Implicit generalized predictive control method for high-speed train

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Abstract: The running process of the train which can high speed running is a typical nonlinear process, and with the higher and higher velocity of the train which can be driven extremely fast, the characteristics of the nonlinear will be stronger than before, which leads to higher requirements for the design of the “Automatic Train Operation” driving system. Aiming at the characteristics of high-speed train running speed fast, complex operation process and strong nonlinearity, the mathematical model establishment and the speed tracking control method are studied. This article uses a data-driven modeling method. Firstly, the actual operation data of high-speed trains based on traction and braking forces are divided into two parts: traction and braking. Then, the linear models of the traction and braking models of the train, which can be driven very fast, are established respectively. These two models adopt the recursive least square method. Then use implicit generalized predictive control to achieve tracking control of high-speed train speed. The simulation results based on the operating process data of CRH380AL is given that this method can make the requirements that belong to high-speed train operation.

1. Introduction
The high-speed train is now a very popular means of transportation in the world. Its existence makes the distance between cities and cities and even countries and countries become closer. It has fast driving speed, high safety performance, strong transportation capacity, and low energy consumption advantages [1]. The operating process of high-speed trains is a complex, large-scale, and uncertain nonlinear dynamic process. The operating speed is much higher than that of subways and light rails, and the railway line conditions are more complex, making it difficult to establish accurate train motion models [2]. Therefore, it is necessary to study the modeling and control methods of high-speed trains, and it has important practical significance and application prospects.

At present, the operation of the train, which can be driven very fast, relies on the guidance of the train control system, and the driver manually operates the control mode, based on the actual operating conditions and the V-S curve (train running speed-travel distance curve) between the given stations [3]. This means that the driver's operating experience and operating skills are critical. An experienced driver can control it well, but safety and punctuality are difficult to be 100% guaranteed. Therefore, the study of accurate high-speed EMU operation process modeling methods and effective and practical operation control strategies has important practical significance for improving the operational performance of high-speed EMUs [4].
In the control of speed tracking during the operation of high-speed trains, the literature [5] combines fuzzy theory with PID controllers to design a fuzzy PID controller. The fuzzy controller is used to calculate the three parameters of P, I, and D, and then these three parameters are used for PID calculation to realize train speed control and achieve better control effects. However, its control force changes rapidly in the transitional phase of operating conditions, which affects the comfort of passengers.

In recent years, in the field of industry and control, in some way, generalized predictive control has been widely used. Literature [6] proposed another way of thinking, applying generalized predictive control to the control of high-speed trains to achieve its high-precision position and speed tracking control. However, the drawbacks of this method are also very obvious. Because of the need for multi-step prediction in the above-mentioned generalized predictive control algorithm, it is necessary to solve the Diophantine equation and matrix inversion multiple times, which is a huge workload. In this article, the author also designs an implicit generalized predictive controller to control the operation of trains running in a fast manner. This change allows the controller to directly identify and obtain the parameters in the optimal control law based on the input/output data, thereby avoiding a large number of intermediate operations brought about by the online solution of the Diophantine equation.

2. Description of the high-speed train dynamics model

It can be seen from the above two documents that the control of the high-speed train operation process is very complicated. Safe punctuality and high-speed and high-density operation are factors that must be considered. In addition to the control objectives, the parking accuracy of high-speed trains, energy consumption, and passenger comfort must also be considered. Therefore, on the basis of control analysis, we need to conduct dynamic analysis and mathematical description of trains running during high-speed operation. Then the dynamics of the CRH380AL high-speed train during operation can be described as follows:

\[
\begin{align*}
\frac{dv}{dt} &= a \\
m\frac{dv}{dt} &= u - w_0 - w_f \\
w_0 &= A_0 + B_0 v + C_0 v^2 
\end{align*}
\]

In formula (1), \( v \) is the operating speed of the high-speed train, \( m \) is the total mass of the high-speed train, \( u \) is the unit control force (traction/braking force) received by the high-speed train, and \( w_f \) is the additional resistance of the high-speed train (the high-speed train passes through ramps, curves). \( w_o \) is the basic resistance experienced by high-speed trains. The basic resistance of trains is composed of many factors, including air resistance, friction resistance, etc. \( A_0 \), \( B_0 \), \( C_0 \) is the resistance coefficient of basic resistance, and the dynamic model of CRH380AL high-speed train operation process can be obtained from formula (1):

\[
m \frac{dv}{dt} + C_0 v^2 + B_0 v + A_0 + w_f = u
\]

In formula (2), the resistance coefficient, \( A_0 \), \( B_0 \), \( C_0 \) is random, and the value is generally obtained by experiment. \( C_0 v^2 \) is a nonlinear function of speed and represents air resistance. As the speed of high-speed trains continues to increase, the proportion of basic resistance \( w_o \) will increase, so the nonlinear characteristics of high-speed trains will become more obvious.

3. High-speed train modeling

Through the study of the above two formulas, it can be seen that the nonlinear system is the most common system. Then the train system is a typical nonlinear system. It does not have high requirements on the model of the controlled object. Only need to know the input and output data of the system can realize the recognition effect of unbiased, minimum variance, and uniform convergence.

By comparing two sets of train control force and train running speed data, two models of traction
and braking can be established to describe the nonlinear dynamic process of high-speed trains. Then, the recursive least square method is used to identify the high-speed train operation process, and the corresponding linear model is established to obtain the traction and braking model of the high-speed train operation process.

3.1 Identification of dynamic model

For the high-speed trains models, which is traction and braking, the recursive least-squares method which is the method used to identify the time-varying parameters in the formula, and the corresponding linear models are obtained. The parameter is given below, and the algorithm of recursive least squares is as follows:

\[
\hat{y}(k) = \hat{y}(k-1) + K(k) [y(k) - \varphi^T(k) \hat{y}(k-1)]
\]

\[
K(k) = \frac{P(k-1) \varphi(k)}{\lambda + \varphi^T(k) P(k-1) \varphi(k)}
\]

\[
P(k) = \frac{1}{\lambda} [I - K(k) \varphi^T(k)] P(k-1)
\]

In the formula, the initial value \( \hat{\theta}(0) \) is a zero vector or a sufficiently small positive real vector; \( P(0) = (10^4 \sim 10^{10}) \), and the forgetting factor \( \lambda \) must be a positive number close to 1, usually not less than 0.9.

For the need of implicit generalized predictive controller design, this paper selects the single-input single-output controlled autoregressive integral moving average process model (CARIMA) for discussion. Because this model can describe non-stationary disturbances, the steady-state error of the system output can be zero, and the deviation caused by step disturbances can be eliminated. The high-speed train model can be defined as:

\[
A_1(z^{-1}) y(k) = B_1(z^{-1}) u(k-1) + \xi(k) / \Delta
\]

4. Implicit Generalized Predictive Speed Tracking Control

It can be clearly seen from the above formula that the traditional generalized predictive control algorithm has good control performance, but the shortcomings are also very obvious. The calculation is large, and the algorithm is very complicated compared to the previously mentioned nonlinear algorithm. Yes, and under the current modeling conditions, this algorithm is still limited by stability \(^9\). This paper combines generalized predictive control and dynamic matrix control and proposes an implicit generalized predictive self-adjusting control algorithm to track the target speed of high-speed trains. This algorithm overcomes the shortcomings of dynamic matrix control and generalized predictive control.

![Figure 1. Implicit generalized predictive speed tracking control block diagram.](image)

It can be seen from Figure 1 that this is a high-speed train implicit generalized prediction speed tracking control block diagram. The error between \( y \) is the output of the predictive control and \( y \) is the target output is used as the input of the implicit generalized predictive controller. The implicit generalized predictive controller is calculated by the correlation calculation Control power \( u \) to realize the speed tracking of high-speed trains.
5. Simulation and analysis
For studying the effectiveness of the model based on the high-speed train and the model based on high-speed train speed tracking control methods, this paper selects a simulation object, which is a new generation of CRH380AL high-speed train running on the Beijing-Shanghai high-speed railway. Then it can be shown in table 1.

| Parameter name                  | Parameter characteristics |
|---------------------------------|---------------------------|
| Total train weight/ t           | 890                       |
| Maximum train speed/ (km* h⁻¹)  | 380                       |
| Continuous train speed/ (km* h⁻¹)| 350                       |
| Unit basic resistance/ N        | $w = 5.2 + 0.038*v + 0.001112*v^2$ |

First, this research collect the operating data of the CRH380AL from Xuzhou East to Jinan West (4610 operating speed and control force data), and divide the actual high-speed train operating data into traction data and braking data according to traction and braking force. Then, use the method mentioned before, the recursive least square method to identify the parameters of the traction braking model, and finally, use the implicit generalized predictive control method, realizing the speed tracking control of the high-speed train for the established traction and braking models.

When the sampling period is 1s, the model set is established as follows:

**Traction model:**

$$y(k) = 1.4965y(k-1) - 0.4965y(k-2) + 0.55\Delta u(k-1) + \xi(k)$$

**Braking model:**

$$y(k) = 2.0016y(k-1) - 1.0016y(k-2) + 0.065\Delta u(k-1) + \xi(k)$$

5.1 Speed tracking control
Based on the established traction and braking model, the implicit generalized predictive control method is adopted (prediction length $p = 6$; control length $m = 2$; time-domain length $Q = 6$; control weighting coefficient $R = 0.8$; softening coefficient $\alpha = 0.3$). The Xuzhou East-Jinan West high-speed train on the Beijing-Shanghai high-speed rail line carries out speed tracking control.

![Figure 2. Speed tracking curve.](image-url)
Figure 2 shows the speed tracking curve, where \( y_t \) is the target speed curve and \( y \) is the speed tracking curve.

![Speed tracking curve](image1)

**Figure 3. Speed tracking error curve.**

Figure 3 shows the velocity tracking error. By observing Figures 2 and 3, we can see that the implicit generalized predictive control method has good tracking performance under traction, constant speed, and braking conditions. This also shows that this method can play the tracking performance very well. Therefore, after adopting the implicit generalized predictive control method, we can obtain the control output to track the target speed well and can easily control the speed error within the allowable range and meet the limit speed condition. This makes it easier to keep the train in a safe range.

![Acceleration tracking curve](image2)

**Figure 4. Acceleration tracking curve.**

Figure 4 shows the acceleration tracking curve of a high-speed train. It can be seen from the figure that the range of acceleration is within and meets the conditions of passenger comfort (the acceleration is less than \( \pm 1 \text{m/s}^2 \), the passenger is very comfortable).

### 6. Conclusions

Based on the establishment of the train traction and braking model, this paper proposes an implicit generalized predictive control method to realize the speed tracking control of high-speed trains. The final results show that the advantage of this control method is not only that it can achieve high-precision, high-stability, and robust high-speed train tracking control, but more importantly, it reduces the amount of calculation and saves time so as to better meet the needs of high-speed trains.

### Acknowledgments

This work was financially supported by the EMU maintenance technology professional group talent training international education innovation team and Innovative teaching team of railway vehicle teachers.
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