Research on Automatic Train Driving Based on Fuzzy Proportion Integration Differentiation Iterative Control

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Abstract. Automatic train driving system is an important subsystem of train operation control system, which can provide passengers with punctual, accurate, efficient and fast transportation services. At the same time, the accurate stop, comfort and stability of the train is an important index to measure the control performance of the train automatic driving system, and the accurate stop plays a vital role in the efficient operation of the train. Based on the characteristics of high-speed train parking, an accurate parking algorithm based on fuzzy PID iterative control was proposed to solve the problem of low parking accuracy caused by frequent switching of control output. On the basis of solving the differential equation of the train braking model, the gradient of the system is obtained, and then the learning parameters of the convergence condition are obtained to overcome the repeated uncertainty in the stopping stage. The simulation results show that the fuzzy PID iterative control for asymptotic stability is an effective method to realize the precise parking of trains, and has strong robustness against the train parameter uncertainties and external disturbances.

1 Introduction

As a core function of automatic train operation system, accurate train stopping is very important for the safe and efficient operation of high-speed train. The stopping accuracy of high-speed train should be guaranteed within 30cm[1]. With the rapid development of high-speed railway in China, it is of great significance to study the accurate parking algorithm of ATO system for high-speed railway. In this process, a variety of different control algorithms have appeared and achieved some results. Literature [2] puts forward a braking model suitable for controller design by analyzing the composition and characteristics of the train braking system. In Literature [3], the parametric model of train braking was obtained by analyzing the experimental data of parking, but the influence of slope resistance and slope was ignored. In Literature [4], a parking controller based on generalized predictive control is designed. Although it meets the requirements of high-precision parking, it is not applicable to high-speed train controllers because the output of the controller is discrete lever level.

Aiming at the above problems, this paper proposes an accurate parking algorithm based on fuzzy PID iterative control. Firstly, based on the analysis of train traction braking dynamics model, the whole train stopping process is summed up as an input-output equation, and the input initial value is adjusted by using fuzzy PID iterative learning method. Then the differential dynamics of the train braking stage are solved to obtain the system gradient, and then the corresponding iterative learning

control parameters satisfying the convergence conditions are obtained. The simulation results show that the algorithm not only meets the requirements of parking accuracy, but also takes into account the requirements of energy saving and passenger ride comfort.

2 Train automatic driving process and traction braking model

2.1 The train's autonomous driving process

In the traditional train driving process, the driver forms a general interval operation plan according to the external factors such as the signal representation, the data of the running line, the management of the running time and so on, combined with the driving experience, and then controls the train to make the train run according to the expected target. In Automatic Train Operation (ATO), the ATO controller replaces the driver to control the Train Operation, as shown in Figure 1 below.
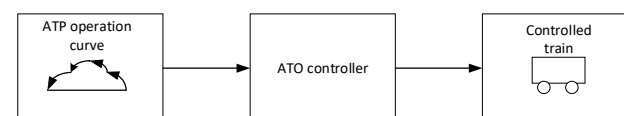

Fig. 1. Automatic train driving system

ATO is an important part of automatic train control system and the core of automatic driving. Automatic Train Control system (ATC) usually includes Automatic Train Supervision system (ATS), Automatic Train

Protection (ATP) and Automatic Train Operation (ATO)[5]. Under the supervision of automatic train protection system ATP, ATO automatically calculates the target running curve of the train by combining the ground information such as the conditions of the line and the signal status, and then controls the operation of the train and automatically generates traction or braking for the train[6]. ATO can automatically adjust the running speed of the train without triggering the ATP command, so that the train can run in the best condition, improve the comfort of passengers and the punctuality of the train, and save energy. At the same time, it can also meet the requirements of the precision of train arrival and the running interval between stations[7].

2.2 Traction brake model

Train braking system is the key equipment to control the speed, stop at the station or ensure the safety of the train in emergency. The existing braking system of high-speed railway is mainly electro-air braking, which can realize deceleration braking by adjusting the ratio of electric braking and air braking. The braking controller realizes the tracking of target acceleration through feedback adjustment, which is a dynamic process[6]. This process can be approximated by a first-order dynamic system, and considering system transmission delays (mechanical and electrical transmission delays), it can be described by the following equation

$$\dot{a}_k(t) = -\frac{1}{\tau} a_k(t) + \frac{1}{\tau} A(t - \sigma) \qquad (1)$$

In the above formula, t refers to the running time of the train; a_k is the control acceleration output by the brake; τ is the time constant of the system response; $A(t)$ is the braking acceleration of the vehicle braking curve; σ is the transmission delay.

The actual acceleration $a(t)$ of the vehicle consists of the control acceleration $a_k(t)$ of the train and the additional acceleration $\Delta a(t)$ caused by the ramp acceleration and resistance in the environment.

$$a(t) = a_k(t) + \Delta a(t) \qquad (2)$$

The speed of the train is determined by the actual acceleration.

$$\dot{V}(t) = a(t) \qquad (3)$$

The target acceleration $a(t)$ is the expected acceleration of the train braking control system, which is generated by the driver or ATO control $U(t)$ (braking instruction), and the relationship between them can be described by the static function relationship.

$$A(t) = F(U(t)) \qquad (4)$$

From the above, it can be seen that the train braking process is a dynamic process that outputs braking instructions from the ATO system controller and controls the actual state of the train through structural time delay such as the control unit. The braking model of the train is shown in Figure 2.
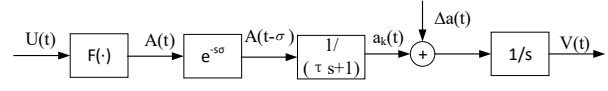

Fig. 2. Train braking model

Equations (1) to (4) describe the dynamic relationship between the traction braking system controlled by ATO, the traction braking command of the train and the dynamic characteristics (speed and acceleration) of the train. Thus, the dynamic state space expression of the train braking stage can be obtained:

$$\dot{x} = Bx + br \qquad (5)$$

In the above equation: B represents the state matrix; b represents the input matrix; r represents the input variable of the control; x represents the current status information of the train, $x = [s\ v\ a\ a_z]$. Where, s, v, a and a_z respectively represent the position, speed, acceleration and temporary acceleration of the train.

The initial state of the train before braking is

$$x_0(t) = [0 \quad v_0 \quad a_k \quad a_{z0}] \qquad (6)$$

After the train completes the braking process, the final state reached, D is the stopping distance of the final train.

$$x_d(t) = [D \quad 0 \quad 0 \quad 0] \qquad (7)$$

Let t_s be the stopping time. When $t > t_s$, the speed of the train after braking and stopping is $v_d = 0$. Define a function

$$R(t) = \begin{cases} f(t) & t < t_s \\ 0 & t \geq t_s \end{cases} \qquad (8)$$

By solving the ordinary differential equation of Equation (5), the general solution can be obtained

$$x(t) = e^{At} x_0 + \int e^{A(t-\sigma)} br(\tau) d\tau \qquad (9)$$

In this paper, the braking model in reference [2] was used for analysis, and the system response time constant $\tau = 1.2s$ and the transmission delay $\sigma = 0.4s$, the corresponding coefficient matrix can be obtained

$$B = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & -2.5 & 2.5 \\ 0 & 0 & 0 & 5/3 \end{pmatrix} \quad b = \begin{pmatrix} 0 \\ 0 \\ -2.5 \\ 10/3 \end{pmatrix} \qquad (10)$$

The dynamic relationship between the final state and the initial state of train braking is described above, and the connecting link is $f(t)$ as defined in Equation (8). The way to stop the train can not only change the lever level of the train, but also change the holding time of different lever level, so the solution of $f(t)$ approaches infinity. In this paper, the method of braking and parking is adopted. Compared with the tracking curve strategy, the braking switching times of traction is reduced. It can not only improve the comfort of the train, but also reduce the wear of the equipment. In equation (8), $f(\tau) = C$, where C is a constant, which is the acceleration value of the output handle of the train during the stop stage. Thus, the final output state D of the train, initial speed, initial

position, and the output power C of the traction handle can be expressed as

$$D = -\int_0^{t_s} \tau f(\tau)d\tau + 0.16v_0 - 0.096a_0 - 0.504a_{z0}$$
$$= -\frac{v_0^2}{2C} + \beta V_0 \quad (11)$$

Among them, the $\beta = 1.6$.

2 Fuzzy PID iterative controller

2.1 Principle of iterative learning

Iterative learning control tries to control the controlled system to correct the unideal control signal by the deviation between the output trajectory and the given trajectory, so as to generate new control signals and improve the tracking performance of the system, that is to find an appropriate input u, so that the state can move along the given trajectory x_d, that is $x=f(u)$[8].

Define the gradient of the system as

$$D(u) = \frac{\partial f(u)}{\partial u} \quad (12)$$

According to the ILC update rate

$$u_{i+1} = u_i + \lambda(x_d - x_i) \quad (13)$$

The output error is

$$e_{i+1} = x_d - x_{i+1} = (x_d - x_i) - (x_{i+1} - x_i)$$
$$= [1 - \lambda D(u_i^*)]e_i \quad (14)$$

In the above formula, u_i^* refers to the input element. As long as the appropriate parameter λ is selected to make $|1 - \lambda D(u_i^*)| < 1$, the convergence of error e can be ensured.

2.2 Fuzzy PID iterative learning control

Fuzzy control has many advantages in the complex system with high uncertainty. The combination of fuzzy control and iterative learning control can make the system have better dynamic tracking performance and improve the convergence speed of the algorithm. In order to improve the system control accuracy, and achieved good control effect, in order to achieve the purpose of smooth running, using fuzzy PID iterative learning control algorithm, using for reference the experience of the traditional PID parameters, and to experience the PID parameters real-time correction, generating higher precision of fuzzy PID learning law, make the system has good dynamic tracking performance, The iterative convergence speed of the system can be improved to meet the needs of safe and stable operation of the system. The structure of fuzzy PID learning control system is shown in Figure 3.
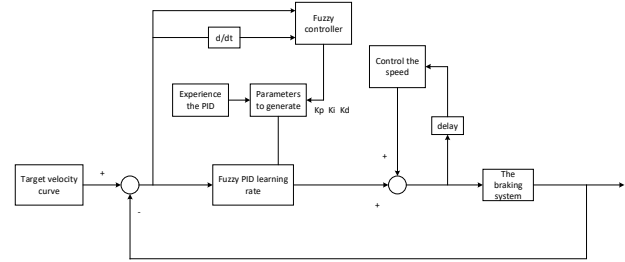

Fig. 3. Fuzzy PID learning control diagram

When PID learning law is adopted, according to the characteristics of the system, it can be seen that K_p is used to improve the response speed of the system and adjust the control precision of the system; K_i is used to eliminate the steady-state error of the system; K_d helps improve the dynamic performance of the system.

Table 1. Fuzzy control rules table

K_P		EC						
		NB	NM	NS	ZE	PS	PM	PB
E	NB	PB	PB	PM	PM	PS	ZE	ZE
	NM	PB	PB	PM	PS	PS	ZE	NS
	NS	PM	PM	PM	PS	ZE	NS	NS
	ZE	PM	PM	PS	ZE	NS	NM	NM
	PS	PS	PS	ZE	NS	NS	NM	NM
	PM	PS	ZE	NS	NM	NM	NM	NB
	PB	ZE	ZE	NM	NM	NM	NB	NB

3 The simulation process

It can be known from Equation (11) that the final stopping position of the train is determined by the initial position, initial speed and braking force of the traction handle when the train enters the stopping stage. Therefore, it is regarded as a control variable, and the initial learning control rate is proposed

$$u_{i+1} = u_i + \lambda e_i \quad (15)$$

In order to realize the high precision tracking of the braking curve of the train braking controller, the controller has good adaptability and robustness in the face of the train running resistance, the additional resistance of the line profile and the unknown disturbance, the fuzzy PID iterative controller is simulated and tested by using MATLAB software.

The dynamic relationship of train braking is shown in Equations (5) ~ (8), and the relevant simulation parameters are shown in Table 2.

Table 2. Simulation parameters

The parameter name	The numerical
Transmission delay T/s	1.2
System response time constant τ /s	0.4
Initial velocity (m · s^{-1})	11.2
Initial acceleration (m · s^{-1})	-0.86
Controller parameter γ_1	0.6
Controller parameter γ_2	0.8

Interference caused by unknown repeatable factors such as slope considered in simulation is normalized into acceleration processing. Simulation results are shown in the figure below.
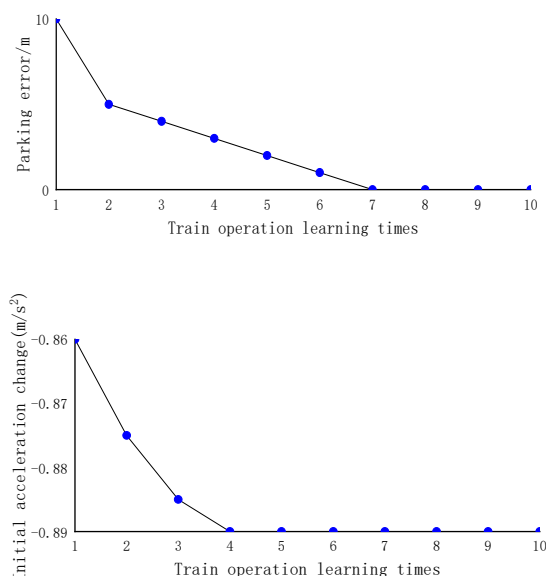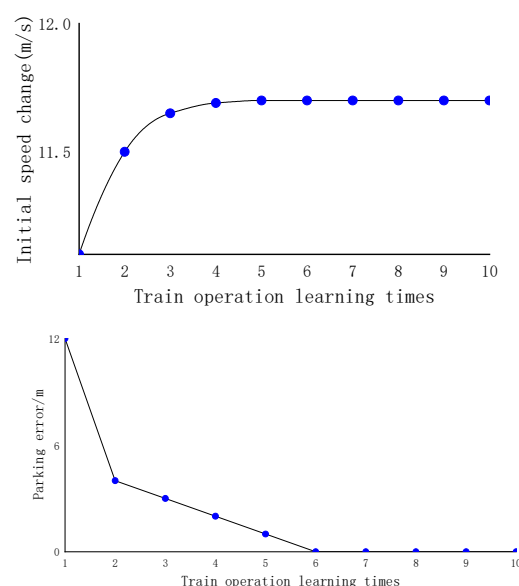

Fig. 4. Initial handle adjustment

Fig. 5. Initial speed adjustment

4 Conclusion

In this paper, the simulation experiment of train stopping accuracy is carried out based on fuzzy PID iterative learning control algorithm, the results show that this method is an effective method to achieve accurate train stopping, and has strong robustness to the uncertain external disturbance and the change of train parameters, which can ensure the safe and efficient operation of the train. The main research contents and results are as follows:

(1) Based on the fuzzy PID iterative learning control algorithm, the traditional PID parameters can be used as a reference for real-time correction of PID parameters to generate a more accurate and higher learning rate.

(2) The learning method with gradient can adjust the initial value and eliminate the repeated disturbance of the deviation of the initial value, so that the system can run more safely and stably.

(3) The simulation results show that the algorithm can satisfy the parking accuracy and give consideration to the passenger's comfort requirements.

In this paper, the iterative learning control with single initial value is adopted in the research process, which belongs to the model of single input and single output. In the future, the research object can be generalized to multi-variable iterative learning control to obtain a more accurate parking mode. Starting from this point, it will be the author's further research on the train braking problem in the next stage.

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