Differential Control Strategy Research of Wheeled Electric Drive ADT Mining Truck

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Abstract: Aiming at the special structure and steering characteristic of wheeled electric-driven articulated underground mining truck, a differential control strategy which takes the equal slip rate as control target was given. The kinematic and dynamic model of electric-driven mining ADT was established and the movement relationship and stress condition of the driving wheels were analyzed during steering. Acceleration sensors in the sample ADT were used to test the actual speed of the vehicle. Results show that the filtered signal has small delay and fast response and can be directly used to estimate the speed. Equal slip rate control strategy is superior to equal torque control strategy because it can make full use of the ground adhesion coefficient and reach reasonable distribution of drive power. Two sides wheel slip rate can be stable -0.08 and sliping situation is avoided in experimental turning. This control strategy has practical effect for reducing tire wear and improving driving power utilization.

1 NTRODUCTION

The operating condition of articulated underground mining trucks is complex, such as narrow road,more corners, wet and slippery ground, and the vehicle body load quality is large. In order to adapt to the narrow underground environment, articulated steering of front and rear body is used, and full wheel drive is used to increase traction force. The 35t wheeled electric-driven articulated underground mining truck is newly developed by University of Science and Technology Beijing,which is the only one using diesel-electric power at home and abroad, wheel drive, and independent control of each drive wheel torque and speed.

Unlike mechanical transmission, there is no differential mechanism on the wheeled electric-driven vehicle. In order to ensure that there is no sliping between the drive wheels during steering, the vehicle loses ground traction and excessive tire wear (Liu Weixin, 2001; M Canale, L Fagiano, M Milanese, et al, 2007; YU Houyu, Huang Miaohua, 2011; Wang Junnian, Wang Qingnian, Song Chuanxue, et al, 2010) It is necessary to adopt accurate model and effective strategy for differential control. Differential control is one of the key technologies for the design of wheeled electric-driven vehicle.

There are many researches on electronic differential control in passenger cars (Li Bin ,Yu Fan, 2008; A G Nalecz, A C Bindemann, 2003; Y H Ge, C S Li, G Z Ni, 2003) ,they established kinematics relationship of each drive wheel mainly through the Ackerman model to control the wheeled electric motor and developed differential control strategy (Fredriksson, Andreasson, Laine, 2004; Umesh Kumar Rout, et.al, 2013; Zhang Daisheng, Li Wei, 2002; Wang Renguang, Liu Zhaodu, Qi Zhiquan,et al, 2007). At present, the rear wheel drive is used for wheeled electric-driven underground mining truck at home and abroad, and the steering differential adopts the equal-torque control strategy. The equal-

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torque control strategy can not meet the requirements of the vehicle's passing ability on a complex roads, and it is prone to inconsistent operation between the wheels, which consumes additional power and wears the tires, resulting in deterioration of steering and handling performance. Therefore, it is necessary to put forward the driving control strategy with sliding rate as the control target, coordinate and control the driving force of each wheel, and avoid the above situation. The control strategy with consistent slip rate needs to calculate the slip of each wheel by monitoring the vehicle speed and the driving wheels ' rotational velocity, and then control the torque to adjust the slip rate of each drive wheel ,so that they tend to be consistent(Shen Jun,Song Jian,Wang Huiyi, 2007). And for full-wheel drive articulated electric-driven vehicles, how to obtain accurate absolute speed is also a key issue, and now there is no good solution for such articulated vehicles.

Taking the steering condition of 35t wheeled electric-driven articulated underground mining truck as the research object, this paper establishes kinematics and dynamics model of the vehicle, and analyzes the relationship between every wheel's rotation speed and torque. The longitudinal acceleration of the prototype is tested with the acceleration sensor in real time and Kalman filter is used to obtain the effective absolute speed of the vehicle. A multi-body dynamics simulation platform including steering wheel angle input model, wheeled electric drive model and underground mine vehicle virtual prototype model were established, and a joint simulation of vehicle steering differential conditions was carried out with the sliding rate controller , takes the equal slip rate as control target. And the results of equal torque control strategy are compared and analyzed.

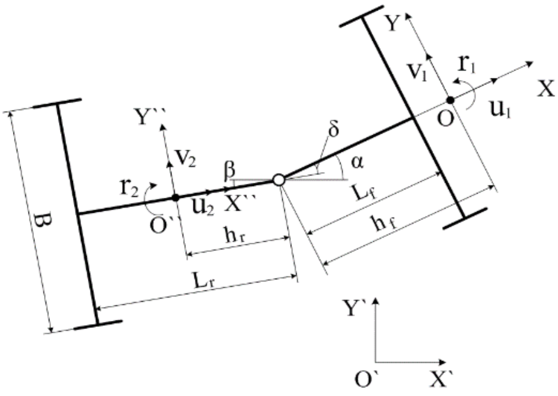

Figure 1. Vehicle kinematic model.

2 MATHEMATICAL MODEL ESTABLISHMENT

2.1 Kinematics Model

In order to accurately describe the slide rate of each wheel, a vehicle kinematics model needs to be established. As shown in Fig 1, the coordinate system O′X′Y′Z′is an absolute coordinate system fixed on the ground. OXYZ and O″X″Y″Z″are the dynamic coordinate systems whose coordinate origin is fixed on the center of mass of the front and rear vehicle bodies respectively. X, X″ axles coincide with the longitudinal axes of the front and rear bodies, and δ denotes the angle between the front and rear bodies.B denotes the distance between the front and rear body, Lf denotes the distance between the front wheel center and the hinged joint, Lr denotes the distance between the rear wheel center and the hinged joint, denotes is the distance between the front body mass center and the hinged joint, and hr denotes the distance between the rear body mass center and the hinged joint. u1, v1, r1 denote the the front car body's longitudinal velocity, transverse velocity, and transverse angle velocity around the Z axis respectively, while u2, v2, r2 denote the the rear car body's longitudinal velocity, transverse velocity, and horizontal angle velocity around the Z″ axis respectively. The sum of r1 and r2 denotes the angle change rate between the front and rear bodies, that is

$$\dot{\delta} = r_1 + r_2 \tag{1}$$

From the motion relationship of each wheel, regarding the steering angle as a known parameter,

$$u_{fl} = (1 - \frac{B}{2L_f \cot\delta + 2L_r\sqrt{1+\cot^2\delta}})u_1 \tag{2}$$

uflu$_{\mathrm{fl}}$, ufr, url, urr denote longitudinal velocity of the center of the left front wheel, right front wheel, left rear wheel and right rear wheel respectively. And derive the slip rate expression of the wheels

$$S_{fl} = \frac{wR - (1 - \frac{B}{2L_f \cot\delta + 2L_r\sqrt{1+\cot^2\delta}})u_1}{wR} \tag{3}$$

Sflu$_{\mathrm{fl}}$, Sfr, Srl, Srrs$_{\mathrm{fl}}$s$_{\mathrm{fr}}$ denote the slip rate of the left front wheel, right front wheel, left rear wheel and right rear wheel respectively. w denote the wheel angular speed to define the speed, and propose the accurate method of estimationing the speed .

2.2 Dynamic Model

The dynamic model of wheeled electric-driven articulated underground mining truck is established to analyze the force relationship between the vehicle and the ground, so as to control the torque of the wheeled traction motor and monitor the speed of the wheel side. Select 3 degrees of freedom for longitudinal, lateral, and yaw-moment to establish a vehicle dynamics model, as shown in Figure 2.

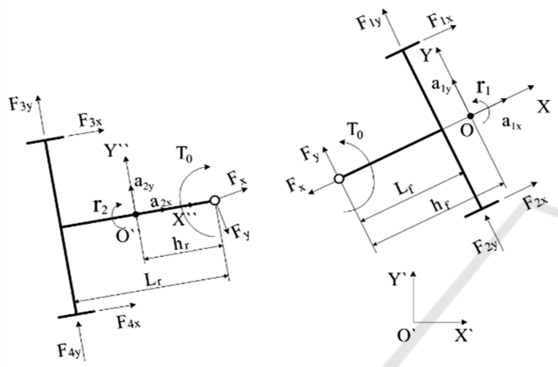

Figure 2 .Vehicle dynamic model.

In Fig 2, a1x and a1y are the acceleration along the X axis and the Y axis at the center of the front body; a2x, a2y are the accelerations along the X″ axis and the Y″ axis at the center of the rear body; Fix, Fiy denote the tangential and lateral forces face the i wheel respectively(i = 1,2,3,4); To is the steering internal torque between the front and rear bodies; Fx and Fy are the forces of the hinged point along the X axis and the Y axis, respectively.

Based on the relative relationship between the front and back of the vehicle body in Fig 2, considering the parameters such as the quality characteristics, acceleration, and moment of inertia of the vehicle, derive the torque balance equation of the vehicle body around the X, Y, Z, X″, Y″, and Z″ axes.

$$I_{zz1}\dot{r}_1 = T_0 - (F_{1y} + F_{2y})(h_f - L_f) + (F_{2x} - F_{1x})\frac{B}{2} - F_y h_f \quad (4)$$

$$I_{zz2}\dot{r} = T_0 + (F_{3x} - F_{4x})\frac{B}{2} - (F_{3y} + F_{4y})(h_r - L_r) + (F_y \cos\delta - F_x \sin\delta)h_r \quad (5)$$

$$m_2(\dot{u}_2 - r_2 v_2) = F_x \cos\delta + F_y \sin\delta + F_{3x} + F_{4x} \quad (6)$$

$$m_2(\dot{v}_2 + r_2 u_2) = F_x \sin\delta - F_y \cos\delta + F_{3y} + F_{4y} \quad (7)$$

From the results of formula, it is known that adjusting the driving force of each wheel and the articulated angle of the front and rear body can control the longitudinal lateral speed of the vehicle body during the steering and change the sliding rate of each drive wheel. However, The above relationship can not accurately describe the quality characteristics of the vehicle itself under dynamic conditions, and the calculation of slip rate is not accurate enough. Subsequent numerical analysis uses multi-body dynamics software to consider the impact of the quality characteristics and operating status of the vehicle on the slip rate.

3 MULTI-BODY DYNAMICS MODEL ESTABLISHMENT

The articulated truck tire is the only part that connects the body and the road. Its force, deformation and motion response have a great influence on the movement of the vehicle. The traditional mathematical model is difficult to describe the characteristics of the vehicle-tire-road coupling model accurately. On the basis of vehicle kinematics, this paper uses multi-body dynamics software to consider the quality characteristics and operation status of the vehicle. The shading and rendering model is shown in Fig 3. Combined with the above analytical dynamics, the force and torque of the tire in contact with the ground are calculated using the UA tire model, which accurately reflects the slide rate and realizes the driving control effect.

The vehicle drive model joint simulation is performed with the multi-body dynamics model, including the motor drive model and the steering wheel input model. The output torque of the motor drive model drives the wheel, and the actual wheel speed is fed back to each motor drive model by the model. The rigid connection between the motor and the wheel is simulated, and the deceleration and torsion are carried out through the wheel side reducer model. The line displacement of the steering cylinder and the driving torque of the wheel are used as the vehicle control signals to simulate the steering wheel angle and throttle pedal input when the driver drives the vehicle. The output of the model is the vehicle operating state parameters, including speed, steering angle, wheel speed, slip rate, etc.

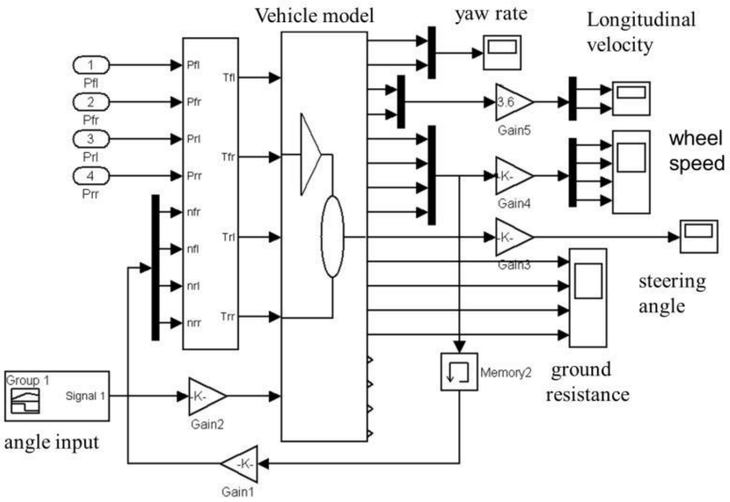

Figure 3 .Vehicle driving model.

4 CONTROL STRATEGY BASED ON CONSISTENT SLIP RATE

The former mentioned vehicle driving model is also a framework for adopting different strategies for control and analysis. The consistent slip rate control strategy is to allocate torque and power according to the slip rate's changes of each wheel under different conditions (Chen Dong, Xu Yin, Liang Huajun, 2013; Wang Renguang, LiuZhaodu, Qi Zhiquan, et al, 2006) .In this paper, the average slip rate of four wheels of articulated vehicles is taken as the target slip rate, the target slip rate and the slip rate of each wheel is transmitted to the power distribution module in real time. Power distribution module based on the deviation of per wheel's actual slip rate from Target slip rate. Calculate the power and speed that each wheel should allocate, adjust the torque and speed of each wheel through the motor drive module, and control that the sliding rate of each wheel is within ideal range and eventually tends to be the same. The control flow is shown in Fig 4.

5 TEST ANALYSIS

5.1 Real Vehicle and other Torque Control Test

In order to evaluate the application effect of the control strategy, the actual vehicle test and joint simulation were carried out. In the test, comprehensive speed estimation and analysis is carried out, which fully reflects the acceleration, deceleration and uniform speed. The design test vehicle is gradually accelerated after 5s start. After reaching the stable speed, it will travel at a constant speed along the fixed circumference and keep the steering wheel angle for two turns. Once again, the vehicle is slowly and continuously accelerated, and after the limit safety speed, the vehicle is slowly braked to reduce the speed until the vehicle stops, and the test is over. The entire process includes acceleration, turning, uniform steering and deceleration. Fig 6 and Table 1 show the test vehicle and vehicle assembly parameters respectively. Fig 5 shows the obvious trace of the circular car mark on the cement road.

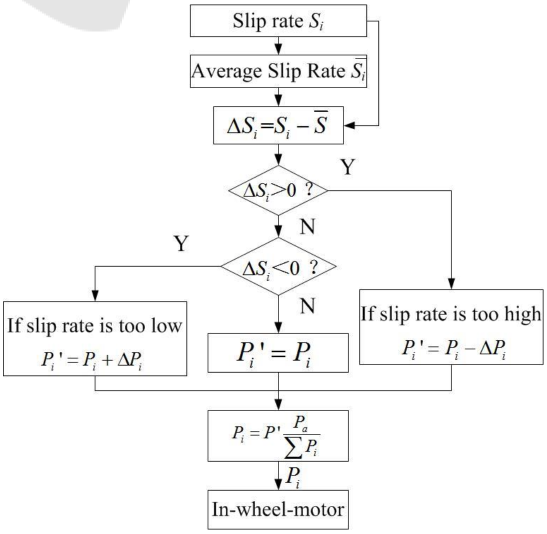

Figure 4. The slip ratio control flow chart.

Table 1. Assembly parameter.

Assembly	parameter	Numerical value
engine	Rated power (speed)/KW(n min^{-1})	399(2100)
Traction motor	rated power / KW	90
	Rated torque / Nm	1200
reducer	Reduction ratio	44
Tire	29.5R29	
quality	Load mass /t	35
	Curb quality /t	29

Figure 5. Testing field of 35 tons electric drive underground articulated mining truck.

In order to fully evaluate the control strategy effect and collect signals, the test uses LMS SCADAS MOBILE SCM05 signal acquisition card, and the sensor sampling frequency is 2560Hz, which meets the test requirements. The INS is installed at the center of the front and rear axles to measure the acceleration and angular velocity of the three orthogonal axes of the front and rear bodies. The rotary encoder is installed under the steering column of the steering wheel to measure the input angle of the steering wheel. The angular displacement sensor is installed at the hinge point to measure the front and rear vehicles. The articulation angle between the bodies is shown in Fig 6. The signals such as the speed and current of the engine, generator and motor are directly output by the CAN bus, which can be easily collected by the USBCAN interface.

Figure 6. Sensor installation position.

5.2 Vehicle Speed Estimation Based on Kalman Filtering

In the slip rate control, the vehicle speed needs to be specifically estimated, and the wheel speed signal must be filtered after removing the coarse error and the measurement error of the system itself, and the traditional vehicle speed estimation method is not applicable to the all-wheel drive vehicle: signal noise. The lower ratio will result in a large error in the direct integration of the longitudinal acceleration signal, which is easy to diverge; the method of obtaining the vehicle speed using the non-driving wheel speed is not applicable to the all-wheel drive of the vehicle. In this paper, the longitudinal acceleration signal and the wheel speed signal are used as input, and the Kalman filter algorithm is used to estimate the front and rear body speeds. The filtering process starts from the known initial value of the state and the initial value of the state covariance matrix, and filters and estimates the input wheel speed. The velocity estimation process of Kalman filtering algorithm consists of two parts: prediction and calibration, which includes state equations and observation equations.

$$x(k+1) = A(k)x(k) + w(k) \tag{8}$$

$$z(k) = B(k)x(k) + n(k) \tag{9}$$

Which

$$\mathbf{x(k)} = \begin{bmatrix} a_e(k) \\ v_e(k) \end{bmatrix}, \quad \mathbf{Z(k)} = \begin{bmatrix} a_m(k) \\ \omega(k)R \end{bmatrix}$$

Where ae, ve represent the estimated values of longitudinal acceleration and longitudinal vehicle speed, respectively, am, ω represent the experimental values of longitudinal acceleration and wheel angular velocity, R represents the rolling radius, Δt represents the time interval, and w1, w2 represent the system noise, na, nv denotes measurement noise, system noise and measurement noise are Gaussian white noise with known statistical information. The estimated vehicle speed after Kalman filtering is of great significance to the specific implementation of the control strategy. To represent the true value of the rolling radius, Gaussian white noise can be added based on the actual fluctuation amount.

Figure 8 is the curve of the longitudinal velocity estimation and measured value of the front body after the filtering process. To see the difference between the two is shown in Fig 9. The analysis shows that the acceleration phase of 5~25s is large, the difference between the two is large, the maximum difference is 0.19m/s; the difference in the steady steering phase is not large, and the acceleration speed reaches the maximum value of 4.5m/s and starts to decelerate. The error is large, 0.2m/s. Generally speaking, in the steady-state steering phase, the difference between the two is small, and the more uniform the data, the more consistent the data is.

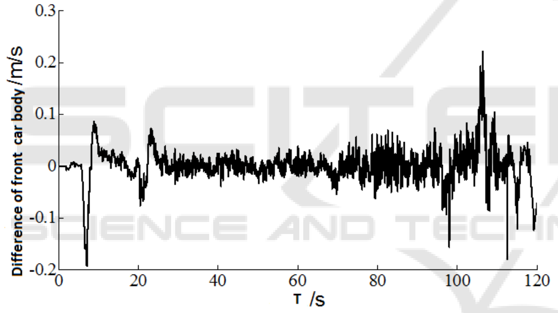

Figure 7. Difference of front car body longitudinal velocity estimated and measured value.

Similarly, the estimated value of the rear body speed is shown in Fig 8. The estimated speed of the front body is greater than the estimated speed of the rear body, and the over-range is about 5%. In the subsequent analysis, the average vehicle body speed can be used as the vehicle speed, and the slip rate of each wheel can be calculated.

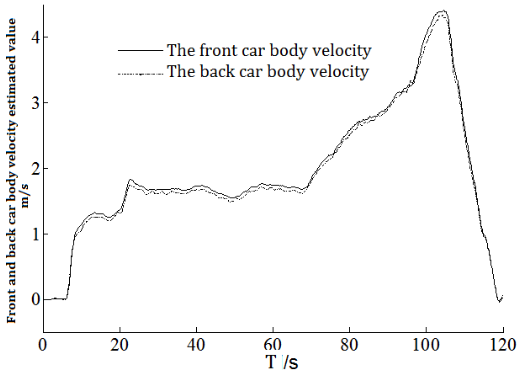

Figure 8. Front and back car body longitudinal velocity estimated value.

As can be seen from the above comparison, the Kalman filtering method is applicable to three situations of acceleration, braking deceleration and uniform velocity. The filtered signal has a small delay, a fast response speed and better smoothing effect, and the effect is obvious at a constant speed driving stage. The filtered signal can be used to directly estimate the speed of the vehicle.

5.3 Simulation and Comparison of Equal Slip Rate Control

The control strategy is simulated jointly by using the multi-body dynamics simulation platform of the whole vehicle, while the equal torque control strategy is adopted in the real vehicle, which needs to be verified by the multi-body dynamic model under the equal torque control strategy to demonstrate the accuracy of the multi-body dynamic model. Then the simulation of equal slip rate strategy is carried out. As mentioned earlier, the hinged vehicle is steadily accelerated to a speed of 15 km / h after starting and steering at a uniform speed. In the process of acceleration and uniform steering, the torque and slip rate data of the two wheels on the same side have little difference. In order to make the diagram clear, the simulation data of the left and right rear wheels and the inner wheels are selected for analysis. The measured slip rate and simulation slip rate are shown in Fig 9.

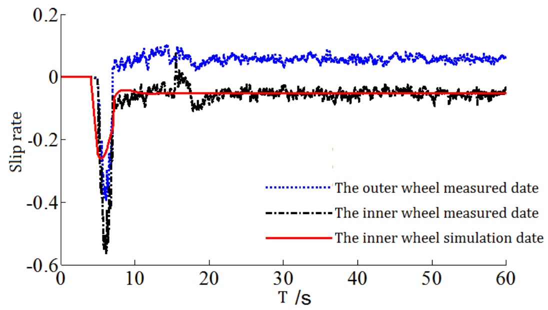

Figure 9. Slip rate under equal-torque control strategy.

It can be seen from Fig 10 that the driver stabilizes the accelerator pedal after 25s under the constant torque control strategy, but the torque of the inner and outer wheel motor is basically the same during the whole process, while the multi-body dynamics simulation model rapidly enters the stable state with the measured data, and finally stabilizes at 680N・m. The above data verify the accuracy of the multi-body dynamics model and can reflect the motion of the vehicle under different strategies. After changing the system model into the equal slip rate control strategy, the slip rate of the outer and inner wheels is shown in Fig 10.

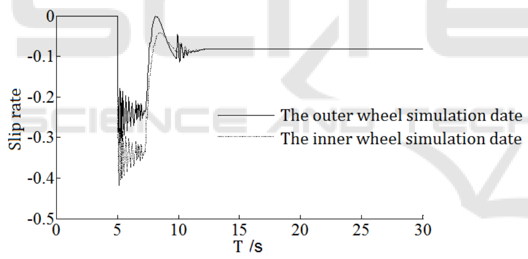

Figure 10. Slip rate under equal slip rate control.

Under the equal slip rate control strategy, the automatic distribution torque of the system quickly enters the steady turning condition, so the result of the first 30s can be discussed. After the turning instruction input and the torque adjustment of the system, the slip rate of the inner and outer side wheels can be stabilized to -0.08, there is no slippage, which increases the utilization of adhesive force.

6 CONCLUSION

This paper takes the steering condition of 35t wheeled electric-driven articulated underground mining truck as the research object. The main results are as follows:

(1) The multi-body dynamic model and kinematic model are in good agreement with the test data of the real vehicle, which can effectively reflect the motion of the vehicle under various working conditions. The Kalman filter speed estimation result has the advantages of small error and good real-time performance, which can accurately reflect the slip rate and other data under each control strategy.

(2) The differential speed control strategy with the equal slip rate is superior to the equal torque control strategy for wheeled electric-driven articulated underground mining truck, which can make full use of the adhesion coefficient, avoid type wear when being dragged and skidded, reduce the fuel consumption.

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