High-speed train speed tracking control based on active disturbance rejection control strategy

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Abstract. The speed tracking control of high-speed trains has the characteristics of nonlinearity, time delay, and multi-factor interference. Aiming at this, a train speed tracking algorithm based on active disturbance rejection control strategy is proposed. First, establish a train control model based on the train dynamics model. Secondly, design a second-order active disturbance rejection controller to set and compensate for unknown disturbances, and then convert the known train parameters to the controlled object for system simulation, the target speed curve is tracked, which proves the feasibility of the auto disturbance rejection control algorithm. Finally, compare traditional PD control algorithms in terms of anti-jamming performance and tracking error. The results show that the high-speed train speed controller based on active disturbance rejection control has greatly improved the tracking speed accuracy and the robustness of the control system.

1. Introduction
With the development of rail transit system, train driving is gradually by train driver and train automatic protection system. The supervised operation has been transformed into the coordination of ATO and ATP, and the performance indexes have been continuously improved, which is mainly reflected in meeting the speed tracking performance, parking accuracy and comfort. ATO working mode can be realized at two levels: offline optimization working mode and online speed tracking control mode [1]. that is, the optimal target speed curve can be calculated by offline optimization algorithm, and then the train can accurately track the target speed curve through the speed tracking control algorithm online, so as to achieve the purpose of automatic driving. The classical PID control algorithm was used in the early automatic driving system, but with the development of modern control theory and intelligent control, in recent years, scholars at home and abroad have carried out in-depth research on the train automatic driving technology. Jie Yang etc proposed a train speed tracking algorithm based on improved particle swarm optimization (PSO) for active disturbance rejection control (ADRC), in which the parameters of ADRC were optimized and set to achieve the optimal speed tracking. In the optimization problem of recommended speed curve of urban rail train considering ATO control strategy, Based on previous research based on ADRC is proposed high-speed train speed tracking control algorithm, using the differential first tracking of target speed tracking controller to eliminate disturbance and noise, followed by using the expansion of state observer to
estimate the disturbance and compensation, finally use the error feedback controller to realize the optimal tracking target speed.

2. Train dynamics model
Control problem is the process of exerting control force to achieve control purpose in the process of system operation. Therefore, the analysis of control object is the premise of solving control problem. Through reference [2], the force analysis of the control object is carried out to establish the mathematical equation of the model.

![Figure 1. Stress analysis of high-speed train](image)

As can be seen in Figure 1, the forces parallel to the train running direction mainly include traction force or braking force, basic resistance and additional line resistance. If the direction of the specified force is the same as the train running direction, it is positive; otherwise, it is negative. The following single point model of the train can be established according to Newton's Second law [6]:

\[
\begin{align*}
\frac{ds}{dt} &= v \\
M(1+Y)\frac{dv}{dt} &= F(t) - w_0(t) + w_j(t)
\end{align*}
\]

Where \( s \) is the displacement, \( v \) is the real-time speed of train operation, \( F \) is the traction or braking force received by the train, \( w_0 \) is the basic resistance received by the train, and \( w_j \) is to compensate the disturbance resistance.

The running state equation of the train can be obtained through the physical modeling of single point:

\[
\begin{align*}
x'_1 &= x_2 \\
x'_2 &= u(t) + f(x_1, x_2, t) \\
y &= x
\end{align*}
\]

Where \( u \) is the system input, \( f \) is the disturbance under the state variable, which \( y \) is the system output.

3. Optimized active Disturbance rejection controller design
ADRC is developed under the inspiration of PID, which is mainly composed of three parts. The first part of the differential tracker, the main purpose is to prevent the direct input controller to lead to the system jump, use the differential tracker to better stabilize the input. The second and most important part of active disturbance rejection control is extended state observer. Its special feature is that the state observer estimates the remaining states by observing part of the output states of the system and compensates the estimated external disturbances. Finally, in the error feedback control law, TD and ESO outputs are combined with nonlinear perturbation compensation to form the output control quantity of the system.
3.1 Controller structure

Figure 2. schematic diagram of active disturbance rejection controller

Figure 2 shows the active disturbance rejection controller designed according to the controlled object. The tracking signal and tracking acceleration signal of the input speed are obtained through the tracking differentiator, and then the tracking speed and tracking acceleration are sent to the error feedback controller after the difference between them and the observation feedback speed and acceleration. The output control signal of the error feedback controller differs from the total disturbance estimated by the observer and then acts on the controlled object to output the final control speed [8].

3.2 Design of differential tracker

Figure 3. Schematic diagram of differential tracker

\[
\begin{align*}
\text{fh} &= \text{fhan}(x_1(k), x_2(k), u(k), r, h) \\
x_1(k+1) &= x_2(k) + T \cdot x_1(k) \\
x_2(k+1) &= x_2(k) + T \cdot \text{fh}
\end{align*}
\]

In the formula, r is the tracking speed factor, h is the filtering factor, T is the integral step, \(x_1\) is the tracking signal of input v, \(x_2\) is the differential signal of v, fh is the time optimal integer function, its detailed expression is the following equation:

\[
d = r \cdot h; d_0 = r \cdot d; y = x_1 + h \cdot x_2; a_0 = (d^2 + 8r + |y|)^{1/2}
\]

\[
a = \begin{cases} 
  x_2 + \frac{(a_0)}{2} \cdot \text{sign}(y) & |y| > d_0 \\
  x_2 + \frac{y}{h} & |y| \leq d_0
\end{cases}
\]

\[
\text{fhan} = \begin{cases} 
  -r \cdot \text{sign}(a) & |a| > d \\
  -r \cdot \frac{y}{b} & |a| \leq d
\end{cases}
\]
Where $d$ is the linear interval of the sign function $\text{sign}(\cdot), a, a_0, d_0, y$ is the intermediate variable of the fastest control synthesis function.

### 3.3 Design of extended state observer

The extended state observer is a disturbance estimation and compensation device that integrates the internal and external disturbances of the system. Its expression is as follows:

\[
\begin{align*}
z_1(k+1) &= z_1(k) + T(z_1(k) - \beta_0 e(k)) \\
z_2(k+1) &= z_2(k) + T(z_2(k) - \beta_2 \text{fal}(e(k), 1/2, \partial) + bu(k)) \\
z_3(k+1) &= z_3(k) + T\beta_0 \text{fal}(e(k), 1/4, \partial) \\
e(k) &= z_1(k) - y(k)
\end{align*}
\]

Where $e$ is the system output error, $z_1, z_2$ is the observation estimation of velocity and acceleration, $z_3$ is the observation estimation of total disturbance of the system, $y(k)$ is the tracking speed output, and $\text{fal}$ is a user-defined linear function.

### 3.4 Error feedback control law design

Error feedback control law is the control response made by integrating feedback input and tracking input, and its expression is as follows:

\[
\begin{align*}
e_1 &= v_1(k) - z_1(k) \\
e_2 &= v_2(k) - z_2(k) \\
u_0 &= \beta_1 \text{fal}(e_1, a_1, \partial_1) + \beta_2 \text{fal}(e_2, a_2, \partial_2) \\
u(k) &= u_0 - z_3(k) / b
\end{align*}
\]

Where $e_1$ is velocity error, $e_2$ is acceleration error, $\beta_1$ is specific column amplification coefficient, and $\beta_2$ is integral amplification coefficient.

### 4. Simulated analysis

In matlab2016a simulation platform simulation platform for simulation test, using S-function function simulation programming input corresponding functions and parameters.

![Figure 4. Simulation diagram of ADRC system](image)

Figure 4 shows the simulation model designed and built, with step signal as the assumed speed input and S-function as the tracking differentiator, set the parameter to $r=10, h=0.01, T=0.001$. S-function1 is an expanded observer module, set the parameter to $d=0, \text{bet}=[100 \ 65 \ 80], b=1, T=0.001$. S-function2 is the simulation model of high-speed train, derived from formula
2. S-function3 is the critical error feedback controller part, set the parameter to $a=[0.75, 1.25], b_1=[100, 10], b=1, d=0$.

As shown in Figure 5, the controller using ADRC has good performance in tracking speed curve, fast tracking speed, no overshoot, and good stability and rapidity.

In order to compare the performance of the ADRC in tracking train speed, this paper also adopts the classical PD controller for comparative analysis, as shown in Figure 6, the comparison results show that the strategy using ADRC to control train tracking speed is obviously superior to PD controller in both rapidity and stability of tracking speed. This proves that the train speed tracking controller designed with ADRC strategy has certain necessity and advantages.

5. Conclusion

In this paper, a high-speed train speed tracking controller based on active disturbance rejection control strategy is designed for high-speed train speed tracking control. Firstly, the single-point model of high-speed train is established. Secondly, a second-order nonlinear active disturbance rejection controller is designed. Then, simulation software is used to verify the speed tracking based on the active disturbance rejection controller. The results show that the controller has excellent performance in tracking rapidity and stability. Finally, by comparing the designed ADRC with the traditional PD controller, it is proved that the ADRC has better control performance in high-speed train speed tracking than the traditional controller, which provides a new idea and direction for engineering design.

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