in-wheel motors independent drive vehicle is performed to verify rationality of this method by simulation.

I. ANALYSIS OF ELECTRONIC DIFFERENTIAL SPEED STEERING

A. Analysis of steering Kinematics

According to the Ackermann-Jeantand mode of steering run when vehicle is running in low speed, as be shown in Fig.1, L is the distance between front and rear wheel, w is the distance between left and right wheel, δ is steering angle.

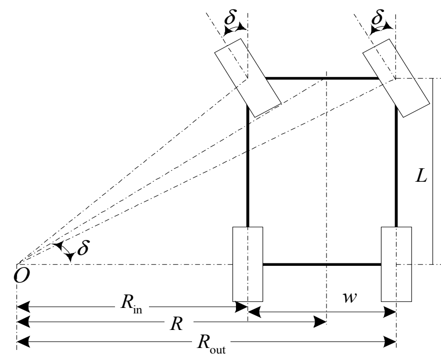

Fig.1 Ackermann-Jeantand steering model.

Ignore the centrifugal force of steering driving and the affect of tires' side slip, static analysis of vehicle steering is performed. Because the four outer rotor in-wheel motors are connected with the four driving wheels directly, the speed of the four motors is equal to the speed of the four driving wheels. The distributive relationship among the speed of the four driving wheels v_{fl}、v_{fr}、v_{rl}、v_{rr} is expressed as:

$$\begin{aligned} v_{fl} &= v(1 - w\tan\delta_{fl}/L) \\ v_{fr} &= v(1 + w\tan\delta_{fr}/L) \\ v_{rl} &= v(1 - w\tan\delta_{rl}/2L) \\ v_{rr} &= v(1 + w\tan\delta_{rr}/2L) \end{aligned} \tag{1}$$

Where v is the vehicular velocity, $\delta_{fl}, \delta_{fr}, \delta_{rl}, \delta_{rr}$ are the four wheels' steering angle. Suppose $\delta_{fl} = \delta_{fr} = \delta_{rl} = \delta_{rr} = \delta$. According to (1), $v_{fl}, v_{fr}, v_{rl}, v_{rr}$ are the variable of v and δ, and change with the change of v and δ.

The Ackermann-Jeantand model expresses the kinematic geometrical relation of inner and outer wheels when steering. The speed distributive relationship is achieved by balancing the force of the four wheels. In general, this model is often used in analyzing the vehicular steering with two driving wheels to realize harmonious speed controlling. There is a certain limitation in this model in steering dynamics, so analyzing the vehicular steering with four independent driving wheels must be analyzed.

B. Analysis of Steering Dynamics

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The entire vehicle model usually includes longitudinal, latitudinal and vertical translation motion and rotation around the three perpendicular axis' six DOF model. The vertical motion, pitch motion and side tilt motion are supposed to be ignored, analyzing the characteristic of four driving wheel vehicle. The initial point of the vehicular motion coordinates is fixed to the vehicular centre of mass and steering wheel's angle is proportional with the steering angle. x axis is attached to the direction of the longitudinal translation motion, y axis is attached to the direction of the latitudinal translation motion, and z axis is attached to the yaw motion, establish a three DOF dynamic model for four wheel driving, as be shown in Fig.2.

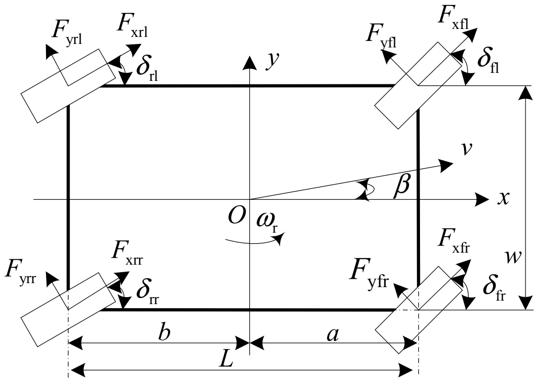


Fig.2 Four-wheel drive dynamics model.

Longitudinal motion equation:

$$\begin{aligned}&F_{\mathrm{xfr}}\cos\delta_{\mathrm{fr}}-F_{\mathrm{xrr}}\cos\delta_{\mathrm{rr}}-F_{\mathrm{yfr}}\sin\delta_{\mathrm{fr}}-F_{\mathrm{yrr}}\sin\delta_{\mathrm{rr}}+\\&F_{\mathrm{xfl}}\cos\delta_{\mathrm{fl}}-F_{\mathrm{xrl}}\cos\delta_{\mathrm{rl}}-F_{\mathrm{yfl}}\sin\delta_{\mathrm{fl}}-F_{\mathrm{yrl}}\sin\delta_{\mathrm{rl}}=m\dot{v}\cos\beta\end{aligned} \tag{2}$$

Latitudinal motion equation:

$$\begin{aligned}&F_{\mathrm{xfr}}\sin\delta_{\mathrm{fr}}+F_{\mathrm{xrr}}\sin\delta_{\mathrm{rr}}+F_{\mathrm{yfr}}\cos\delta_{\mathrm{fr}}-F_{\mathrm{yrr}}\cos\delta_{\mathrm{rr}}+\\&F_{\mathrm{xfl}}\sin\delta_{\mathrm{fl}}+F_{\mathrm{xrl}}\sin\delta_{\mathrm{rl}}+F_{\mathrm{yfl}}\cos\delta_{\mathrm{fl}}-F_{\mathrm{yrl}}\cos\delta_{\mathrm{rl}}=m\dot{v}\sin\beta\end{aligned} \tag{3}$$

Yaw motion equation:

$$\begin{aligned}&a(F_{\mathrm{xfr}}\sin\delta_{\mathrm{fr}}+F_{\mathrm{yfr}}\cos\delta_{\mathrm{fr}})-b(F_{\mathrm{xrr}}\sin\delta_{\mathrm{rr}}+F_{\mathrm{yrr}}\cos\delta_{\mathrm{rr}})+\\&a(F_{\mathrm{xfl}}\sin\delta_{\mathrm{fl}}+F_{\mathrm{yfl}}\cos\delta_{\mathrm{fl}})-b(F_{\mathrm{xrl}}\sin\delta_{\mathrm{rl}}+F_{\mathrm{yrl}}\cos\delta_{\mathrm{rl}})=J\ddot{\varphi}\end{aligned} \tag{4}$$

Where J is inertia moment of body, m is vehicle mass, a,b are the distance between body centre of mass and front/rear wheel axis respectively, β is the slide slip angle, φ is the yaw angle, $\omega_{\mathrm{r}}=\dot{\varphi}$ is yaw angular velocity. $F_{\mathrm{xfl}},F_{\mathrm{xfr}},F_{\mathrm{xrl}},F_{\mathrm{xrr}}$ are the longitudinal force of the front-left, front-right, rear-left, rear-right wheel; $F_{\mathrm{yfl}},F_{\mathrm{yfr}},F_{\mathrm{yrl}},F_{\mathrm{yrr}}$ are the lateral force of the front-left, front-right, rear-left, rear-right wheel respectively.

From (2)-(4), it is easy to see that the four wheels force model is a nonlinear system with multiple inputs and multiple outputs. Therefore it is really difficult to distribute torque for the four in-wheel motors by precise calculation, and the classical PID control is very hard to meet the demand of steering maneuvering. According to the given steering angle and velocity, comprehensive electronic differential speed controller is used in this paper to calculate four wheels' objective speed and four neural networks PID controllers are used to distribute torque to the four in-wheel motors coordinately.

II. ELECTRONIC DIFFERENTIAL SPEED CONTROL METHOD

A. Structure of Electronic Differential Speed Control System

An electronic differential speed control system is established as shown in Fig.3 to calculate the speed difference and control the torque distribution for the four in-wheel motors. Power battery pack and engine generator set would together in parallel supply the energy convertor, then power the DC power bus through the energy convertor. When the voltage on the bus goes beyond the limitation, the energy absorber begins to work and absorb the redundant energy. Comprehensive electronic differential speed controller would calculate vehicular velocity v, steering angle δ, four wheels steering angle $\delta_{\mathrm{fl}},\delta_{\mathrm{fr}},\delta_{\mathrm{rl}},\delta_{\mathrm{rr}}$ and four wheels velocity $v_{\mathrm{fl}},v_{\mathrm{fr}},v_{\mathrm{rl}},v_{\mathrm{rr}}$ according to the signal from steering wheel and pedal. The comprehensive controlling strategy based on neural networks PID is used to perform speed-torque coordinate control of electric differential. Torque signals on the CAN bus would be sent to the four motors controller to control the four driving wheels' torque to realize the vehicular electronic differential speed control continuous steering.

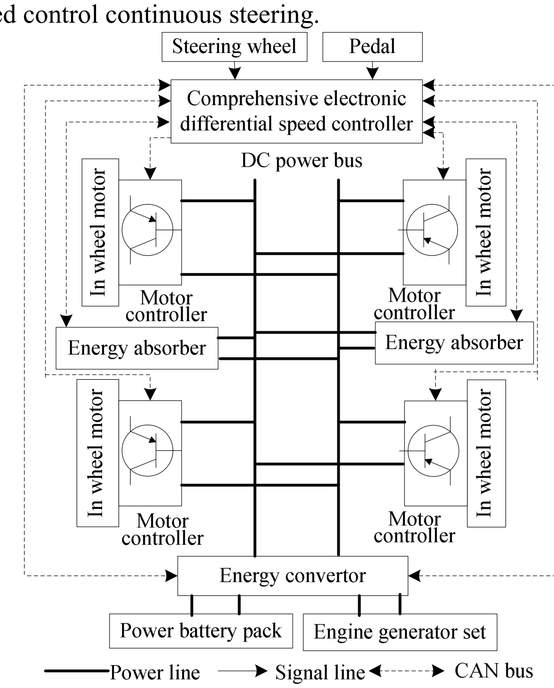


Fig.3 Electronic differential speed control system.

B. Strategy of Neural Networks PID Differential Speed Control

1) Neural Networks PID: Neural networks PID controller adopt three layers nerve cell structure network shown in Fig.4, sigmoid function using the controller out layer's output can be expressed as:

$$T_{j,\mathrm{ref}}=u_j=f_j(x)=\frac{1}{a(1+e^{-\mathrm{ax}})}\quad j=1,2 \tag{5}$$

Input of the output layer is:

$$x(t)=k_{pj}(t)e_{pj}(t)+k_{ij}(t)e_{ij}(t)+k_{dj}(t)e_{dj}(t) \tag{6}$$

Where k_{pj}, k_{ij}, k_{dj} are the coefficient of proportion, differential and integral respectively, they are the power coefficient of neural networks PID. e_{pj}, e_{ij}, e_{dj} are the inputs of three layers neural networks, $e_{pj}(t)=\omega_{j,\mathrm{ref}}(t)-\omega_j(t)$, ω_j is angular velocity, $e_{ij}(t)=\int_0^t e_{pj}(t)dt$, $e_{dj}(t)=de_{pj}(t)/dt$.

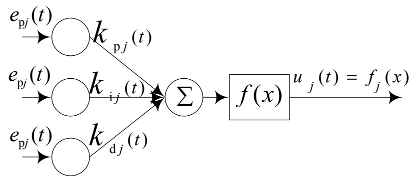


Fig.4 Structure block diagram of neural networks PID.

Reverse spread method is adopted to perform online self-learning training to make error $e=[e_{p1},e_{p2}]^{\mathrm{T}}$ approach zero, the root-mean-square performance function is expressed as:

$$E_j(t)=\frac{1}{2}(e_{pj}(t))^2$$

(7)

Adopt grads descend method, modify power coefficient[5]:

$$\begin{cases} k_{pj}(t)=k_{pj}(0)-\eta_{pj}\int_0^t \frac{\partial E_j(t)}{\partial k_{pj}}dt, \\ k_{ij}(t)=k_{ij}(0)-\eta_{ij}\int_0^t \frac{\partial E_j(t)}{\partial k_{ij}}dt, j=1,2 \\ k_{dj}(t)=k_{dj}(0)-\eta_{dj}\int_0^t \frac{\partial E_j(t)}{\partial k_{dj}}dt. \end{cases} \tag{8}$$

Where $\eta_{pj}, \eta_{ij}, \eta_{dj}$ are the learning rates, determine the speed of constringency.

According to (5)-(8), we can derive the followings:

$$\begin{cases} k_{pj}(t)=k_{pj}(0)-\eta_{pj}\int_0^t e_{pj}(t)e_{pj}(t)\frac{e^{-ax})}{(1+e^{-ax})^2}dt, \\ k_{ij}(t)=k_{ij}(0)-\eta_{ij}\int_0^t e_{pj}(t)e_{ij}(t)\frac{e^{-ax})}{(1+e^{-ax})^2}dt, j=1,2 \\ k_{dj}(t)=k_{dj}(0)-\eta_{dj}\int_0^t e_{pj}(t)e_{dj}(t)\frac{e^{-ax})}{(1+e^{-ax})^2}dt. \end{cases} \tag{9}$$

From (9), according to e_{pj}, e_{ij}, e_{dj} calculated online, neural networks PID controller would do the online self-learning training through front feedback networks reverse spread to make motor speed error $e=[e_{p1},e_{p2}]^{\mathrm{T}}$ close in upon zero, modify the power coefficient k_{pj}, k_{ij}, k_{dj} online, control the output motors given toque in real time, obtain the vehicular velocity and steering angle expected by driver at last.

2) Comprehensive Control of Electronic Differential Speed and Torque: Steering wheel's angle is proportional with the steering angle, the steering wheel's angle displacement signal is corresponding to the steering angle δ_{ref} expected by driver, and the range of steering wheel's angle is [-60°, +60°]. Accelerating pedal displacement signal is corresponding to the vehicular velocity v_{ref} expected by driver, and the range of pedal angle displacement is [0, +45°].

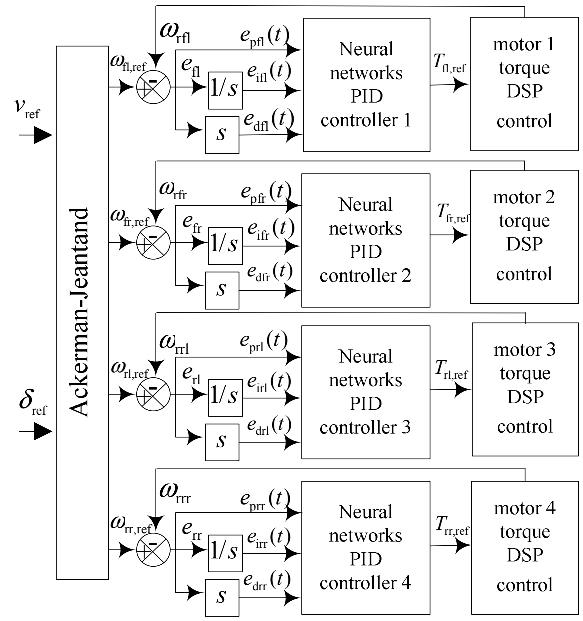


Fig.5 comprehensive control strategy of speed and torque based on Neural Networks PID electronic differential.

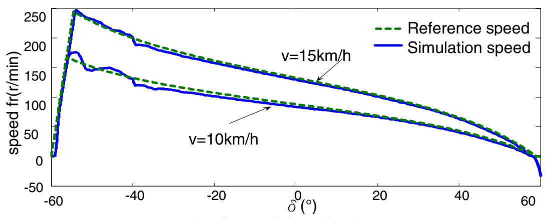
Comprehensive coordinately control strategy of speed and torque is adopted for four in-wheel motors independent driving vehicular steering, as be shown in Fig.5. The strategy is realized by comprehensive electronic differential. Based on v_{ref} and δ_{ref} , comprehensive electronic differential calculates the four in-wheel motors' steering angular speed $\omega_{\mathrm{fr,ref}}, \omega_{\mathrm{fl,ref}}, \omega_{\mathrm{rr,ref}}, \omega_{\mathrm{rl,ref}}$, then compares them in real time with simulation $\omega_{\mathrm{fr}}, \omega_{\mathrm{fl}}, \omega_{\mathrm{rr}}, \omega_{\mathrm{rl}}$ collected by four motors' rotor position sensor. Adopted four NNPID controllers to make motors' speed error $e=[e_{\mathrm{pfr}}, e_{\mathrm{pfl}}, e_{\mathrm{prr}}, e_{\mathrm{prl}}]^{\mathrm{T}}$ approach zero, and generates the four motors' reference torque $T_{\mathrm{fr,ref}}, T_{\mathrm{fl,ref}}, T_{\mathrm{rr,ref}}, T_{\mathrm{rl,ref}}$. Which are distributed to the four motor controllers by CAN bus in real time.

III. ANALYSIS OF SIMULATION RESULT

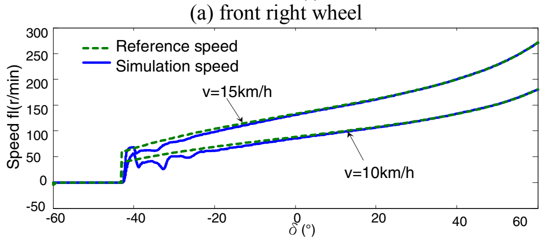
Digital signal processor DSPTMS320LF2812 is adopted in comprehensive electronic differential to realize the comprehensive control strategy of electronic differential speed and torque shown in Fig.5. Modeling and simulating is performed in Simulink of Matlab. External rotor brushless motor is adopted as in-wheel motor with rated power 2kW, rated speed 1000r/min, rated torque 20N · m. DSPTMS320LF2812 is used to realize direct torque control algorithms, thus realize the control of motor torque.

Assume given vehicular velocity are 10km/h and 15km/h respectively, while steering wheel's angle change from -60° to +60°, the changing curves of the four in-wheel motors' simulation speed and given speed are shown in Fig.6 and

Fig.7, Curves of speed difference between front wheels and between rear wheels are shown in Fig.8 and Fig.9. It can be drawn from Fig.6 and Fig.7 that there is obvious speed difference between left and right wheels, the speed of the two rear wheels is lower than the speed of the two front wheels, the changing rule of the four wheels speed and the theoretical analysis are consistent. From Fig.8 and Fig.9, it can be drawn that accompany with the increase of vehicle speed and direction angle, speed difference become bigger and speed difference between two rear wheels is smaller than it between two front wheels. In addition, there is a certain error between the motors' simulation speed and given speed, the error is quite big at the beginning of start-up, it become small gradually after regulated by NNPID comprehensive control strategy, and the output of speed is relatively stable.

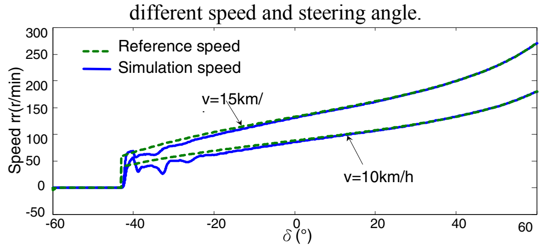


(a) front right wheel

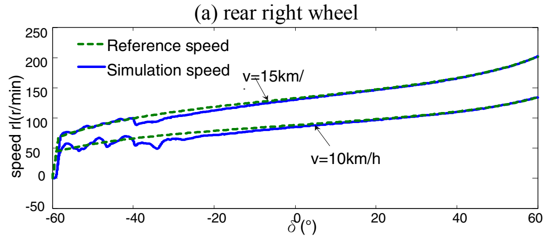


(b) front left wheel

Fig.6 Curves of speed difference between right and left front-wheel with different speed and steering angle.



(a) rear right wheel



(b) rear left wheel

Fig.7 Curves of speed difference between right and left rear-wheel with different speed and steering angle.

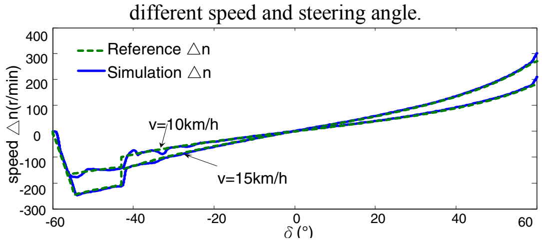


Fig.8 Curves of speed difference between right and left front-wheel with different speed and steering angle.

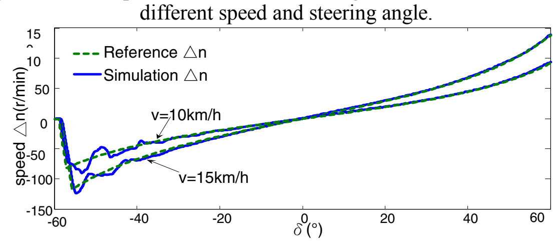


Fig.9 Curves of speed difference between right and left rear-wheel with different speed and steering angle.

IV. CONCLUSION

The three DOF steering dynamics model of the four in-wheel motors independent driving vehicle is a nonlinear system with multiple inputs and multiple outputs. The comprehensive control strategy which based on neural networks PID control electronic differential speed speed-torque is adopted to distribute torque to the four in-wheel motors coordinately. The results of simulation indicate that the control strategy is feasible and reasonable.

Motor's control properties can affect vehicular steering properties directly, therefore the four in-wheel motors independent driving vehicle should adopt motors and motor controllers with high control properties. Electronic differential speed control strategy should combine with motor control strategy to make optimization and perfection in order to meet the requirement of vehicular steering properties.

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