ICIC Express Letters
Part B: Applications
Volume **8**, Number **3**, March **2017**

ICIC International ©2017 ISSN 2185-2766
pp. 593–600

ADAPTIVE ROBUST CONTROL FOR THE SPEED SYSTEM OF COLD STRIP MAIN ROLLING MILL BASED ON GLOBAL INTEGRAL SLIDING MODE

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Received September 2016; accepted December 2016

Abstract. *To weaken the influences of parameter perturbations, load disturbance and other uncertainties on the speed tracking control performance of cold strip main rolling mill, an adaptive robust control strategy is proposed based on global integral sliding mode in this paper. Firstly, nonlinear disturbance observer (NDO) is built to conduct dynamic observation for the mismatched uncertainty in the system speed loop, and the observed value is introduced into the designed global integral sliding mode controller for compensation, so as to improve the tracking precision of the speed system effectively. Secondly, robust controller for the system current loop is designed based on backstepping, so as to effectively improve the* L_2 *interference suppression performance for the matched uncertainty* Δ. *Theoretical analysis shows that t he proposed control strategy can ensure the robust stability of the closed-loop system. Finally, simulation research is carried out on the speed system of a 1422 mm cold strip main rolling mill by using the actual data, and results show the superiority of the proposed control strategy in comparison with the strategies of linear sliding mode control (LSMC) and cascade PI control.*

Keywords: Cold strip main rolling mill, Speed tracking control, Global integral sliding mode, Nonlinear disturbance observer (NDO), Backstepping, Adaptive robust control

1. Introduction.

The automatic control system of cold strip rolling mill mainly includes rolling mill speed control system, strip steel tension control system, strip steel thickness control system, and strip steel plate shape control system, and so on [1], in which rolling mill speed control system plays a very important role in normal, safe and efficient production of cold strip rolling mill [2], and fast, stable and accurate speed tracking control has become an important development direction of modern cold strip rolling mill [3]. However, in the actual rolling process of cold strip rolling mill, the system is influenced by parameter perturbations, load disturbance and other uncertainties, which restrict the further improvement of control precision of cold strip rolling mill.

In order to improve the tracking control precision and robust stability of the speed system of cold strip rolling mill, extensive and in-depth studies have been conducted. In [4], aiming at the rolling mill speed system with actuator input saturation characteristic and bounded disturbance, sufficient conditions that the closed-loop system satisfies invariance and L_2 interference suppression performance were given, and state feedback controller was designed based on linear matrix inequality. [5] regarded the load disturbance and unmodeled dynamics of the system as an integrated disturbance, and extended state observer was constructed to conduct dynamic observation and compensation, then a speed robust controller was designed based on active disturbance rejection control method. [6] proposed a speed control strategy based on flying gauge change (FGC) characteristics of cold strip rolling mill, in which the strip tension setpoint before FGC as the control target avoided the interference of the FGC stand to the others. [7] conducted feedforward compensation for the designed robust controller by using the singular perturbation theory, which not only improved the system robustness effectively, but also realized speed sensorless control for the rolling mill system. [8] adjusted the PID control parameters online by using the fuzzy logic, while this control method has some deficiencies; for example, the online adjustment time is relatively long.

Therefore, for the speed system of cold strip main rolling mill, an adaptive robust control strategy is proposed based on global integral sliding mode in this paper. First, nonlinear disturbance observer (NDO) can be constructed to conduct dynamic observation for the mismatched uncertainty in the system speed loop, which is helpful to improve the tracking control precision of the system. Next, global integral sliding mode controller for the system speed loop can be designed, which is helpful to improve the robust stability of the system. Once more, robust controller for the system current loop can be designed based on backstepping which is helpful to realize L_2 interference suppression for the matched uncertainty Δ. Finally, simulation research is conducted on a 1422 mm cold strip main rolling mill by comparing with the strategies of linear sliding mode control (LSMC, which has relatively strong robustness) and cascade PI control (which is widely used in practice), and the results show that the proposed control strategy can not only improve the tracking precision and robustness of the system, but also have better dynamic and static performance.

The remainder of this paper is organized as follows. In Section 2, the system model is described and the control problems are formulated. In Section 3, NDO is designed to counteract the mismatched uncertainty, and then global integral sliding mode controller for the system speed loop, and robust controller for the system current loop are designed. In Section 4, simulation research is performed to illustrate the validity of the proposed control strategy. The conclusions are given in Section 5.

2. System Description and Control Problems Formulation.

2.1. System description. Reversible cold strip rolling mill is mainly composed of left coiler, main rolling mill, right coiler, guide rollers, and so on [9]. Structure diagram of reversible cold strip rolling mill is shown as Figure 1.

In Figure 1, the main rolling mill plays a very important role in normal, safe and efficient production of cold strip rolling mill, and it is usually driven by DC motor, and thus, it has a relatively wide speed range and can bear relatively frequent load impact. According to related rolling theory and dynamic equations of DC motor, mathematic model for the

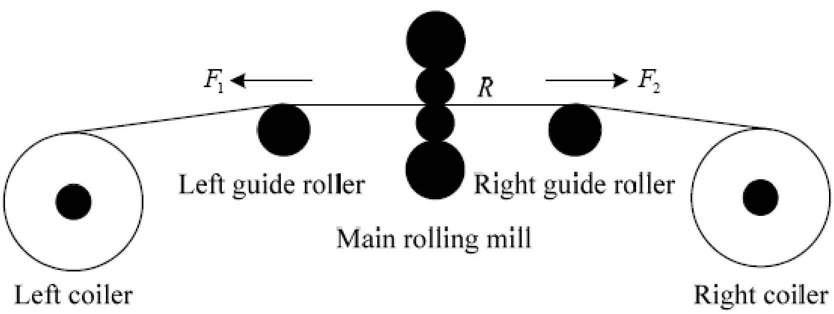


FIGURE 1. Structure diagram of reversible cold strip rolling mill

speed system of cold strip main rolling mill is described as follows [10]:

$$\begin{cases} \dot{V} = \dfrac{KR}{J\eta}I + \dfrac{R^2}{J\eta^2}(F_2 - F_1) - \dfrac{B_u}{J}V - \dfrac{M_z R}{J\eta^2} + D \\ \dot{I} = \dfrac{Ks}{l}u - \dfrac{K\eta}{lR}V - \dfrac{r}{l}I + \Delta \end{cases} \tag{1}$$

where K is the torque coefficient of motor; V and R are the linear velocity and radius of the work roll of main rolling mill, respectively; J is the rotational inertia; η is the reduction ratio; F_1, F_2 are the strip tension on both sides of the main rolling mill; B_u is the friction coefficient; M_z is the rolling torque; D is the mismatched uncertainty, including parameter perturbations and load disturbance; Δ is the matched uncertainty caused by parameter perturbations; I, r and l are the current, resistance and inductance of the armature circuit, respectively; u and Ks are the control voltage and amplification of the rectifier unit in DC motor, respectively.

2.2. Control problems formulation.

The control target of this paper is to realize tracking control for the given value of the system, i.e., $V \rightarrow V^*$. However, as can be clearly seen in system (1) that during the production process of cold strip main rolling mill, the speed system suffers the influences of parameter perturbations (ΔB_u, Δr), load disturbance (ΔM_z) and other uncertainties. Therefore, from the perspective of control theory, the control problems of system (1) can be formulated as follows.

1) Design disturbance observer to realize dynamic observation for the mismatched uncertainty D in system (1).

2) Design controller u to realize tracking control for the speed system of cold strip main rolling mill, and corresponding closed-loop system satisfies: when $\Delta = 0$, the closed-loop system is asymptotically stable; when $\Delta \neq 0$, the closed-loop system is bounded, and the matched uncertainty Δ has L_2 gain for the system performance output.

3. Design of Controller for the Speed System of Cold Strip Main Rolling Mill.

The speed system (1) includes speed loop and current loop, so we design the speed loop controller first, and take the output of system speed loop as the given value of the system current loop based on backstepping, then complete the design of controller for the speed system of cold strip main rolling mill. The control diagram is shown in Figure 2.

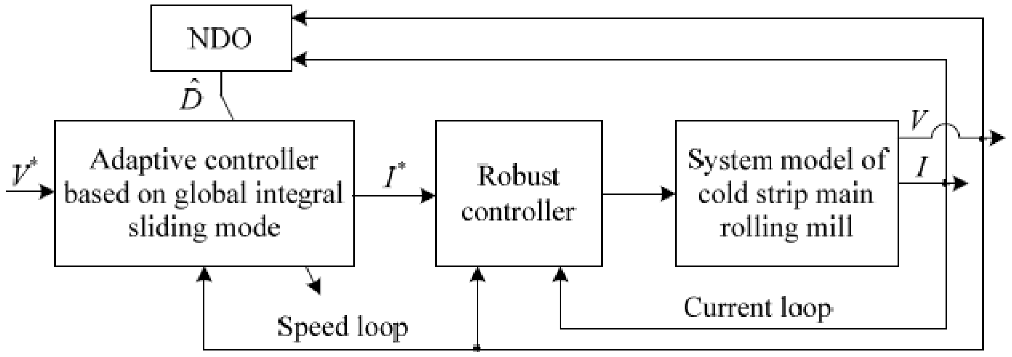


FIGURE 2. Control diagram for the speed system of cold strip main rolling mill

3.1. Design of global integral sliding mode adaptive controller for the system speed loop.

For the system speed loop in Equation (1):

$$\dot{V} = \frac{KR}{J\eta}I + \frac{R^2}{J\eta^2}(F_2 - F_1) - \frac{B_u}{J}V - \frac{M_z R}{J\eta^2} + D \tag{2}$$

where $D = -\frac{\Delta B_u}{J}V - \frac{\Delta M_z R}{J\eta^2}$ is the mismatched uncertainty, which is caused by the parameter perturbation ΔB_u and load disturbance ΔM_z in the system speed loop.

To counteract the mismatched uncertainty D in Equation (2), we build the following NDO to observe it dynamically [11]:

$$\begin{cases} \hat{D} = Z + PV \\ \dot{Z} = P\left(-PV - \dfrac{KR}{J\eta}I - \dfrac{R^2}{J\eta^2}\left(F_2 - F_1\right) + \dfrac{B_u}{J}V + \dfrac{M_z R}{J\eta^2}\right) - PZ \end{cases} \tag{3}$$

where $\hat{D}$ is the observation of D, $P \in \mathrm{R}^+$ is the gain of NDO, Z is the internal state.

Define $\widetilde{D} = D - \hat{D}$ as the observation error of NDO, and assume the change of D is slow relative to the dynamic features of NDO, i.e., $\dot{D} \approx 0$, then the dynamic equation of $\widetilde{D}$ can be written as follows:

$$\begin{aligned} \dot{\widetilde{D}} = \dot{D} - \dot{\hat{D}} = -\dot{Z} - P\dot{V} = P\left(Z + PV\right) \\ -P\left(\dot{V} - \frac{KR}{J\eta}I - \frac{R^2}{J\eta^2}\left(F_2 - F_1\right) + \frac{B_u}{J}V + \frac{M_z R}{J\eta^2}\right) \\ = P\hat{D} - PD = -P\widetilde{D} \end{aligned} \tag{4}$$

Furthermore, define the tracking error of the speed loop of cold strip main rolling mill as

$$e_1 = V^* - V \tag{5}$$

Take the time derivative of e_1, and we can get

$$\dot{e}_1 = \dot{V}^* - \frac{KR}{J\eta}I - \frac{R^2}{J\eta^2}\left(F_2 - F_1\right) + \frac{B_u}{J}V + \frac{M_z R}{J\eta^2} - D \tag{6}$$

To improve the tracking control precision and robust stability of the system in the entire global process, a global integral sliding mode surface is adopted

$$S = e_1 + k_1 \int_0^t e_1 d\iota - q\left(t\right) \tag{7}$$

where $q(t) = e_1(0)e^{-\lambda t}$ is global integral sliding factor, and λ, $k_1 \in \mathrm{R}^+$ are the sliding mode surface parameters.

Take the time derivative of Equation (7), and we can get

$$\dot{S} = \dot{e}_1 + k_1 e_1 - \dot{q}\left(t\right) = \dot{V}^* - \frac{KR}{J\eta}I - \frac{R^2}{J\eta^2}\left(F_2 - F_1\right) + \frac{B_u}{J}V + \frac{M_z R}{J\eta^2} - D + k_1 e_1 - \dot{q}\left(t\right) \tag{8}$$

Assume that the observation error $\widetilde{D}$ is bounded, that is $\left|\widetilde{D}\right| \leq \rho$, then the controller of the system speed loop (2) can be designed as

$$I = \upsilon = \frac{J\eta}{KR}\left(\dot{V}^* - \frac{R^2}{J\eta^2}\left(F_2 - F_1\right) + \frac{B_u}{J}V + \frac{M_z R}{J\eta^2} - \hat{D} + k_1 e_1 + k_2 S - \dot{q}(t) + \hat{\rho}\mathrm{sgn}\left(S\right)\right) \tag{9}$$

where $k_2 \in \mathrm{R}^+$ is the controller parameter; $\hat{\rho}$ is the estimation value of ρ, and the adaptive law can be designed as

$$\dot{\hat{\rho}} = \sigma\left|S\right| \tag{10}$$

where $\sigma \in \mathrm{R}^+$ is the adaptive law parameter and the estimation error can be defined as $\tilde{\rho} = \rho - \hat{\rho}$.

Theorem 3.1. *For the speed loop (2) of cold strip main rolling mill, if we construct nonlinear disturbance observer (3), adopt global integral sliding mode surface (7), design global integral sliding mode controller and adaptive law (9) and (10), then the speed loop (2) of cold strip main rolling mill is asymptotically stable.*

Proof: Choose the Lyapunov function candidate as

$$\psi_1 = \frac{1}{2}\left(S^2 + \frac{\tilde{\rho}^2}{\sigma} + \widetilde{D}^2\right) \tag{11}$$

Take the time derivative of Equation (11), and we can get

$$\begin{aligned}\dot{\psi}_1 &= S\dot{S} - \frac{\tilde{\rho}\dot{\hat{\rho}}}{\sigma} - P\widetilde{D}^2 \\ &= S\left[\dot{V}^* - \frac{KR}{J\eta}I - \frac{R^2}{J\eta^2}(F_2 - F_1) + \frac{B_u}{J}V + \frac{M_zR}{J\eta^2} - D + k_1e_1 - \dot{q}(t)\right] \\ &\quad - \frac{\tilde{\rho}\dot{\hat{\rho}}}{\sigma} - P\widetilde{D}^2 \\ &\le -k_2S^2 + \tilde{\rho}\,|S| - P\widetilde{D}^2 - \frac{1}{\sigma}\tilde{\rho}\dot{\hat{\rho}} = -k_2S^2 - P\widetilde{D}^2 \le 0 \end{aligned} \tag{12}$$

Therefore, the speed loop (2) of cold strip main rolling mill is asymptotically stable.

3.2. Design of robust controller for the system current loop.

For the system current loop in Equation (1):

$$\dot{I} = \frac{Ks}{l}u - \frac{K\eta}{lR}V - \frac{r}{l}I + \Delta \tag{13}$$

where $\Delta = -\frac{\Delta r}{l}I$ is the matched uncertainty.

Based on backstepping, take the output υ of the system speed loop as the given value of the system current loop (13), that is

$$I^* = \frac{J\eta}{KR}\left(\dot{V}^* - \frac{R^2}{J\eta^2}(F_2 - F_1) + \frac{B_u}{J}V + \frac{M_zR}{J\eta^2} - \hat{D} + k_1e_1 + k_2S - \dot{q}(t) + \hat{\rho}\,\mathrm{sgn}(S)\right) \tag{14}$$

Define the tracking error of the system current loop of cold strip main rolling mill as

$$e_2 = I^* - I \tag{15}$$

Take the time derivative of Equation (15), and we can get

$$\dot{e}_2 = \dot{I}^* - \frac{Ks}{l}u + \frac{K\eta}{lR}V + \frac{r}{l}I - \Delta \tag{16}$$

Theorem 3.2. *For the current loop (13) of cold strip main rolling mill, define the interference evaluation signal $z = he_2$, in which h is the weighting coefficient, and design the robust controller for the system current loop as*

$$u = \frac{l}{Ks}\left(\dot{I}^* + \frac{K\eta}{lR}V + \frac{r}{l}I + k_3e_2 + \frac{1}{4\gamma^2}e_2\right) \tag{17}$$

where $k_3 \in \mathrm{R}^+$ is the controller parameter, and γ is the interference suppression level.

If we choose $k_3 \ge h^2$, then the system current loop (13) satisfies the following performances: 1) when $\Delta = 0$, the system current loop (13) is asymptotically stable; 2) when $\Delta \neq 0$, the system current loop (13) is bounded stable, and has L_2 interference suppression characteristic for the matched uncertainty Δ.

Proof: Choose the Lyapunov function candidate as

$$\psi_2 = \frac{1}{2}e_2^2 \tag{18}$$

Take the time derivative of Equation (18), and we can get

$$\dot{\psi}_2 = e_2\dot{e}_2 = e_2\left(\dot{I}^* - \dot{I}\right) = e_2\left(\dot{I}^* - \frac{Ks}{l}u + \frac{K\eta}{lR}V + \frac{r}{l}I - \Delta\right)$$

$$
\begin{aligned}
&= -k_3e_2^2 - e_2\Delta - \frac{e_2^2}{4\gamma^2} \\
&\le -k_3e_2^2 + \frac{e_2^2}{4\gamma^2} + \gamma^2\Delta^2 - \frac{e_2^2}{4\gamma^2} = -\left(k_3 - h^2\right)e^2 + \gamma^2\left\|\Delta\right\|^2 - \left\|z\right\|^2
\end{aligned} \tag{19}
$$

By Equation (19), if we choose $k_3 \ge h^2$, then Theorem 3.2 can be proved based on Lyapunov stability theory and L_2 interference suppression theory.

Lemma 3.1. *Combine Theorem 3.1 and Theorem 3.2 together, and then we know that under the actions of controllers (9) and (17), nonlinear disturbance observer (3), and adaptive law (10), the speed system (1) of cold strip main rolling mill with parameter perturbations (ΔB_u, Δr) and load disturbance (ΔM_z) satisfies: 1) when $\Delta = 0$, the closed-loop system is asymptotically stable; 2) when $\Delta \neq 0$, the closed-loop system is bounded, and Δ has L_2 gain for the system performance output.*

4. **Simulation Research.** In this section, the simulation research is carried out on the speed system of a 1422 mm cold strip rolling mill by using the actual data, and through comparing with the strategies of linear sliding mode control (LSMC) and cascade PI control to verify the superiority of the proposed control strategy.

Choose the actual parameters of a 1422 mm cold strip main rolling mill as follows: $K = 32.6089\ \mathrm{N\cdot m/A}$, $F_1 = 100$ kN, $F_2 = 120$ kN, $J = 1274.5\ \mathrm{kg\cdot m^2}$, $l = 1.28 \times 10^{-3}$ H, $\eta = 1$, $r = 0.0159\ \Omega$, $R = 0.20635$ m, $M_z = 25\ \mathrm{kN\cdot m}$, $B_u = 0.5699\ \mathrm{kg\cdot m^{2/s}}$, $Ks = 135$.

The main parameters of the proposed control strategy are chosen as $P = 500$, $\lambda = 10$, $k_1 = 80$, $k_2 = 100$, $k_3 = 10$, $\sigma = 0.01$, $\gamma = 0.1$.

For the LSMC strategy, the controller is designed as

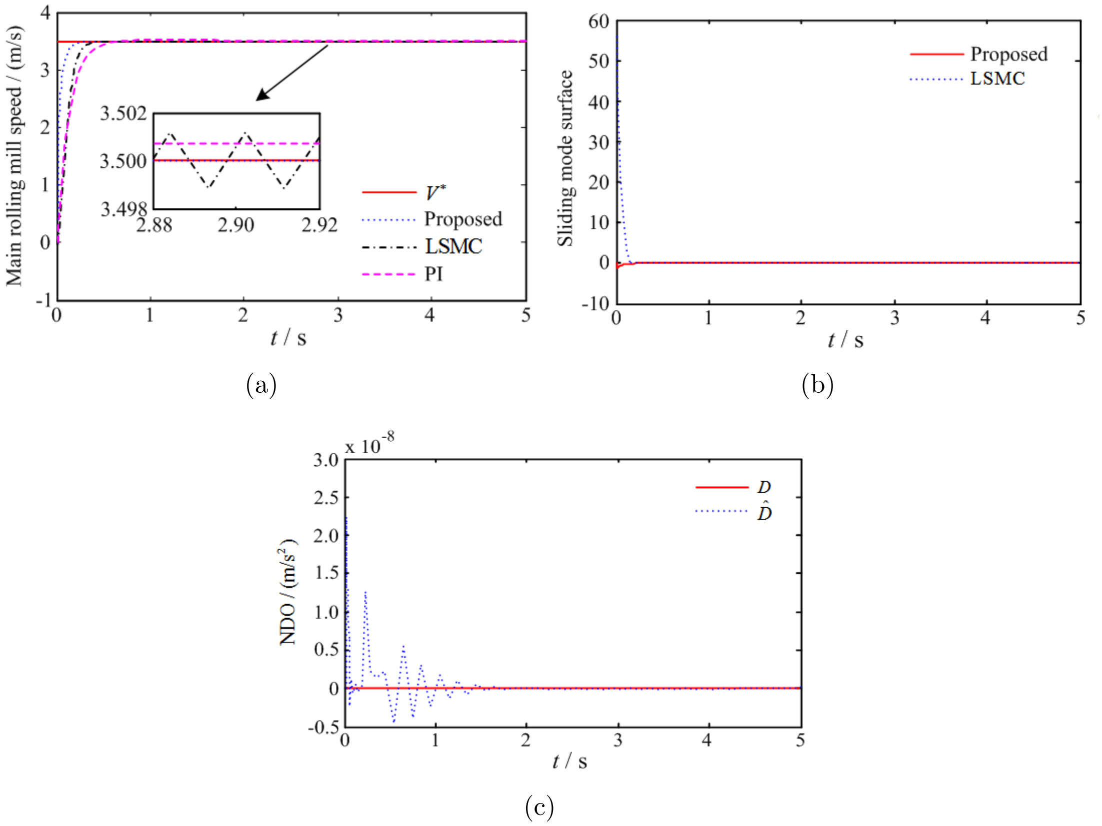
$$
u = \frac{1}{Ks}\left(rI + \frac{K\eta}{R}V\right) + \frac{J\eta l}{KRKs}\left(c_1e_2 + \ddot{V}^* + \frac{B_u}{J}\dot{V} + c_2S + c_3\mathrm{sgn}(S)\right)
$$

where $e_1 = V_2^* - V_2$, $e_2 = \dot{e}_1$, $S = c_1e_1 + e_2$; $c_1 = 10$, $c_2 = 17$, $c_3 = 100$.

For the cascade PI control strategy, the control parameters of the speed loop and the current loop are chosen as $K_{ps} = 1700$, $K_{Is} = 1500$, $K_{Pc} = 20$, $K_{Ic} = 0.01$, respectively.

Control response curves without parameter perturbations and load disturbance are shown as Figure 3. As can be clearly seen in Figure 3(a), under the action of the proposed control strategy, the speed system of cold strip main rolling mill has faster dynamic response speed, more stable operation than those in both LSMC strategy and cascade PI control strategy. In Figure 3(b), the adopted global integral sliding mode surface can make the system state locates on the sliding surface at initial moment, which can improve the robust stability of the system in the whole global process effectively. Figure 3(c) is observation curve of NDO.

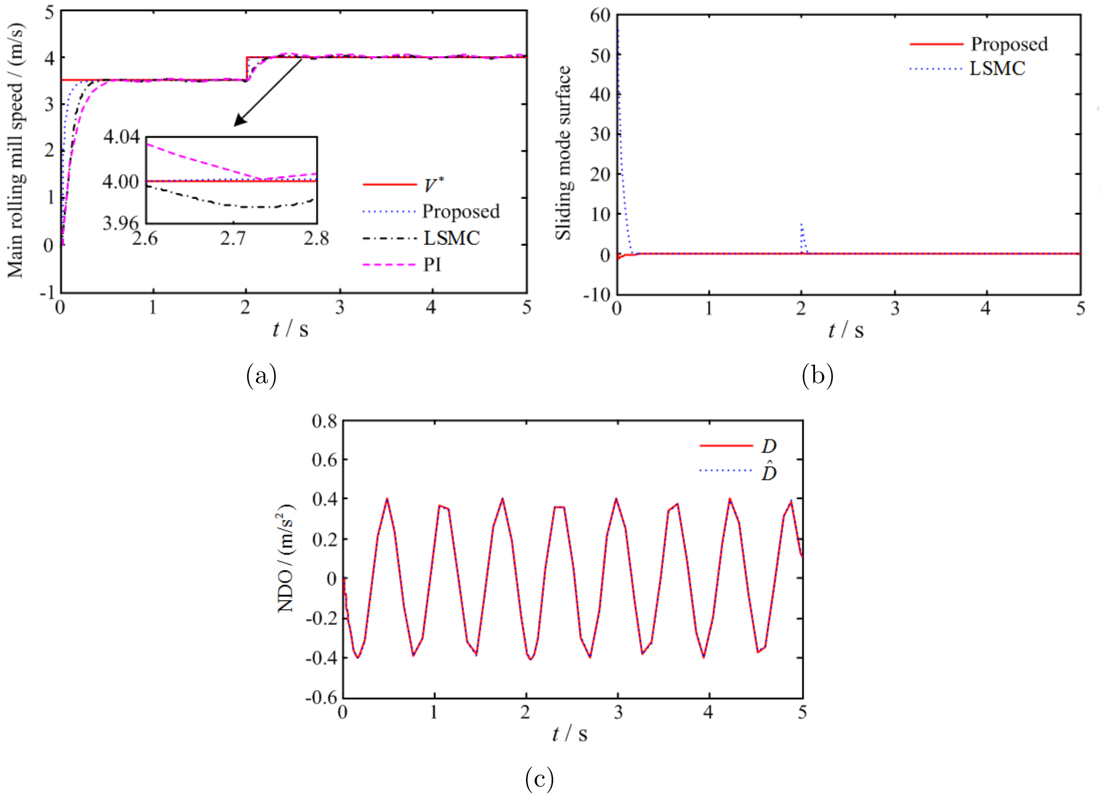
Control response curves with parameter perturbations, load disturbance and setpoint change are shown as Figure 4. Assume B_u changes into $1.1B_u$, r changes into $1.1r$, and the load disturbance is $\Delta M_z = 2500\sin(10t)\ \mathrm{N\cdot m}$; moreover, at the time of $t = 2$ s, the setpoint of the main rolling mill speed V^* rises from 3.5 m/s to 4 m/s. As can be clearly seen in Figure 4(a), under the action of the proposed control strategy, the speed system of cold strip main rolling mill has better dynamic performance, higher tracking control precision and stronger robust stability than those in both LSMC strategy and cascade PI control strategy. In Figure 4(b), comparing with the linear sliding mode surface, the adopted global integral sliding mode surface not only has faster approach speed, but also weakens the system chattering effectively. In Figure 4(c), the constructed NDO realizes effectively dynamic observation for the mismatched uncertainty D of the system.



(a) (b)

(c)

FIGURE 3. Control response curves without parameter perturbations and load disturbance



(a) (b)

(c)

FIGURE 4. Control response curves with parameter perturbations, load disturbance and setpoint change

5. **Conclusions.** Speed tracking control problem for the cold strip main rolling mill with parameter perturbations, load disturbance and other uncertainties has been investigated in this paper, and an adaptive robust control strategy was proposed based on global integral sliding mode. Firstly, NDO was built to counteract the mismatched uncertainty in the system speed loop, which improved the control precision of the system effectively. Secondly, global integral sliding mode controller for the speed loop of main rolling mill was designed to enhance the robust stability of the system. Thirdly, robust controller for the system current loop was designed based on backstepping, which realized L_2 interference suppression for the matched uncertainty Δ. Theoretical analysis has shown that the proposed control strategy can ensure the robust stability of the closed-loop system. Finally, comparing with the strategies of LSMC and cascade PI control, simulation results illustrated that the speed system of cold strip main rolling mill can not only realize effective tracking control, but also has better dynamic and static performance, and anti-interference ability under the action of the proposed control strategy. In the future, we plan to study the decoupling and coordinated control between the speed and tension of cold strip rolling mill.

Acknowledgments. This work is supported by the Natural Science Foundation of Hebei Province (F2016203263), Selected Postdoctoral Scientific Research Foundation Project of Hebei Province (B2016003017), Science and Technology Research Youth Foundation Project in Colleges and Universities of Hebei Province (QN2016122), Basic Research Specific Subject (Young Subject) of Yanshan University (16LGA005), and Doctor Foundation of Yanshan University (B960).

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