Research on the Traction Fuzzy Control of Articulated Vehicles Based on Matlab

Jing LENG¹, Fan HE^{2,a}

¹Department of Information Technology, Hubei University of Police, Wuhan 430034, China

²School of Computer Science and Technology, Wuhan University of Technology, Wuhan 430070, China

Abstract. In this paper, the slip rate of the articulated electric-wheel vehicles is monitored with the traction control system during running. Using fuzzy control system to control the traction force can effectively control the output torque of the motor so as to realize the effective control of the slip rate in different running roads. The full vehicle dynamic model of the articulated electric-wheel vehicles was built, and the dynamic equation of the steering process was analyzed. The motor control model and the traction fuzzy controller suitable for the system were constructed. Based on Matlab, the fuzzy controller was integrated with the full vehicle model to build the fuzzy control analysis model of full vehicle traction force. The running condition of the full vehicle on the low adhesion coefficient road and bisectional road was analyzed. The analysis results show that when vehicles run at different adhesion coefficients, the slip rate fuzzy control system can effectively reduce the skidding degree of wheels, so that the adhesive force provided by the pavement can be used to the maximum extent, so as to ensure the vehicle stability and improve the running safety, and the control has achieved good results.

1 Introduction

The rational use of the traction output torque can not only improve the power of the vehicle, but also reduce the impact and wear of the mechanical parts, so as to improve their service life. It is also beneficial for driving safety and personal safety to control the slip rate within a reasonable range. In the operation of the heavy-duty electric-wheel vehicles, there are often slip and idling phenomena, in which there are many uncertain factors[1]. Fuzzy control solves this problem very well. The traction control system is applied to the heavy-duty electric-wheel vehicles to monitor the vehicle slip ratio. Through fuzzy control system, the output torque of motor is controlled, so as to achieve good results in vehicle control.

Taking the full wheel driven articulated vehicle as the research object, the whole vehicle dynamic analysis platform is set up. The traction control system of ordinary vehicle is applied to the heavy-duty electric-wheel vehicles to build the system of monitoring vehicle slip ratio, and the output torque of wheel edge motor is controlled by fuzzy control system. The whole vehicle dynamics model is set up to complete the dynamic equation of the steering motion of the vehicle body. The control model of wheel edge motor and the traction fuzzy controller suitable for this system are set up. Based on Matlab, the fuzzy controller is integrated with the full vehicle model to build the full vehicle analysis model to analyze the running condition

of the full vehicle under the condition of low adhesion road, bisectional road and butt road, so as to check the control effect.

2 Full Vehicle Model

2.1 Motor Control Model

On the whole, the system is an asynchronous motor, which is input into three phase voltage u_A , u_B and u_C , and the output is the rotational speed ω . From the inside, through a series of coordinate transformations, it becomes a direct current(DC) motor that is input by i_c and i_m and output by ω [7]. The principle of the motor vector control system is shown in Figure 1.

Figure 1. Schematic diagram of vector control

The given signal and the feedback signal are first passed through the DC speed control system controller together. The required magnetic linkage current and armature current are calculated by the controller. Then

* Corresponding author: hefan@whut.edu.cn

combined with the angle difference, the two-phase currents i_α and i_β in the static coordinate system are obtained through the inverse rotation transformation, and then the currents u_A , u_B and u_C in the static three phase coordinate system are obtained through the 2/3 transformation module. Finally, the three current signals and the frequency signal ω_1 which is obtained by the DC speed control system controller in the first step are added to the frequency converter to get the three-phase current required by the asynchronous motor speed regulation. Then the asynchronous motor can be controlled by inputting this current to it[8].

The angle between the rotational magnetomotive force and two axes of d and q is not specified when the synchronous rotation coordinate transformation is carried out. Now, if the d axis is in the direction of the rotor total flux linkage vector, it is the M axis, and the vertical direction is called the T axis. So, the two phase rotating coordinate system is determined, which is called the M and T coordinate system, and also the rotating coordinate system directed by the rotor flux linkage. The vector control model based on rotor orientation can be summed up to the following three equations, including torque, rotational speed, and flux linkage[9].

$$T_e = n_p \cdot \frac{L_m}{L_r} \cdot i_{st} \cdot \psi_r \quad (1)$$

$$\omega_s = \frac{L_m i_{st}}{T_r \psi_r} \quad (2)$$

$$\psi_r = \frac{L_m}{T_r p + 1} \cdot i_{sm} \quad (3)$$

In the formula, L_m is the mutual inductance between the stator and the rotor, H; p is the number of pole-pairs; Ψ_r is the rotor flux, Wb; L_r is the rotor inductance, H; i_{st} is the stator current, A; i_{sm} is the stator torque current component, A; T_e is the output torque, N.m; ψ_r is the flux linkage space vector; n_p is motor speed, rpm.

The system uses a double closed loop structure: a torque loop and a current loop. The rotate speed is controlled by the PI link, and the current loop is added to the hysteresis regulation to control the inverter. In order to facilitate the observation and research, the system is divided into functional independent sub modules and encapsulated. The building model is shown in Figure 2.

Figure 2. Motor control model

2.2 Full Vehicle Dynamic Model

The full vehicle dynamic model is set up. In order to simplify the problem, it is assumed that: The effect of the ground unevenness is not considered when the vehicle is moving; The influence of the vehicle steering system is neglected, and the steering angle is input directly; The air resistance is not considered, and the influence of the wheel aligning torque is ignored. The tire side bias characteristic is in the linear range; The swing angle and motion are very small when there is only the small disturbance of the balance state attachment, and the motion equation of the vehicle is considered to be linear; The mechanical properties of each tire are the same[10]. The force model of the articulated vehicle is shown in Figure 3.

Figure 3. Vehicle dynamics model

In the figure, a_{1x} , a_{1y} , a_{2x} and a_{2y} are the accelerated speed at the center of mass; The F_{ix} and F_{iy} are the tangential force and lateral force ($i=1-4$) of the i -th wheel; T_0 is the steering internal torque between the front and back body; F_x and F_y are the acting forces at the hinge point. The vehicle does not exist suspension system, therefore, the lateral movement of the front and back body is not considered. The degree of freedom of the yaw, longitudinal and transverse directions is only considered. During the steering, the translation of the vehicle in Z axis direction and the rotation around the Y axis direction are ignored.

For front vehicle body:

Moment balance equation around Z axis:

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

In the formula, I_{zz1} is the moment of inertia for the total mass of the front body around the Z axis; δ is the angle between the front and back bodies, °; B is the wheelbase of the front and back body, m; L_f is the distance between the rear wheel center and the articulated point, m; h_f is the distance between the center of mass of the front body and the hinge point; h_r is the distance between the center of mass of the rear body and the hinge point, m.

Force balance equation along the X axis:

$$m_1(\dot{u}_1 - r_1 v_1) = F_{1x} + F_{2x} - F_x \quad (5)$$

Force balance equation along the Y axis:

$$m_1(\dot{u}_2 + r_1 u_1) = F_y + F_{1y} + F_{2y} \quad (6)$$

For the back vehicle body:

Moment balance equation around Z" axis:

$$I_{zz2}\dot{r} = T_0 + (F_{3x} - F_{4x})\frac{B}{2} - (F_{3y} + F_{4y})(h_r - L_r) + (F_y \cos \delta - F_x \sin \delta)h_r \quad (7)$$

Force balance equation along the X" axis:

$$m_2(\dot{u}_2 - r_2 v_2) = F_x \cos \delta + F_y \sin \delta + F_{3x} + F_{4x} \quad (8)$$

Force balance equation along the Y" axis:

$$m_2(\dot{v}_2 + r_2 u_2) = F_x \sin \delta - F_y \cos \delta + F_{3y} + F_{4y} \quad (9)$$

The relationship between the longitudinal and transverse acceleration of the back body and the velocity of the front vehicle body can be obtained according to the acceleration transformation relation:

$$\begin{aligned} a_{2x} &= \dot{u}_2 - r_2 v_2 = (\dot{u}_1 - r_1 v_1 + h_f r_1^2) \cos \delta \\ &\quad - (\dot{v}_1 + r_1 u_1 - h_f r_1^2) \sin \delta + h_f r_2^2 \\ a_{2y} &= \dot{v}_2 + r_2 u_2 = (\dot{u}_1 - r_1 v_1 + h_f r_1^2) \sin \delta \\ &\quad + (\dot{v}_1 + r_1 u_1 - h_f r_1^2) \cos \delta + h_f r_2^2 \end{aligned} \quad (10)$$

Sorting out the formula (4) - (9). The intermediate variable F_x and F_y are eliminated, and the formula (10) is input. The steering dynamics equation of vehicle body is obtained:

$$\begin{cases} (m_1 + m_2)\dot{u}_1 - (m_1 + m_2)r_1 v_1 + m_2 h_f r_1^2 + m_2 h_f r_2^2 \cos \delta + m_2 h_f r_2^2 \sin \delta \\ = F_{1x} + F_{2x} + (F_{3x} + F_{4x}) \cos \delta + (F_{3y} + F_{4y}) \sin \delta \\ (m_1 + m_2)\dot{v}_1 - (m_1 + m_2)r_1 u_1 - m_2 h_f r_1^2 + m_2 h_f r_2^2 \sin \delta + m_2 h_f r_2^2 \cos \delta \\ = F_{1y} + F_{2y} + (F_{3y} + F_{4y}) \cos \delta - (F_{3x} + F_{4x}) \sin \delta \\ I_{zz1}\dot{r}_1 + m_1 h_f \dot{v}_1 + m_1 h_f r_1 u_1 = T_0 + (F_{2x} - F_{1x})B + (F_{1y} + F_{2y})L_f \\ I_{zz2}\dot{r}_2 + m_2 h_f \dot{u}_1 \sin \delta - m_2 h_f r_1 v_1 \sin \delta + m_2 h_f r_1^2 \sin \delta + m_2 h_f r_1^2 \cos \delta \\ + m_2 h_f r_1 u_1 \cos \delta - m_2 h_f r_1 v_1 \cos \delta + m_2 h_f r_2^2 \\ = T_0 + (F_{3x} - F_{4x})B + (F_{3y} + F_{4y})L_r \end{cases} \quad (11)$$

3 Fuzzy Control of Slip Rate

When controlling the slip rate, the optimal slip rate of the current tire-road is identified as a reference input. The torque selector is used to compare the torque of operation demand value and input reference value. The small is taken as the set value of the motor. The optimal slip rate control is shown in Figure 4.

Figure 4. Optimal anti-slip control

3.1 Fuzzy Controller

The three core components of the control system are the controller C, the controlled object G and the feedback sensing channel H. The basic principles are as follows:

Figure 5. Control principle of the traditional control system

In the Figure 5, G is a controlled object, H is a feedback sensing channel, and C is the transfer function or state equation of the controller. The symbolic meaning of the input signals of each part: r is the reference signal; v is the feedback output signal; u is the control signal; d is the interference signal; y is the output signal of the controlled object; n is the noise signal. The difference between the fuzzy control system and the traditional system lies in the use of the fuzzy controller FC instead of the traditional controller C.

3.2 System Analysis and Input-Output Domain

Because of the randomness of the pavement conditions, the slip rate is also irregular and nonlinear. In a word, the control system needs to monitor the slip rate in real time. When the slip rate is less than the stable slip rate in the stable state, the torque can be improved properly, however, when the slip rate is greater than the stable state, that is skidding, then the output torque value should be reduced. And the decrease of the amount varies with the slip rate error. For the antiskid control of traditional vehicles, the general input amount is only the slip rate. In order to control more accurately, the slip rate error E and its change rate ES are selected as the control quantity. First, we should set an ideal slip rate S_0 , where 0.2 is taken. The two control amounts are as follows:

$$\begin{cases} E = S - S_0 = S - 0.2 \\ ES = \frac{dE}{dt} \end{cases} \quad (12)$$

It can be seen from the actual situation that the basic domain of the slip rate is [0,1], so the domain of E is [-0.2,0.8]. The actual domain of the change rate of slip rate is difficult to be determined because it may produce a very high slip rate change according to the severity of the pavement condition. The change rate of the slip rate is restricted, and the actual domain of it stipulated by people is [-50,50]. The excess parts are calculated according to the boundary value. The EC fuzzy domain[-1,1] is given, and the quantization factor from the real domain to the fuzzy domain is:

$$k_j = \frac{1}{50} \quad (13)$$

The amount of control is the amount of change in the output torque of the motor. The real domain[-100,500] is

given to T , the fuzzy domain is $[-2,10]$. The output ratio factor is determined by formula(15), thus determining the input and output quantity.

3.3 Controller Structure and Membership Function

A two-dimensional FC controller is used, and the structure box is shown in Figure 6:

In the figure 6, k_e and k_{ec} are quantization factors. The modules in the fuzzy core controller in the rear are in turn the conversion operation from clear to fuzzy, the approximate reasoning operation, and the clear module. k_u is the proportional factor module. In the knowledge base, μ is the membership function base, which stores the membership function of the model; R is the control rule base, storing the conditions for judging and the reasoning algorithm; f_d is the clear method library, storing the algorithm used to clear the fuzzy quantity. The membership function of the fuzzy subset is determined. The fuzzy subset distribution follows completeness, consistency and interactivity. According to the principle, the membership function is determined. In order to improve the response sensitivity and ensure the power and safety of the vehicle, the triangle membership function is selected.

Figure 6. Structure of fuzzy controller

For the fuzzy domain $[-0.2,0.8]$ of slip rate error, it is divided into 5 parts: negative N $[-0.2,0]$, extremely small ES $[-0.2,0.3]$, small S $[0,0.6]$, medium M $[0.3,0.8]$ and big B $[0.6,0.8]$. For the domain of the slip rate error change rate, it is divided into 3 parts: negative NB $[-1,0]$, zero NONE $[-1,1]$, positive PB $[0,1]$. For the adjustment torque, it is divided into 6 parts: negative N $[-2,0]$, zero ZE $[-2,2]$, small PS $[0,4]$, medium PM $[2,7]$, big PB $[4,10]$ and extremely big EPB $[7,10]$.

3.4 Fuzzy Control Rules

When designing the control system, the most important thing is the fuzzy control rule. The control rules of the model are shown in Table 1.

Table 1. Fuzzy control rules

Slip rate deviation	Slip rate deviation domain	Slip rate deviation change rate	Domain of slip rate deviation change rate	Torque	Torque domain
Negative N	$[-0.2,0]$	none		Negative N	$[-2,0]$
Extremely small	$[-0.2,0.3]$	none		Small	$[0,4]$
Extremely small	$[-0.2,0.3]$	Positive		Small	$[0,4]$
Small	$[0]$	Negative	$[-1,0]$	Invariant	
Small	$[0]$	None		Small	$[0,4]$
Small	$[0]$	Positive	$[0,1]$	Small	$[0,4]$
Medium	$[0.3]$	Negative	$[-1,0]$	Small	$[0,4]$
Medium	$[0.3]$	None		Medium	$[2,7]$
Medium	$[0.3]$	Positive	$[0,1]$	Big	$[4,10]$
Big	$[0.6]$	Negative	$[-1,0]$	Medium	$[2,7]$
Big	$[0.6]$	None		Big	$[4,10]$
Big	$[0.6]$	Positive	$[0,1]$	Extremely big	$[7,10]$

In Matlab, according to the above rules, the statement and fuzzy control surface of input and output quantity are written, as shown in Figure 7 (a), so as to build a single tire fuzzy control system model. Based on Matlab, the fuzzy controller is integrated with the full vehicle model to build a full vehicle analysis model, as shown in Figure 7(b).

(a) Fuzzy control surface

(b) A single tire
Figure 7. Model of fuzzy control system

4 Multi-Pavement Traction Fuzzy Control Analysis

In order to control the torque, the model has been partially modified to eliminate the speed loop and directly simulate the driver to give a command torque of 1000Nm. The control unit adjusts the motor output torque in real time as the slip rate changes. After encapsulating the model, we made the comparison of the following conditions.

4.1 Low Adhesion Coefficient Uniform Road Operation

The compressed snow path is selected as experimental road conditions, the driver gives the target torque of 1000Nm, the left is not controlled simulation results, and the right is the fuzzy control simulation results. Because of the same force of the left and right tires, the simulation results are the same, so we show the analysis result of one tire in Figure 8.

(a) The curves of slip ratio before and after controlling

(b) The curves of adhesion coefficient before and after controlling

(c) The curves of acceleration before and after controlling

(d) The curves of speed before and after controlling

Figure 8. Analysis results of low and uniform pavement

We can see from Figure 8 that, first of all, from Figure 8 (a), slip rate can be clearly seen. When starting with no control, vehicles skid seriously, and slip rate closes to 1, and then gradually falls. In the end, it can still reach 0.6. After adding traction control, slip rate is improved significantly, and the whole process value is around 0.2. From Figure 8 (b), we can see that the adhesion coefficient of vehicle operation has been obviously improved. However, the peak adhesion coefficient of compressed snow path is only 0.2, therefore, there is no obvious difference. This system still controls the adhesion coefficient near the peak value. Also for this reason, the acceleration and speed of the body of Figure 8 (c) and (d) do not increase violently. This is also consistent with the actual situation. When the ground cannot provide greater adhesion, the main function of fuzzy control is to control the output torque, so as to provide the right size of force and save energy.

4.2 Operation on Bisectonal Road

The vehicle-like wheels on both sides run on different roads. The left planning wheel runs on the gravel road with high adhesion. The right wheel runs on the snow road with low adhesion. The initial conditions remain unchanged. The analysis processes are shown in Figure 9 (a) and Figure 9 (b), the results of the analysis after adding fuzzy control are shown in Figure 9 (c) and Figure 9 (d).

(a) The slip rate curves of left and right wheels

Figure 9. Results of open circuit analysis

We can see from Figure 9 (a) and 9 (b), the skidding of the tires in the snow is very serious and is not regular. This will seriously affect the driver's driving operation, and even cannot ensure that the car is running in a straight line. In such a case, the car will automatically turn and be unable to control, so it is a great threat to traffic safety. From above 9 (c) and 9 (d), we can see that at the beginning stage, the slip rate is controlled at 0.2 of the best slip rate. The running on the high attachment road is good, and the low adhesion road is no longer as slippery as before, and the adhesion coefficient also keeps close to the maximum adhesion coefficient of the ice and snow road. It can be seen that the stability and safety of the vehicle have been improved after the control.

5 Conclusions

In this paper, the traction control system is applied to heavy duty electric wheeled vehicles, and the slip rate of the vehicle is monitored. The traction force is controlled by the fuzzy control system so that the output torque of the motor can be controlled effectively and the slip rate control can be realized on different roads. For a certain type of articulated electric wheel vehicle, a complete vehicle dynamics model is set up to complete the kinematic equation of steering motion of the vehicle body, and a motor control model and a traction fuzzy controller suitable for the system are established. Based on Matlab, the fuzzy controller is integrated with the vehicle model to build a vehicle model, and the operation

of the vehicle with low attachment road, bisectional road and docking road is analyzed. Analysis results show that:

(1) After the fuzzy controlling the slip rate, under the most severe ground conditions, it can reduce the slipping degree and stabilize the vehicle near the highest adhesion coefficient of the road surface to give full play to the adhesive force given by the road surface.

(2) When two wheels are facing different road conditions, the driving stability of the vehicle is also ensured and traffic safety is improved. When the vehicle enters the low-adhesion road surface from a high adhesion road surface, the vehicle won't be suddenly violently skidding, so the vehicle will not be out of control.

References

1. Zhang Zhaoliang. Comparative Analysis of Anti-slip Control Method of Electric Vehicle [J]. Shanghai Auto, 2011(2):11-15.
2. Banerjee A, Pramanik A, Das K K. Validation of anti-slip control for traction system using Hardware-In-the-Loop simulation[C]// Vehicle Power and Propulsion Conference, 2007. VPPC 2007. IEEE. 2007:440-447.
3. Achour T, Debbou M, Pietrzak-David M. Control strategy of a dual induction motor: Anti-slip control application[J]. Control Engineering Practice, 2015, 36(1):58-71.
4. Farzad T, Reza K, Shahrokh F A, et al. Fuzzy Based Stability Enhancement System for a Four-Motor-Wheel Electric Vehicle [J]. SAE paper, 2012, 36(1):1588-1592.
5. Dong Z, He P, Han C, et al. The design of anti-slip control for in-wheel motor at the limited conditions in a four in-wheel-motor drive electric vehicle[C]// Mechatronics and Machine Vision in Practice (M2VIP), 2012 19th International Conference. IEEE, 2012:526-530.
6. Feng Yanbiao, Yang Jue, Ji Zhiyi, et al. Fuzzy anti-slip control based on optimal slip control[J]. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE), 2015, 31(8): 119-125.
7. Zhao Feng, Luo Yugong, Li Keqiang, et al. Hierarchical Traction Control for Hybrid Electric Vehicle and Hardware-in-loop Test [J]. Transactions of the Chinese Society for Agricultural Machinery, 2011, 42(4):8-12.
8. Lin W S, Chang L H, Yang P C. Adaptive critic anti-slip control of wheeled autonomous robot[J]. Iet Control Theory & Applications, 2007, 1(1):51-57.
9. Zuo Zhiyu, Ni Jing, Han Lvhu, et al. Design of drive electro-hydraulic anti-slip regulation based on fuzzy-PID control [J]. Machinery Design & Manufacture, 2010(12):4-5.
10. Chen Tangjian, Chen Yong, Zhao Fang, et al. Control and Simulation Analysis of Handling and Stability of Electric Vehicle with All Motorized

Wheels [J]. Journal of System Simulation, 2013, 25(12):3033-3038.