Simulation of Comfort Algorithm for Automatic Driving of Urban Rail Train

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***Abstract*—The automation and intelligence of transportation vehicles is the focus and hotspot of the future research and development of the entire transportation industry, which can effectively improve a series of social problems such as traffic accidents, exhaust pollution, and traffic jams caused by the current increase in the number of transportation vehicles. With the rapid development of rail transit in our country, more and more people choose urban rail transit for travel, which is greatly convenient for travel. The comfort of Automatic Train Operation (ATO) system is an inevitable consideration when people choose it. Aiming at the comfort of ATO system, this paper designs a train operation target curve that can meet the comfort index of train. At the same time, two simulation models are established by using the SIMULINK module of MATLAB software to compare the experiments. One model is the train simulation model based on PID control, and the other model is the train simulation model based on fuzzy PID. The final simulation results show that fuzzy PID control has stronger superiority in train comfort in the process of train motion simulation, and the traditional PID control is not as good as fuzzy PID control in train comfort.**

Keywords-Comfort; Urban Rail Transit; Target Curve; PID Control; Fuzzy PID Control

I. INTRODUCTION

In recent years, the technology of unmanned train driving has developed rapidly, and has been put into a small range of actual operation in many cities. The research on the unmanned Train system is comprehensive and multi-angle, including the Operation research of the whole Automatic Train Operation (ATO) system, the research on the topology structure of multiple trains, the research on the train communication technology, the research on the train modeling and analysis. Research on the control method of train speed and so on. K. I. Yurenko et al. systematically analyzed the characteristics, advantages and disadvantages of known types of Automatic Train Driving (ATD) systems from the perspective of modern technology and automatic control theory. The improved classification of each ATD system according to the structure and function principle of the system is proposed [1], so that the developers on the locomotive can compare different construction methods of the automatic driving system according to the system specifications, and promote the continuous development of the automatic driving technology system.

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With the development of rail transit and communication technology in the world, new signal and control systems are also constantly updating the current communication-based train control, with continuous two-way communication track with the train, which can provide timely information about the train and line status. Mariano Di Claudio et al. improved the consistency between the analysis and implementation phases by adopting a model-driven [2] approach to describe the development of ATO systems. The main modules of the system, starting from the functional requirements, are modeled in UML notation, while state diagrams are used to show their behavior, and the consistency, completeness and correctness of the model are verified. P. Caramia et al. summarized the research on multiple ATO systems, pointed out the mainstream research direction of using numerical algorithms to solve optimization problems, and summarized multiple control objectives of current autonomous train systems, including energy saving, punctuality and ride comfort [3]. South Korea also leads the world in the research of autonomous Train system, including the improvement of Automatic Train Stop (ATS) system [4]. The in-depth study of the Automatic Train Protection system (ATP) system [5], and the research of the radio based overall train control system in Korea [6].

A relay feedback self-tuning Proportional Differential (PD) control system developed by Reza Dwi Utomo and Lei Chen for ATO system [7], The proposed controller is evaluated by three key performances: whether it follows the predetermined trajectory, whether it runs on time, and whether it has better integrated absolute error and integrated square error compared with the traditional controller. The results show that the proposed controller is superior to the traditional controller.

II. RELATED WORK

A. Research status of train comfort

With the rapid development of China's economy, subways, high-speed railways and bullet trains have become an important tool for more people to travel. Passenger comfort has become another issue to be considered in automatic train control. How to meet the comfort requirements of passengers while improving the speed is another challenge in front of us. Feng et al. transformed the train model into solving the optimal constraint problem, simplified the optimal driving problem by reducing the variable dimension, considered the infinite-dimensional driving problem with finite-dimensional decision variables, and designed a controller with predictive correction to solve the tracking path, so as to establish a driving strategy with optimal ride comfort. In the invention patent of Dong Li Jing et al., in order to improve the comfort of trains, it is considered that the jerk degree is directly involved in the design of the controller, and a high-order control method for the jerk degree is proposed. Combined with the distributed controller design, the comfort of trains can be effectively improved, and the control of multi-train formation also increases the overall operation efficiency.

In the research results of more scholars, the train comfort is considered as a posterior index. After completing the design process of the train controller, whether the controller meets the design requirements of the controller comfort is verified through the constraints and design requirements of the comfort. By comparing the advantages and disadvantages of fuzzy control, neural network control and genetic algorithm in the system, the control performance of ATO system is designed and optimized. Such a design method does not consider the comfort of the train, resulting in the design of the train controller in some extreme cases may not meet the comfort requirements.

B. Research status of multi-train cooperative interference suppression

In the process of high-speed train operation, due to the different operation scenarios, the resistance is nonlinear and cannot be accurately expressed, which brings disturbance to the whole control system is inevitable. According to the track constraints of maglev train and the design index of passenger comfort, Long proposed an adaptive disturbance control algorithm and verified its feasibility and superiority by simulation. Ze et al. studied the adaptive fault compensation problem for high-speed trains in the presence of time-varying system parameters, disturbances and actuator faults, and discussed the adaptive failure compensation problem with unknown bounds of disturbances in the presence of parameter failures. By introducing nonlinear damping into the controller, a fault compensation controller [47 is proposed for the model where the system parameters are not separable to achieve an arbitrary degree of position tracking accuracy. In the process of train operation, the loss caused by the traction process and the braking process is inevitable. In view of this phenomenon, Mi gen long et al., considering the time-varying external disturbance in the process of real train operation, the basic running resistance and additional resistance of the train are regarded as disturbance terms, and an optimal preview control algorithm is designed. Finally, the prediction and tracking of train speed were realized. Mssashi Asuka et al proposed an Automatic Train Control method to adapt to the situation of train disturbance. This method assumes that digital automatic train control (ATC) equipment is used to transmit the detection time of the track limit to the train approaching the station. Using this information, each train controls its acceleration through a method consisting of two methods: First, by setting a specified limit speed, the train controls its running time to arrive at the next station in accordance with the predicted delay. Second, the train predicts the time to arrive at the current braking profile generated by the digital ATC, and the time to transition the braking profile forward. By comparison, the train correctly chooses the coast driving mode in advance to avoid slowing down due to the current braking profile The effectiveness of the proposed method in terms of driving conditions, energy consumption and delay reduction is evaluated through simulations.

III. TECHNICAL MODEL

Autonomous driving (ATO), also known as automated driving, autonomous driving technology, or autonomous driving systems, is the technology that enables cars and other vehicles to operate autonomously without human intervention through the use of various sensor and processor technologies. In order to achieve the purpose of improving passenger comfort and punctuality, and saving energy, the automatic driving system uses on-board equipment to control the traction and braking of the train to realize the automatic driving system, and the optimization algorithm can improve the performance of the system. Therefore, in order to improve the performance of ATO, it is crucial to study how to optimize the automatic driving algorithm [8].

When the passenger flow of the city increases, especially during the morning and evening rush hours, the passenger flow of the urban rail train increases sharply. Due to the influence of train vibration, acceleration and deceleration, passengers will be unstable and even uncomfortable, which will affect the ride comfort [9]. ATO applies traction braking to the train in the braking state, which will also cause a large impact rate due to the long delay of the train's response to traction braking [10].

The rapid development of electronic communication technology has made great changes in railway management and operation. Informatization and intelligence of train management and operation have become a new direction of railway development [11].

In order to improve the comfort of urban rail trains, this paper mainly studies two aspects.

(1) Firstly, the target curve of train operation is designed, and the optimal design is found by analyzing the influence on comfort.

(2) PID algorithm, fuzzy PID algorithm and other algorithms are used to track the target curve, and the differences between different algorithms are compared.

A second-order transfer function is used to describe the model of the train. Through the analysis and identification of the experimental data, the transfer function can be expressed by Equation (1) [12].

$$G(\mathrm{s}) = \frac{0.07128}{s^2 + 0.4356s + 0.0324} \tag{1}$$

A. Comfort evaluation index

In the process of train operation, there are many factors that affect the comfort of the train, among which the main influencing factors are interior noise, pressure, temperature, odor, toilet facilities, vibration, etc. [10]. Many evaluation criteria of ride comfort have been proposed abroad, and their research on ride comfort evaluation criteria is relatively mature, such as UIC513 standard of the International Railway Union, Sperling standard of Germany, ISO2631 standard of the International Organization for Standardization, etc. [13]. Many domestic scholars have studied how to evaluate the riding comfort of urban rail transit trains by using the UIC513 standard. UIC513 comfort evaluates the riding comfort by using the train's lateral, longitudinal and vertical acceleration [14-16]. Sperling smoothness index is mainly used to comprehensively evaluate the lateral and vertical vibration acceleration of vehicle operation [17]. IS02631 standard quantified the vibration exposure limit value of human body in the range of vibration frequency from 1 Hz to 80Hz.

From the perspective of ATO system, in order to ensure the comfort of passengers, the acceleration of the train should not be greater than $1.52m/s^2$ [18]. TB/T2543-1995 "Passenger train Longitudinal Impulse Evaluation Method" points out that the train impulse acceleration change rate can be used to evaluate the train driver's operation stability, and on this basis, the train longitudinal acceleration change rate (i.e., impact rate) is used as an index to evaluate the comfort of high-speed ATO system [19]. The analysis shows that the change in acceleration leads to worse comfort. The rate of change of acceleration is the impact rate, the higher the impact rate, the worse the comfort. The expression formula of impact rate is as follows.

$$J = \frac{\Delta a}{\Delta t} \tag{2}$$

In the expression, J is the impact rate, a is the acceleration, and t is the time. The comfort index of ATO system of high-speed train: the impact rate is not greater than $0.5m/s^3$ in starting and stopping stages, and not greater than $0.4m/s^3$ in other stages.

B. Train operation target curve design

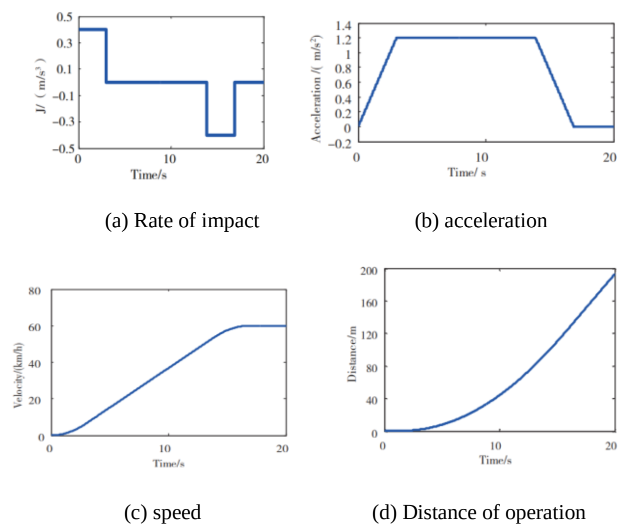
In order to improve the ride comfort of urban rail transit, the precondition is to set the train operation target curve that meets the comfort requirements.

Through the analysis, it is concluded that there are two typical stages of train operation: speed adjustment stage and constant speed operation stage. In the constant speed operation phase, the acceleration is equal to zero, so it meets the comfort requirements. However, the speed adjustment phase is certainly accompanied by a change in the acceleration of the combined external force, and the change in acceleration and its acceleration itself are key factors affecting comfort. Therefore, this paper mainly designs the target curve of the train starting phase.

When ATO regulates the speed of the train, a large traction force cannot be applied to the train immediately, otherwise the ride comfort will be seriously affected; therefore, the traction stage should be gradually increased to reduce the impact rate. In the process of train operation, the traction force cannot be withdrawn immediately after the desired target speed is reached [20], so as not to cause harm to passengers. Therefore, the traction force should be gradually increased and then gradually decreased in the starting phase, which not only increases the ride comfort of the train, but also saves energy.

Considering the longitudinal impact between the train vehicles, a certain margin is set for the comfort parameters, and the maximum value of the impact rate is $0.4m/s^3$ and the maximum value of the acceleration is $1.2m/s^2$ in the starting phase. In order to reduce the impact on the rapidity of the automatic driving system, the train acceleration was linearly increased with the impact rate of $0.4m/s^3$ and the impact rate was reduced to zero when the acceleration reached $1.2m/s^2$ Then the velocity is linearly increased with an acceleration of $1.2m/s^2$ Finally, with an impact rate of $-0.4m/s^3$ the train acceleration linearly decreases to zero, the train speed reaches the target speed, and the start phase is completed.

The target speed of 60km/h in the starting phase is taken as the target for the design, and the curve of the impact rate, acceleration, speed and running distance of the train as a function of speed is shown in Figure 1.



(a) Rate of impact (b) acceleration

(c) speed (d) Distance of operation

Figure 1 Variation of impact rate, acceleration, speed and running distance with speed in the start-up phase

Affected by the characteristics of the line, the driver must keep the speed of the train within the speed limit when operating the train, so as not to trigger the ATO to brake the train and cause unnecessary harm to the passengers. Therefore, the design of the train operation target curve is transformed into the design of the change law of the speed with the running distance. Therefore, by using the speed and distance change law with time, the change law of the train starting stage is obtained by calculation and data fitting, as shown in Table I. The change law of the target speed in the train starting stage with the travel distance is listed in Table 1. When the train reaches the target speed, the train enters the constant speed running state, and the target curve of train operation used in this paper is shown in Figure 1.

In the table above, a_0 =13.64, a_1 =-1.108, b_1 =-3.603, a_2 =0.5904, b_2 =-0.7355, a_3 =0.1957, b_3 =-0.01202, a_4 =0.01595, b_4 =0.01363, w =0.0326.

TABLE I THE VARIATION OF TRAIN SPEED WITH RUNNING DISTANCE IN THE STARTING STAGE

Speed of operation /m	**Speed of train /** $Km \bullet h^{-1}$
$0 \sim 1.8$	$3.6\left(1.8s^2\right)^{\frac{1}{3}}$
$1.8 \sim 92.706$	$3.6\left(-1.8+0.6\left(3+\left(\frac{20s}{3}-3\right)^{0.5}\right)\right)$
$92.706 \sim 140.6$	$3.6*\begin{pmatrix} a_0+a_1*\cos(x+w)+b_1*\sin(x*w) \\ +a_2*\cos(2*x*w)+b_2\sin(2*x*w) \\ +a_3*\cos(3*x*w)+b_3\sin(3*x*w) \\ +a_4*\cos(4*x*w)+b_4\sin(4*x*w) \end{pmatrix}$
	$3.6\begin{bmatrix} a_0+a_1\cos(xw)+b_1\sin(xw) \\ +a_2\cos(2xw)+b_2\sin(2xw)+a_3\cos(3xw) \\ +b_3\sin(3xw)+a_4\cos(4xw)+b_4\sin(4xw) \end{bmatrix}$

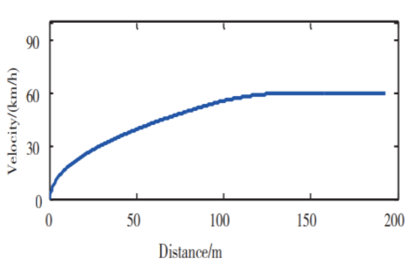


Figure 2 Train operation target curve

IV. EXPERIMENTAL AND ANALYSIS

A. Controller design and its simulation

1) Traditional PID controller

Traditional PID control uses proportion, integral and differential effects to adjust the controlled object, so that it can respond quickly, accurately and smoothly according to the control requirements [19]. The proportional, integral and differential parameters are empirically established to be 16, 10 and 38, respectively, and the PID control system is shown in Figure 3.

The SIMULINK module of MATLAB software is used to complete the construction of PID controller and train speed control model based on PID controller, and train stability simulation is carried out through this model. The train speed control model based on PID controller is shown in Figure 4.

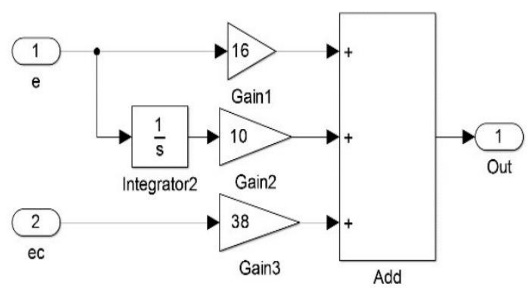


Figure 3 PID control system

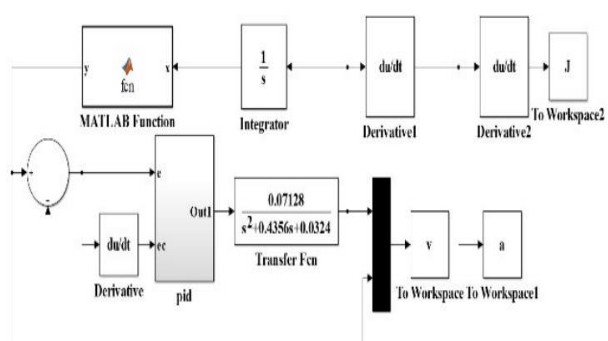


Figure 4 Train speed control model based on PID controller

2) *Design of fuzzy PID controller*

Fuzzy PID controller is composed of PID controller and fuzzy controller, which has good robustness and stability.

The input variables of the fuzzy PID controller are the deviation e and the deviation change rate ec. The output variables are the proportional system ΔK_P , the integral coefficient ΔK_I , and the differential coefficient ΔK_D of the PID controller. The range of input variable e is [-0.3, 0.3], the range of ec is [-0.1, 0.1], and the range of output variable is both [-6, 6]. Fuzzy subsets of input and output variables are {negative large, negative medium, negative small, zero, positive small, median, positive large}, which can also be expressed as {NB, NM, NS, ZO, PS, PM, PB}, and their membership functions are all triangles. The fuzzy PID control system is shown in Figure 5, and the train speed control model based on fuzzy PID controller is shown in Figure 6.

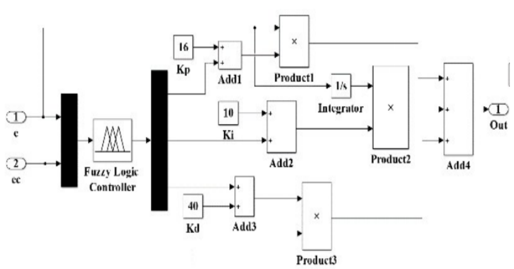


Figure 5 Fuzzy PID control system

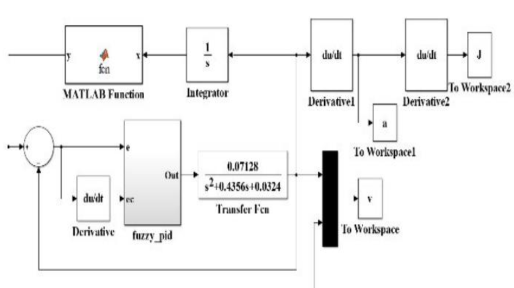


Figure 6 Train speed control model based on fuzzy PID controller

B. *Simulation result generation*

According to the model created in Figures 4 and 6, the simulation is carried out to facilitate the analysis of the correlation index with the comfort of the train in the next step. The tracking situation of train speed under the action of PID controller is shown in Figure 7, and the results of train speed control by fuzzy PID controller are compared. The changes of impact rate and acceleration with time under the action of two control methods are shown in Figure 9 and 10, respectively.

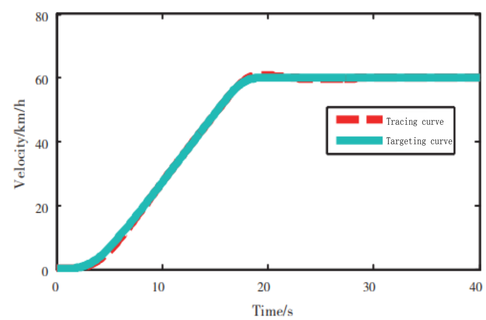


Figure 7 The v-t target curve and tracking curve of train operation under the action of PID controller

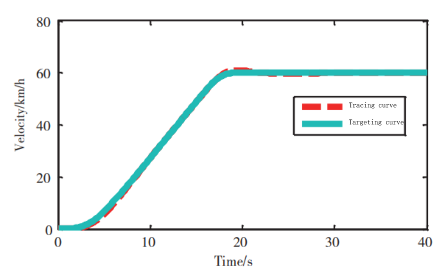


Figure 8 The v-t target curve and tracking curve of train operation under the action of fuzzy PID controller

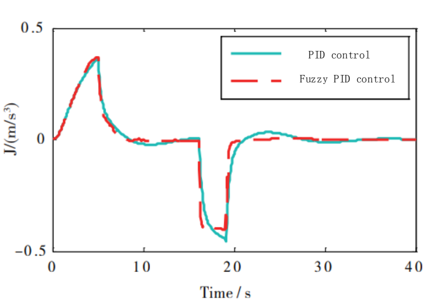


Figure 9 Curve of train impact rate with time

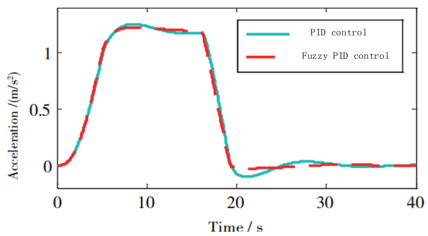


Figure 10 Curve of train acceleration over time

C. Analysis of experimental results

Combining Figure 7 and Figure 8, it can be seen that under the action of PID controller and fuzzy PID controller, the tracking characteristics of the train to the target speed curve are ideal, however, under the action of fuzzy PID control, the overshoot of the speed is relatively small. As can be seen from FIG. 9, the impact rate in the process of train operation under the two control functions meets the comfort requirements. However, under the PID control condition, the impact rate has an overshoot of 10% relative to the set value of $0.4m/s^3$, and the fuzzy PID fully meets the requirements of the set value without overshoot. As can be seen from Figure 10, the acceleration of the train in the process of operation under the two kinds of control meets the comfort requirements, but the acceleration has an overshoot of no more than 5% compared with the set value $1.2m/s^2$, while the overshoot of fuzzy PID control is smaller. It can also be seen from Figs. 9 and 10 that both controllers fully meet the requirements of comfort when moving from the starting phase to the constant speed operation phase.

V. Conclusions

In this paper, with the help of MATLAB system simulation software, aiming at the performance index of urban rail train comfort, the target curve in line with the comfort of train operation is designed, and the PID control system and fuzzy PID control system are built to track the train speed model. Through the comparison and analysis of the tracking curve, the following conclusions are drawn: when the train enters the stage of constant speed operation, the comfort of the train fully meets the standard requirements. However, compared with the traditional PID control, the fuzzy PID control has stronger stability in tracking the train speed in the acceleration phase. Not only its acceleration meets the comfort requirements, but also the impact rate meets the design requirements. In improving the comfort of the train, the fuzzy PID shows greater superiority.

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