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Optimal Learning Slip Ratio Control for Tractor-semitrailer Braking in a Turn based on Fuzzy Logic

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ABSTRACT
The research on braking performance a of tractor-semitrailer is a hard and difficult point in the field of vehicle reliability and safety technology. In this paper, the tire braking model and the dynamic characteristic model of the brake torque with the variable of the controlling air pressure were established. We also established a nonlinear kinematic model of the tractor-semitrailer when it brakes on a curve. The parameters and variables of the model were measured and determined by the road experiment test. The optimal control strategy for the tractor-semitrailer based on the optimal slipping ratio was proposed. Then the PID controller and the fuzzy controller were designed respectively. Simulation results show that the reasonable control strategy can significantly improve the braking directional stability when a tractor-semitrailer runs on a curving road. The research results provide technical references for improving the lateral stability when a tractor-semitrailer brakes on a curve, and it also provides a technical reference for the road traffic safety.

KEY WORDS: Optimal learning control, Fuzzy logic algorithm, Computing simulation, Intelligent system, Vehicle dynamics, Tractor-Semitrailer

1 INTRODUCTION

WITH increasing the investment scale for highway construction and the development of freight vehicle technology in China, the road freight transport has turned into a stage of rapid development and taken an important position in the integrated transport service system. Road freight transport has become a major part in economic development. As one of the main carrying tools in the road transportation system, the semi-trailer train plays an important role. At the same time, because of its vehicle performance and safety performance, it guarantees the safety and smoothness for the personnel, goods, vehicles and other traffic participants in the cargo transport process. Research results have indicated that the braking system modeling and control strategy of the semi-trailer train are important factors that affect the safety of the braking system. Bad performance or failure of the braking system could directly lead to traffic accidents.

Hubert L. and Dietz from the German Stuttgart Automobile Research Institute conducted a study on the lateral stability of the combination vehicle in 1937 (Ahn, et al., 2017; Guan, et al., 2002; Thanpattranon, et al., 2016). In the 1960s, many scholars began to study the braking performance of freight cars and articulated semi-trailers (Chieh et al., 2000; Chadwick et al., 2014; Goel et al., 1983; Khalaji et al., 2016; Zhang et al., 2017). In the 1990s, the advanced control technology was widely used for improving the braking performance or the vehicle operating stability. In recent years, studies on braking stability of the combination vehicle have made great progress, and the research results focus on three aspects; folding, rollover and ABS. For literature (Gaspar et al., 2005; Li et al., 2017; Li et al., 2007; Wang et al., 2005; You

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et al., 2015; Zhang et al., 2016), an accurate 15 degrees of freedom simulation model was established by methods of Lagrange, which is combined with the Extended Kalman Filter to realize the measurement of the longitudinal slip ratio, lateral acceleration of the traction vehicle and yaw rate velocity. For literature (Kress et al.,2009; Huang et al., 2010; Huang et al., 2017;You et al., 2014; Zhang et al., 2017), it establishes the 14 degrees of freedom model to evaluate the roll angle and the semi-trailer train lateral acceleration. Based on that, it develops the linear active control system to prevent the rollover occurrence. For literature (Abdur et al., 2016; Bao et al., 2016; Ozdalyan et al., 2008), it establishes the mathematical models of bike and trailer automobile train by methods of Lagrange equation and Newton's mechanics. For literature (Demir et al., 2014; Zhang et al., 2016), it establishes the semi-trailer train model with 8 degrees of freedom, which carries on the simulation analysis by means of Matlab/Simulink and validates the accuracy of the established model by steering and braking tests. For literature (Ding et al., 2014; Shuwen et al., 2014), it establishes the braking simulation model of the semi-trailer train with Matlab/ Simulink software and analyses the effect that braking deceleration has on the load transferring during the brake process, as well as the effect that load transferring has on the wheel lock sequence, and analyzes the effect of ABS arrangement form on the braking performance.

Literature has shown that the research works in this field focuses on mechanics and kinematics with the braking performance of the combination vehicle, but there is less research works on the semi-trailer train braking performance on a curve, and it is not enough due to limitations by the technical conditions. This paper establishes a semi-trailer train tire model and nonlinear dynamics model when braking on a curve. We measure and determine the model parameters and variables through road tests, and put forward the strategy method based on the braking control on a curve with optimum slip rate. The research results can give a useful reference for the brakes design and the semi-trailer train selective assembly.

The structure of this paper is as follows: Section 2 describes braking in a turn modeling of the semi-trailer train. Section 3 checks the model parameter, Section 4 designs the braking control laws based on optimal slip ratio, and we give a conclusion in Section 5. Finally, the last section concludes acknowledgments.

2 CORNERING BRAKING MODELING

2.1 Tire Model

IN order to accurately describe the mechanical characteristics of a tire with power and movement, and to carry out unified analysis, and establish the tire mechanics model, the Society of Automotive Engineers (SAE) has worked out a standard tire movement coordinate system. This coordinate system is defined as a three-dimensional right-handed coordinate system under the normal direction coordinate.

If a tire is free from the lateral force, when the driver steps on the brake pedal, the brake torque, through the transmission of power, will act on the wheel and make the wheel decelerate. Meanwhile a brake force will be generated in the contact area between the tire and ground. When the tire tread is getting into the ground-contact area and the fore-end distorts under the drawing force, the sidewall will also correspondingly have shear deformation.

Commonly, we used slip the ratio, which indicates the length of the sliding distance, or the degree of braking during the increase of the brake torque. The slip ratio is defined as the ratio of the difference between the wheel translator velocity and the wheel tangential velocity with respect to the wheel translator velocity. Shown as Eq(1).

$$s = \frac{u_a - \omega R}{u_a} \times 100\% \tag{1}$$

In the formula,

s—longitudinal slip ratio of wheel;

u_a—wheel translatory velocity;

ω—wheel angular velocity;

R-- rolling radius of wheel.

2.2 Brake Torque Modeling

The air brake is a widely used braking mode in road freight transport combination vehicle. In order to control the service brake of a semi-trailer train, it needs the power conversion device to convert the input air pressure in the brake chamber to mechanical action that realizes the braking function. The brake chamber in the braking system of semi-trailer train and the brake drum assembly are coordinated to achieve the above functions.

The braking force generated by each wheel in the pneumatic braking system can be expressed as (Chou, Y. C., & Nakajima, M., 2016; Jia et al., 2015; Rajamani et al., 2011) and shown as Eq (2).

$$M_{\mu} = P_t A_0 \eta_m BF\left(\frac{l_a}{2l_b}\right)R_r \tag{2}$$

Where:

A_0—active area of brake chamber;

P_t—pressure of brake chamber;

η_m—braking efficiency of brake chamber, brake shoe and brake mechanism;

BF—braking ratio of brake drum (Braking ratio is the friction force generated by the friction surface of the brake drum and the braking force of the brake shoe);

R_r—radius of brake drum;

l_a—effective length of the intermittent adjusting mechanism;

l_b—effective radius of cam.

2.3 Cornering Braking Model

A semi-trailer train is a complex multi-body dynamic system. This paper mainly studies the cornering braking stability of the semi-trailer train. Based on the analysis of the lateral force, longitudinal force and its motion, the mathematical model of the semi-trailer train cornering braking was established. In order to accurately describe the force and the semi-trailer train movement in the process of cornering braking, a detailed description of the semi-trailer train movement condition was required. So, it needs to introduce more freedom degrees, which greatly increases the complexity and the analysis difficulty.

In order to facilitate the research work, based on the analysis of the key factors, this paper simplifies the following aspects when establishing the cornering braking model of semi-trailer train:

1) The semi-trailer train is regarded as two rigid bodies, which realizes the restraint of the mutual movement via the coupling of the traction pin and the traction seat.

2) The movement with two degrees of suspension roll and pitching in the process of semi-trailer train cornering braking is ignored, and only the longitudinal with lateral load transfer caused by cornering braking was taken into account.

3) It was assumed that the tire characteristics were consistent with the Brush model, regardless of the influence from the aligning torque generated by the angle of roll and the side slip angle.

4) It considers the rolling resistance and air resistance of the vehicle, but ignores the resistance moment caused by the rotational energy.

In order to accurately describe the motion state of the vehicle, a coordinate system must be set up. The setting of a coordinate system directly affects the complexity of the vehicle motion description, so it should be set according to the vehicle motion characteristics. Based on refs. (Deng et al., 2016; Dixit et al., 2016; Tseng et al., 2007), this paper establishes a fixed coordinate system on the ground as well as the tractor and semi-trailer coordinate systems. Among them, the traction vehicle and semi-trailer coordinate system take each centroid as the coordinate's origin. The vehicles forward direction is the X axis and the Y axis points to the driver right side. The Z axis is vertical down according to the right-hand rule.

In the semi-trailer train, the front-axle of the towing tractor has a single tire on each side; the rear axle of the towing tractor and semi-trailer are dual-axis with two tires on each side. In order to facilitate the mechanical analysis and control strategy research, it simplifies the towing tractor and semi-trailer with dual-axis, and two tires on each side to the type of single axle and single tire. The parameters of the vehicle can refer to the standard definition of reference (Cao, X., & Zhu, D., 2015; Gao et al., 2016; Yin et al.2017; Zhang et al., 2017).

It analyzes the movement condition and the force situation of the semi-trailer train when braking on a curve, and gets the motion equation of the towing tractor and the semi-trailer.

The motion equation of towing tractor:

$$\begin{cases} m_1(\dot{u}_1 - v_1 r_1) = \sum F_{x1} \\ m_1\left(\dot{v}_1 + u_1 r_1\right) = \sum F_{y1} \\ I_{1z}\dot{r}_1 = \sum M_{z1} \end{cases} \tag{3}$$

The motion equation of semi-trailer:

$$\begin{cases} m_2(\dot{u}_2 - v_2 r_2) = \sum F_{x2} \\ m_2\left(\dot{v}_2 + u_2 r_2\right) = \sum F_{y2} \\ I_{2z}\dot{r}_2 = \sum M_{z2} \end{cases} \tag{4}$$

3 MODEL PARAMETER CHECK

THE model parameter is the link between the theoretical model and the real vehicle and it is also one of the necessary conditions to realize the mutual authentication between the vehicle test and the theoretical model. Therefore, the model parameter confirmation is an extremely important link in simulation. The authors' measure variables related to the model like the tire parameter, rolling resistance, air resistance coefficient and brake torque parameter through road tests to analyze and determine the performance index of the tractor-semitrailer cornering braking. And validate the accuracy of model through the prototype comparison test under the same condition (Abdurrahim et al., 2016; Huynh et al., 2017; Wang et al., 2015; Xu et al., 2016; Zhang et al., 2017).

The straight braking test of the semi-trailer train is conducted in the test field for road traffic of the Ministry of Communications. The combination vehicle performance tester VTRS1 developed for the Ministry of Communications' Western Transportation Construction Project; "Researches on Technical Conditions and Test Methods for Safe Operation of Freight Vehicles" is applied. The test equipment mainly consists of the wheel speed module, GPS module, pedal force module and the embedded host as well as the necessary auxiliary equipment installation. Figure 1 is the testing experiment platform.

Comparisons between test results and simulations results are shown in Figure 2. The comparative analysis between the test data and the simulation data indicates that the maximum error of the braking distance is 3.31%. Besides, the maximum error of the wheel angular velocity before it first reaches the speed zero is 1.14 rad/s and the maximum error of the vehicle deceleration is 0.48m/ s2. Therefore, there is no significant difference between the test data and the simulation data.

Figure. 1. Testing Experiment Platform.

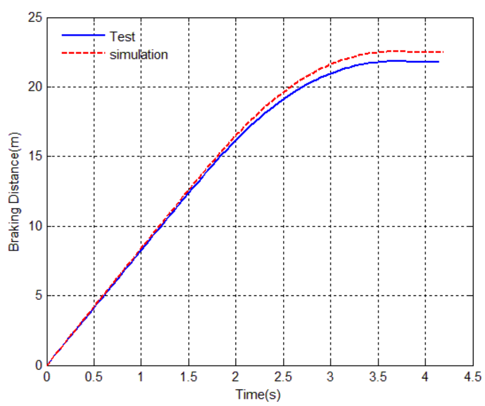

Figure 2. Comparison between Test and Simulation Braking Distances.

4 BRAKING CONTROL BASED ON OPTIMAL SLIP RATIO

4.1 PID Control based on Slip Ratio

IN order to improve the comprehensive performance of the semi-trailer train, the slip ratio needs to be effectively controlled as is the key parameter. Under the condition that the wheel rolling radius of the wheel is fixed, the wheel sliding rate is the function of vehicle running speed and wheel angular velocity, and the slip rate can also be regarded as the function of the brake torque, the braking force in the contact area between tire and ground as well as the vehicle speed. And then it can control the brake torque through the output pressure of the brake chamber. This paper puts forward the research work of PID control and fuzzy control based on the optimal slip ratio.

As the object of this paper, the simulation model of tractor-semitrailer is complex and nonlinear. One advantage of the PID control is being simple and more stable, which makes up the discontinuity of traditional logic threshold braking control. However, the conventional PID control cannot guarantee the stability and reliability of the braking control under the non-linear characteristics of vehicles. The fuzzy control is based on the fuzzy set theory, fuzzy linguistic variables and fuzzy logic reasoning. It is independent of the controlled object mathematical model. It has a strict theory foundation and easy engineering practice. As we know, it is difficult to describe and control the model, even theoretically good simulation, because the tire is a strong non-linear body, and the braking condition is complicated and changeable. As a result, the implementation process may not be satisfactory. The fuzzy control is suitable for this variable condition, especially, the nonlinear characteristics of tractor-semitrailer, so the fuzzy controller for the braking system is a useful attempt. Therefore, the optimization of the braking slip rate based on fuzzy control is studied, and the results show that the fuzzy control has better control effect.

4.2 Fuzzy Control based on Slip Ratio

Although there is the conventional PID control remedy the non-consistency of the traditional logic threshold braking control and the certain stability, but under the situation of the vehicle nonlinear characteristics and road condition changes, the conventional PID control cannot guarantee the stability and reliability of the brake control. Fuzzy control does not depend on the mathematical model of the controlled object, but with a rigorous theoretical basis, it is easy to put into engineering practice. It is an important method of intelligent control engineering research. For the road surface with low adhesion coefficient, the thesis carries out the research on the cornering braking control of semi-trailer train based on fuzzy theory. Figure 3 shows the comparison of the left front wheel slip ratio for towing tractor controlled by PID and the logical threshold. Figure 4 is the basic principles of fuzzy control. According to the design process of the fuzzy controller, the final fuzzy output obtained through fuzzy process. Fuzzy logic reasoning and accurate calculation is shown in Figure 5. In this text, the vehicle test speed is about 50km/hour.

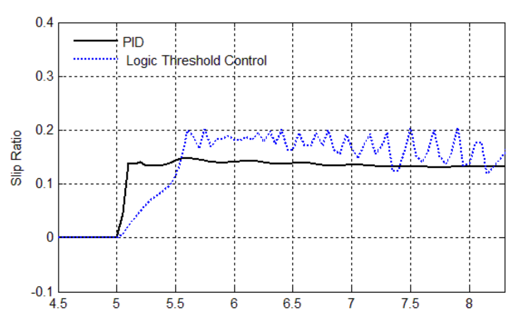

Figure 3. Comparison of the Left Front Wheel Slip Ratio for Towing Tractor Controlled by the PID and the Logical Threshold.

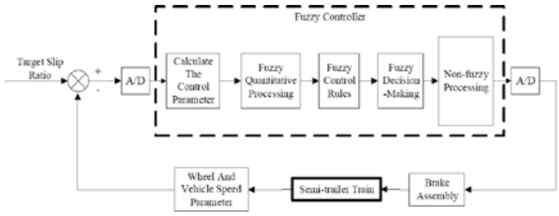

Figure 4. Basic Principles of Fuzzy Control.

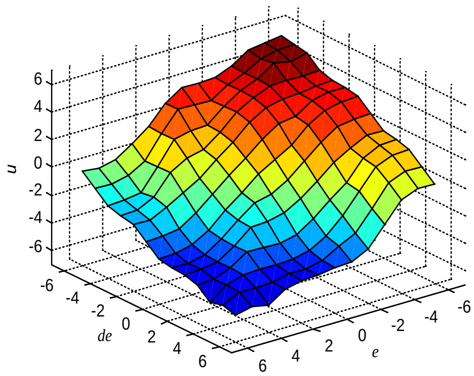

Figure 5. Output Curve of a Fuzzy Controller.

From the simulation results of the braking distance, when wheel speed and the speed of the towing tractor in the cornering braking of semi-trailer train under PID control and fuzzy control with low adhesion coefficient. Figure 6 and 7 are the simulation results of the braking distance, wheel speed and the speed of the towing tractor in the cornering braking of a semi-trailer train under PID control and fuzzy control with low adhesion coefficient (=0.2). So, it can be seen that the braking distance of the PID control is less than the fuzzy control, reducing to 154.4m from 162.9m. The main reason is that under the control of PID, the folding occurs when the semi-trailer train brakes, so that the drag of semi-trailer train increases. On the road with low adhesion coefficient, PID parameters adopt the same coefficient with high adhesion coefficient road. Due to changes in road parameters, the control fails and the wheels of semi-trailer train lock when braking. Influenced by the lateral force, braking jack-knifing occurs, and the articulation angle of the semi-trailer train is up to around 64deg when the braking terminates. Under the fuzzy control, the change of semi-trailer train's articulation angle is relatively smooth and the locking of the wheels does not occur, indicating that fuzzy control has good control effect on the low adhesion coefficient road and can adapt to different road adhesion coefficients. Compared with the PID controller, it has better adaptability to pavement.

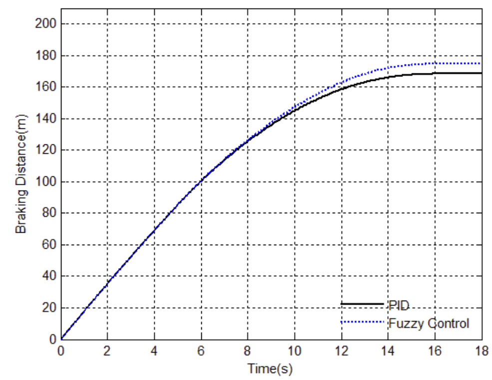

Figure 6. Braking Distances of PID Control and Fuzzy Control on the Road with Low Adhesion Coefficient.

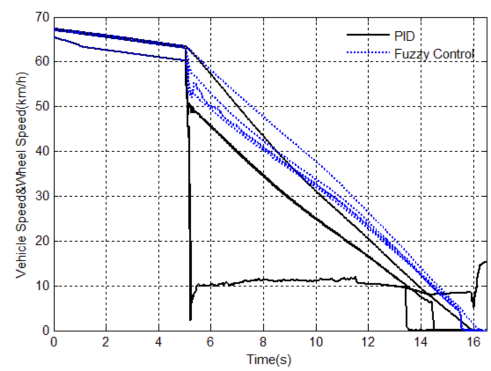

Figure 7. Wheel Speed and Towing Tractor Speed by PID Control and Fuzzy Control on the Road with a Low Adhesion Coefficient.

Through the system test and the simulation analysis research, in Table 1, comparison of brake control methods for semi-trailer train in cornering braking is obtained. According to the table, compared with the logic threshold control and PID control, the fuzzy control has improved significantly in consistency, nonlinearity and has a certain stability as well as strong adaptability to different attachment coefficients. At the same time, Table 1 presents a detailed description of the advantages and disadvantages of the logic threshold value, which PID control and fuzzy control set. PID control and fuzzy control are relatively good, but there are also some problems under the limited condition. A follow-up study can combine the two methods to form the fuzzy PID control according to the different operating conditions, to make full use of their advantages and ultimately improves the control effect on cornering braking of semi-trailer train.

Table 1. Comparison of Brake Control Methods for a Semi-Trailer Train.

Characteristic Index	Logic Threshold Control	Optimal Slip Ratio	
		PID Control	Fuzzy Control
Consistency	Bad	Good	Mediocre
Nonlinearity	Bad	Mediocre	Good
Stability	Bad	Mediocre	Mediocre
Portability	Bad	Bad	Mediocre
Reliability	Good	Good	Good
Cost price	Low	Low	Low

5 CONCLUSIONS

AS one of the main carrying tools for the road freight transportation system, a semi-trailer train plays an important role. Compared with the semi-trailer, the coupling action between the towing tractor and the trailer makes the semi-trailer train have a more complex dynamic system. Improper structural parameters, operation parameters and control parameters will lead to folding, spin, sideslip and other non-stability phenomenon of a semi-trailer train in the braking process. During the cornering braking of semi-trailer train, the non-stability phenomenon may cause serious traffic accidents easily.

Based on the theory of vehicle kinematics and kinetics, this paper establishes the tire braking model, dynamic characteristics model of brake torque that changes with control pressure, nonlinear motion model of the cornering braking for a semi-trailer train and measures, as well as identifies model parameters and variables through road tests to validate the model consistency and the test parameters. Finally, it proposes an optimal control strategy based on the optimal slip ratio for a semi-trailer on the curving road, and it designs the PID controller and fuzzy controller respectively. Besides, this paper makes a detailed analysis of the braking performance of the controllers under the conditions with different adhesion coefficients through comparison. The research results provide a reference for improving the direction stability of a semi-trailer train’s cornering breaking, which also provides a reference for road transportation safety (Zhang et al., 2017; Sun et al, 2018).

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7 DISCLOSURE STATEMENT

NO potential conflict of interest was reported by the authors.

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9 NOTES ON CONTRIBUTORS

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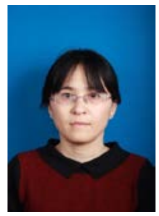

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