Tracking control via sliding mode for heavy-haul trains with input saturation

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Abstract
To address the tracking control problem of heavy-haul trains (HHTs) with input saturation during operation, an anti-saturation sliding mode (SMES) control method based on dynamic auxiliary compensator (DAC) is presented. Firstly, an HHT model with nonlinear coupling and uncertain disturbances is built. Secondly, a new type of DAC is introduced to overcome the difficulty of traditional dynamic auxiliary compensator (TDAC) with a large upper bound on the compensation signal. Finally, an anti-saturation SMES control algorithm is designed to reduce the influence of input saturation on the tracking accuracy of each carriage. Simulation results verify the effectiveness of the algorithm in terms of tracking accuracy, anti-interference, and anti-saturation.

Keywords
Heavy-haul trains, input saturation, dynamic auxiliary compensator, sliding mode control

Introduction
During actual operation, HHTs are restricted by Automatic Train Protection (ATP) System due to various operating conditions (e.g. road sections and environments). This results in train speed restrictions. In addition, the output of controller does not match that of actuator, causing input saturation. Therefore, improving the tracking accuracy of HHTs under the influence of input saturation has become a popular research topic amongst many scholars.

The last few decades have witnessed progress in the development of anti-saturation tracking control technology for HHTs. Saturation error is traditionally treated as a system disturbance to obtain a good control effect. However, the real-time tracking performance is different from the expected effect. Therefore, in order to ensure that the faults caused by input saturation are quickly and effectively suppressed during train operation, we need to consider two control objectives. First, an auxiliary system is designed to ensure the stability of train system and improve its dynamic adjustment capability. Second, a designed anti-saturation controller improves the tracking accuracy of the train while ensuring the stable operation. The introduction of dynamic and static auxiliary compensator compensates the deviation caused by input saturation, and becomes an effective control strategy.

However, due to the complexity of the train operation, the static auxiliary compensator is slightly insufficient in the performance of dynamic adjustment. Ji et al. presented an adaptive iterative learning control strategy, which compensated for the nonlinear effects brought by input saturation and solved the problem of time-varying time lag in high-speed train operation. Li et al. designed an anti-saturation controller based on a static auxiliary compensator to realise the problem of multi-car and multi-train input saturation separately. Lin et al. responded to high-speed trains with input saturation, the control algorithm of adaptive neural network can tracked the error in a bounded range. A static auxiliary compensator that satisfies the effect of system tracking control is adopted for saturation error compensation in above method. However, the static auxiliary compensator does not consider internal state variables. Thus, the adjustment range and the tracking accuracy have certain limitations.

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To simultaneously stabilise the HHTs system and its state during operation, DAC effectively compensates for the deficiency of static auxiliary compensator by considering internal variables. Zhao et al.\(^2\) studied the input saturation problem of a robot manipulator, and designed an adaptive neural controller by combining a dynamic auxiliary system to make position error converge to a bounded domain. Under the influence of input-constrained faults, Bai et al.\(^2\) used the influence of input-constrained faults, uses input and output observations to design a fault filter to suppress the effects of residual interference. Although the above researches improve the tracking accuracy, the upper bound of the DAC compensation signal is extremely large.\(^2\) Consequently, the high precision requirements in practical applications are difficult to satisfy in practical applications.

This paper introduces a DAC to address the input saturation problem for HHTs. An anti-saturation SMES controller is designed by combining an improved DAC with the SMES control algorithm to ensure the displacement and speed of the \(i\)th carriage, respectively. \(k_i\) and \(h_i\) are the coefficients of spring and damping of the \(i\)th carriage, respectively. The running resistance of the train during its operation is

\[
D_{fi} = a_{i1} + a_{i2}v_i + a_{i3}v_i^2 + \Phi_i
\]

where \(a_{i1}, a_{i2},\) and \(a_{i3}\) are the known basic resistance coefficients, \(\Phi_i\) includes the additional resistance for ramps, curves and tunnels.

To meet the research needs, equation (4) is rewritten as

\[
X'_i = AX_i + Bu_i + Cd_i
\]

where

\[
X_i = [x_i \quad v_i]^T; \quad A = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}; \\
H_i = 1/m_i; \quad B = C = [0 \quad H_i]^T
\]

\[
d_i = k_i\Delta x_i - k_{i-1}\Delta x_{i-1} + h_i\Delta v_i - h_{i-1}\Delta v_{i-1} - D_{fi}; \\
\Delta x_{i-1} = x_i - x_{i-1};
\]

\[
\Delta x_i = x_{i + 1} - x_i; \quad \Delta v_{i-1} = v_i - v_{i-1}; \quad \Delta v_i = v_{i + 1} - v_i,
\]

where \(d_i\) represents the unknown compound disturbance to which the train is subjected during operation, the coupling spring–damping coupling force is determined by displacement difference \(\Delta x\) and speed difference \(\Delta v\) between adjacent carriages. \(D_{fi}\) is the measured running resistance during train operation.

Remark 1. During the operation, the unknown compound disturbances \(d_i\) are mainly composed of the coupler spring–damping coupling force and the running resistance. If the springs between the carriages are in a variable range, the distance between adjacent carriages will not increase indefinitely. Furthermore, \(\Delta x\), \(\Delta v\), and \(D_{fi}\) between the adjacent carriages are bounded. Therefore, compound disturbance \(d_i\) is bounded, that is, \(|d_i| \leq d_0\), and \(d_0\) is a positive constant.

In the framework of the above train dynamics model, designing controller \(u_i\) can ensure the displacement of each carriage of train \(x_i\) to track target displacement \(x_{ti}\).
Design and stability analysis of anti-saturation SMES controller

For an input saturation during the stable operation of HHTs, a DAC is designed to suppress the influence of the input saturation. Letting

$$-u_{\min} \leq u_i \leq u_{\max}$$  \hspace{1cm} (6)

where $u_{\min}$ and $u_{\max}$ are known controller lower bound and upper bound of the input saturation, respectively.

Therefore, control input signal $u_i$ is defined by

$$u_i = \text{sat}(u_0) = \begin{cases} u_{\max} & \text{if } u_0 > u_{\max} \\ u_0 & \text{if } u_{\min} \leq u_0 \leq u_{\max} \\ -u_{\min} & \text{if } u_0 < -u_{\min} \end{cases}$$  \hspace{1cm} (7)

where $u_i$ is the actual controller acting on the train system through the actuator, and $u_0$ is the anti-saturation controller to be designed.30

Design of input saturation DAC

When considering the control state of input saturation, anti-saturation controller $u_0$ is designed to deal with the input saturation. Using the principle of the input saturation error amplification, a stable dynamic auxiliary compensation system is designed to compensate for the saturation error. A DAC is designed as

$$\rho_i' = -k_a \rho_i - \frac{H \varepsilon_2 \Delta u + \frac{1}{2} (\Delta u)^2 + k_b \varepsilon_2^2}{|\rho_i|^2} \rho_i + \Delta u, |\rho_i| \geq \varepsilon$$  \hspace{1cm} (8)

where $\Delta u = u_i - u_0, \varepsilon_2 = \varepsilon_{i2} + \varepsilon_{i1}, k_a > 0, k_b > 0, \rho_i$ is the compensation signal of the anti-saturation compensator, and $\varepsilon$ is a small positive constant. The structure of the train during the saturation operation is shown in Figure 1.

Remark 2. In the actual stable operation of HHTs, $\Delta u$ is determined by actual controller $u_i$ and anti-saturation controller $u_0$. Equation (7) indicates that anti-saturation controller $u_0$ and actual controller $u_i$ are bounded. Thus, $\Delta u$ is bounded; Let $||\Delta u|| < \theta$, and $\theta$ is a known constant.

Lemma 1.31,32 Assume that $V(t) \geq 0$ is a bounded continuous function defined for $\forall t \geq 0$. If $V(t) \leq - \phi V(t) + \varphi, \phi$, and $\varphi$ are positive constants, then

$$V(t) \leq \frac{\varphi}{\phi} + \left[ V(0) - \frac{\varphi}{\phi} \right] e^{-\phi t}$$

Lemma 2.33,34 For $\forall (x, y) \in R^n$, the following inequality is established:

$$xy \leq \frac{p^2}{a} |x|^{a} + \frac{1}{b} p^2 |y|^b,$$

where $p > 0$ and $a > 1, b > 1$ and $(a - 1)(b - 1) = 1$.

The stability analysis of the designed DAC is shown as follows.

A Lyapunov function is defined as follows

$$V_2 = \frac{1}{2} \rho_i^2$$  \hspace{1cm} (9)

From (6), (11), and Lemma 2, we obtain a derivative as

$$V_2' = p \rho_i' = p \left[ -k_a \rho_i - \frac{H \varepsilon_2 \Delta u + \frac{1}{2} (\Delta u)^2 + k_b \varepsilon_2^2}{|\rho_i|^2} \rho_i + \Delta u, |\rho_i| \geq \varepsilon \right.$$

If $|\rho_i| \leq \varepsilon$, then

$$|\rho_i| \leq \frac{\varepsilon}{k_a - \frac{1}{2}}$$

Define $\alpha = k_a - \frac{1}{2}$ and $\beta = \frac{1}{2} H_i \theta^2$, then

$$V_2' \leq -2 \alpha V_2 + \beta$$  \hspace{1cm} (12)

According to Lemma 1, the compensation signal is semi-globally consistent and finally bounded. The upper bound is

$$|\rho_i| \leq \sqrt{\frac{\beta}{\alpha} + 2 \left[ V_2(0) - \frac{\beta}{2 \alpha} \right]} e^{-2\alpha t} = \Theta$$  \hspace{1cm} (13)
Therefore, the compensation signal $\rho_i$ of the DAC tends to be bounded and stable.

**Remark 3.** The literature\(^{23}\) provides the compensation signal $\rho_i$ stabilisation formula of the TDAC

$$V'_4 = \rho_i \leq - \left( k_u - \frac{1}{2} \right) \rho_i^2 + \frac{1}{2} H_u \Delta u^2 + \frac{1}{2} H_i e_{2g}^2$$

$$\leq - \left( k_u - \frac{1}{2} \right) \rho_i^2 + \frac{1}{2} H_i \rho_i^2 + \frac{1}{2} H_i e_{2g}^2$$

(14)

Define unknown function $\frac{1}{2} H_i e_{2g}^2 = \chi > 0$, then

$$V'_4 \leq -2\alpha V_3 + \beta + \chi$$

(15)

The upper bound is obtained by Lemma 1 as

$$|\rho_i| \leq \sqrt{\frac{H_0 + \chi}{\alpha}} + 2 \left[ V_3(0) - \frac{H_0 + \chi}{2\alpha} \right] e^{-2\alpha t} = \Theta_1$$

(16)

The specific value or upper bound $\chi$ in (16) must be known to solve the upper bound $\Theta_1$ of compensation signal $\rho_i$. Thus, the engineering solutions are difficult. In this paper, without considering $\chi$, we have achieved the solution of compensation signal $\rho_i$ and narrowed its upper bound by comparing equations (13) and (16).

**Design of anti-saturation SMES controller**

Considering the problem of input saturation during train operation, a SMES controller is designed to reduce the impact of saturation for ensuring the stable operation of trains. Displacement error is defined as follows\(^{35,36}\)

$$e_{ii} = x_i - x_d$$

(17)

where $x_d$ is the target displacement and is $n$-order derivable.

The SMES function is designed as

$$s_i = c_i e_{ii} + e_{ii}'$$

(18)

where $c_i$ is a constant to be designed and $c_i > 0$.

The anti-saturation SMES controller is designed as

$$u_{10} = \frac{1}{H_i} \left[ -c_i (v_i - x_d') + x_d' + \rho_i - \eta_i \text{sgn}(s_i) \right]$$

(19)

From equation (7), we conclude that when considering the saturation control state of inputs, the actual controller acting on the train system is

$$u_i = \text{sat}(u_{10})$$

(20)

**Theorem 1.** For the HHTs Model (5), an actual SMES controller with input saturation (7) is designed. Given parameter settings $0 \leq c_i \leq 2$, $k_u \geq 1$ and $k_h \geq \frac{1}{2} (1 + n\eta_{\max})$, the system signals are semi-globally uniform and ultimately bounded. Displacement tracking error $e_{ii}$ converges to the bounded domain of the origin $\Omega_{eii} = \{ e_{ii} \in \mathbb{R}^n | |e_{ii}| \leq D \}$, where

$$D = \sqrt{\mu + 2 \left[ V(0) - \frac{1}{2\mu} e^{-2\mu} \right]}$$

with $L$ and $\mu$ as defined in (27).

**Proof.** When $|\rho_i| \geq e$, a Lyapunov function is defined as

$$V = \frac{1}{2} \sum_{i=1}^{n} (e_{ii}^2 + e_{ii}'^2 + e_{ii}^2)$$

(21)

From the formula (6) and (11), we obtain a derivative as

$$V' = \sum_{i=1}^{n} (e_{ii}e_{ii} + e_{ii}'e_{ii}' + \rho_i')$$

$$= \sum_{i=1}^{n} \left[ e_{ii}(e_{ii} - e_{ii}') + e_{ii}'(H_u u_i + H_d d_i + e_{ii} - e_{ii} - x_d') \right]$$

$$-k_u \rho_i^2 - \left[ H_i e_{2g} + \frac{1}{2} (\Delta u)^2 + k_h e_{2g}^2 \right] + \Delta u_p$$

(22)

From Lemma 2, we obtain

$$H_i e_{2g} - |H_i e_{2g} - H_i e_{2g} u_0| = H_i e_{2g} u_0$$

$$e_{ii}^2 \leq \frac{1}{2} (e_{ii}^2 + e_{ii}^2)$$

$$\Delta u_p \leq \frac{1}{2} (\Delta u)^2 + \frac{1}{2} \rho_i^2$$

$$H_i e_{2g} - |H_i e_{2g} - H_i e_{2g} u_0| = H_i e_{2g} u_0$$

Equation (22) is written as

$$\leq \sum_{i=1}^{n} \left[ e_{ii}(e_{ii} - e_{ii}') + e_{ii}'(H_u u_i + H_d d_i + e_{ii} - e_{ii} - x_d') \right]$$

$$-k_u \rho_i^2 - \left[ H_i e_{2g} + \frac{1}{2} (\Delta u)^2 + k_h e_{2g}^2 \right] + \Delta u_p$$

(23)

$$\leq -\left( 1 - \frac{1}{2} c_i \right) \sum_{i=1}^{n} e_{ii}^2 - \left( \frac{1}{2} c_i - \frac{3}{2} + k_h \right) \sum_{i=1}^{n} e_{ii}^2$$

$$- (k_u - 1) \sum_{i=1}^{n} \rho_i^2 - \sum_{i=1}^{n} \eta_i e_{2g} \text{sgn}(s_i) - H_i d_i$$

(24)

Select the design parameters $\eta_{\max} = \max\{ \eta_1, \ldots, \eta_n \}$, we have

$$\leq -\left( 1 - \frac{1}{2} c_i \right) \sum_{i=1}^{n} e_{ii}^2 - \left( \frac{1}{2} c_i - \frac{3}{2} + k_h \right) \sum_{i=1}^{n} e_{ii}^2$$

$$- (k_u - 1) \sum_{i=1}^{n} \rho_i^2 + \frac{1}{2} n \eta_{\max} + nd_0 \sum_{i=1}^{n} H_i$$

(25)
When \((1 - \frac{1}{2} c_i) > 0, \quad (\frac{1}{2} c_i - \frac{3}{2} + k_b - \frac{1}{2} n \eta_{\text{max}}) > 0, \quad (k_a - 1) > 0\),

Equation (25) is written as

\[
V' \leq -2\mu V + L
\tag{26}
\]

where

\[
\mu = \min \left( \left(1 - \frac{1}{2} c_i\right), \left(\frac{1}{2} c_i - \frac{3}{2} + k_b - \frac{1}{2} n \eta_{\text{max}}\right), (k_a - 1) \right), \quad L = \frac{1}{2} n^2 \eta_{\text{max}} + nd_0 \sum_{i=1}^{n} H_i
\tag{27}
\]

From Lemma 1, we infer that all signals are semi-globally consistent and finally bounded. Through equation (26), we derive

\[
|e_{ij}| \leq \sqrt{\frac{L}{\mu}} + \left[V(0) - \frac{L}{2\mu}\right] e^{-2\mu t} = D
\tag{28}
\]

Equation (28) is reduced to

\[
\lim_{t \to \infty} |e_{ij}| = \lim_{t \to \infty} |x_i - x_d| \leq \sqrt{\frac{L}{\mu}}
\tag{29}
\]

Similarly

\[
\lim_{t \to \infty} |e_{ij}| = \lim_{t \to \infty} |e_{ij}' + e_{ij}| \leq \sqrt{\frac{L}{\mu}}
\tag{30}
\]

Therefore, the system in the operation of HHTs has input saturation in tracking control, when \(|\rho| \geq \varepsilon\), and the above proof is valid. There is no saturation in the system tracking control, when \(|\rho| < \varepsilon, \rho_i = 0\), and the proof is also valid.

**Remark 4.** Equations (29) and (30) infer that \(e_{ij}\) and \(e_{ij}'\) are both bounded, and the bound of \(s_i\) in the SMES (18) is guaranteed. This implies that the designed anti-saturation SMES controller (19) is valid.

**Remark 5.** When \(k_a \geq 1\) and \(k_b \geq \frac{1}{2}(1 + n \eta_{\text{max}})\) hold, the stability of dynamic auxiliary compensation (9) and train operation systems (21) are simultaneously guaranteed.

**Remark 6.** According to (8), (13), and (30), the upper bound of compensation signal change rate \(\rho_i\) is obtained as

\[
|\rho_i| = \left|\frac{\eta_{\text{max}}}{|\rho_i|} - \frac{H_i e_{\text{max}}^2}{|\rho_i|} \right| + \frac{1}{2}(\Delta u)^2 + k_b e_{\text{max}}^2 \rho_i + \Delta u
\leq k_a |\rho_i| \left(1 + \frac{1}{2} H_i \Delta u^2 + \left(\frac{1}{2} H_i + k_b\right) e_{\text{max}}^2\right) + |\Delta u|
\leq k_a \Theta \left(1 + \frac{1}{2} \Theta^2 (1 + H_i) + \left(\frac{1}{2} H_i + k_b\right) \Theta^2\right) + \Delta = N
\tag{31}
\]

**Simulation results**

In this section, the effectiveness and feasibility of the designed anti-saturation control method are verified by a series of four-carriage train simulations. The parameters of the dynamic model of HHT operation are shown in Table 1.

| Parameters | Value | Unit |
|------------|-------|------|
| \(m_1, m_2, m_3, m_4\) | \(8 \times 10^6\) | kg |
| \(a_{11}\) | \(1.6 \times 10^{-4}\) | N/kg |
| \(a_{21}\) | \(7.7616 \times 10^{-4}\) | Ns/mkg |
| \(a_{31}\) | \(1.176 \times 10^{-2}\) | Ns^2/m^2kg |
| \(k_a\) | \(3 \times 10^3\) | N/m |
| \(h\) | \(4 \times 10^5\) | Ns/m |

![Figure 2. Velocity–displacement tracking diagram.](image)

Therefore, the DAC (8) is bounded and meets the engineering controllability requirement.

**Simulation of input-free saturation tracking control**

For HHTs without considering input saturation control state, the effect of the actual controller is explained by the tracking effect of the displacement and speed of each carriage. Figure 2 shows the 3D response curve of
the speed and displacement of each carriage in the
expected trajectory.

Figures 3 and 4 illustrate the error curve of the
expected trajectory of each carriage in the train.

Figure 3(a) shows that there is only a sudden signal,
each carriage tracks the desired trajectory within 2 s.
To reflect the variability in the actual operation of the
train, mutation disturbance is injected at 10 s, and dis-
placement tracking is realized at 12 s. Figure 3(b) shows
that each car realizes the tracking of the desired trajec-
tory within 4 and 12 s in the case of abrupt signals plus
Gaussian noise.

Figure 4(a) displays that the speed error of the train
converges to 0 within 0.05 s. Figure 4(b) shows that the
train achieves speed error convergence to 0 within 0.2 s.
Meanwhile, the speed tracking diagram shows that the
sudden disturbance and Gaussian noise does not affect
the tracking accuracy.

Figure 5 shows the tracking control effect of each-
carriage during train operation. The figure illustrates
the changes in the controller or torque experienced by
each carriage during stable operation when input
saturation has not occurred.

Simulation of input saturation tracking
When the train is running steadily, the controller or
torque for each carriage suddenly changes and causes
input saturation, causing the train to run abnormally.
The simulation reaches the limit of the torque by limit-
ing the upper and lower limits of the controller for
ensuring that the controller parameters remain
unchanged.

Figure 6 presents the effect diagram of the controller
output state when input saturation occurs. The compar-
ision of Figures 5 and 6 shows that the input saturation

![Figure 3. Multi-carriages displacement tracking error: (a) the abrupt signal and (b) the abrupt signal plus Gaussian noise.](image1)

![Figure 4. Multi-carriages Speed tracking error: (a) the abrupt signal and (b) the abrupt signal plus Gaussian noise.](image2)
of the controller is mainly reflected in following three aspects: the start tracking state, the disturbance joining state, and the controller amplitude.

In this case, the two control effects of the classic anti-saturation control in Zhao et al.\textsuperscript{23} and the designed improved anti-saturation control are compared. Figures 7 and 8 show the displacement and speed error tracking diagrams of the classic anti-saturation control in Zhao et al.\textsuperscript{23} respectively.

From Figure 7(a) and (b), it is found that the peak displacement error caused by the 10 s disturbance is 0.9% and 1.25%, respectively, and the peak value of the displacement error caused by the controller amplitude limitation is 2% and 80%, respectively. Quickly converge to 0.13% and 0.8% bounded areas.

From Figure 8(a) and (b), it is found that the peak speed error caused by the 10 s disturbance is 8% and 7%, respectively. The peak value of the speed error caused by the controller amplitude limitation is 1.5% and 5%, respectively. The train speed tracking error can quickly converge to 0.1%, 0.5% bounded areas. Figures 7 and 8 shows that the buffeting effect is poor during convergence.

This paper designs an improved anti-saturation controller. Figures 9 and 10 are the improved anti-saturation control displacement speed tracking error diagrams. From Figure 9(a) and (b), the peak value of the displacement error caused by the addition of the 10s disturbance is reduced to 0.6% and 1%, respectively, caused by the controller amplitude limitation is
0.16% and 0.15 respectively. The convergence limit of train displacement tracking error is reduced to 0.04% and 0.2%.

From Figure 10(a) and (b), the peak speed error caused by the 10 s disturbance is reduced to 6%, 0.8%, respectively, and the peak amplitude error caused by the controller amplitude limit is 0.1%, 5%, respectively. The speed tracking error convergence limit is reduced to 0.02% and 0.02%.

Figures 9 and 10 shows that the buffeting during the convergence process is well-suppressed.

When input saturation occurs, the comparison results indicate that the designed improved anti-saturation controller designed without changing the controller parameters not only achieves significant effects in suppressing the disturbances caused by input saturation and controller amplitude limitation, but also improves the convergence accuracy of the displacement and velocity tracking errors.

**Conclusion**

This study investigates the tracking control problem of HHTs with nonlinear coupling and uncertain disturbances when input saturation occurs. An anti-saturation SMES control method based on a DAC is presented to realise the bounded tracking of the target curve by each carriage. The introduction of a new type of DAC proves the stability of the dynamic auxiliary compensation system. Meanwhile, it effectively solves and reduces the upper bound of a compensation signal...
and enhances the engineering practicability and controllability. Finally, when the control parameters are unchanged, simulation shows that the algorithm has good anti-interference and anti-saturation capabilities and improves the tracking control accuracy compared with the traditional anti-saturation control.

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