A SLIDING MODE CONTROLLER INTEGRATED MOMENT OF INERTIA OBSERVER OF WEB HANDLING SYSTEMS

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ABSTRACT

This study presents web handling systems with the characteristic of a changing moment of inertia and operating radius of rolls. Commonly, sliding mode control (SMC) is used to control the web tension of this system due to its robustness against modeling imprecision. However, this method still needs to consider the components of uncertainty, precisely the moment of inertia. A sliding mode controller integrated moment of inertia observer is the novel of the paper. The stability of the controlled system is proved by using Lyapunov's stability theory, also presented in this paper. The simulation results are compared to clarify that the proposed controller has reliable performance.

Keywords: *Lyapunov's stability theory, moment of inertia, uncertainty components, web handling systems.*

TÓM TẮT

Nghiên cứu này trình bày về hệ thống xử lý vật liệu dạng băng với đặc trưng có mômen quán tính và bán kính của các lô cuộn và lô tở thay đổi. Thông thường, điều khiển chế độ trượt (SMC) được sử dụng để điều khiển lực căng của vật liệu dạng băng của hệ thống này do tính bền vững của nó chống lại sự thiếu chính xác của mô hình. Tuy nhiên, phương pháp này vẫn cần xét đến các thành phần bất định, chính xác là mômen quán tính của các lô cuộn và lô tở. Một bộ điều khiển chế độ trượt tích hợp bộ quan sát mômen quán tính là điểm mới của bài báo. Tính ổn định của hệ thống điều khiển được chứng minh bằng cách sử dụng lý thuyết ổn định của Lyapunov, cũng được trình bày trong bài báo này. Các kết quả mô phỏng được so sánh để làm rõ rằng bộ điều khiển được đề xuất có hiệu quả đáng tin cậy.

Từ khóa: *Lý thuyết ổn định Lyapunov, mô men quán tính, các thành phần bất định, hệ thống xử lý vật liệu dạng băng.*

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1. INTRODUCTION

Web handling systems are making significant contributions to the overall development of traditional technology industries as well as modern technology industries [1-3]. The system is a complex nonlinear system with many inputs and many outputs. The state variables of the system have strict feedback, interact, and influence each other. In addition, this system is greatly affected by uncertainties as well as external disturbances when operating at high power and speed [4]. However, it is also the motivation for researchers to improve the technology in product improvement by developing different control algorithms.

The goal of every controller is to ensure the system's quality, such as the velocity and tension of the materials segment. That is especially true for the tension control of the materials segment because it affects the quality of the output product, leading to economic losses [5-7]. Due to their popularity and financial efficiency, proportional-integral-derivative (PID) controllers are an effective way to solve the tension control problem. However, the PID controller lacks robustness and adapts to nonlinear models with uncertainty and changes in model parameters. For this problem, nonlinear control algorithms under the backstepping technique are a solution developed by many researchers and have had specific results [8,9]. In [10, 11], the authors have designed a controller that is a perfect combination of the backstepping technique and a modified genetic algorithm (GA). Although it has partially solved the nonlinearity of the system, this technique, in some cases, is also susceptible to disturbances, as in the study [12], and has not considered the system of many active conduction rolls [11, 12]. Furthermore, calculating a virtual control signal faces numerous challenges due to unknown nonlinear components. One of the researcher's proposals to counter this effect is to develop an SMC suitable for nonlinear, multiple-input, and multiple-output (MIMO) systems. It is more powerful and superior to PID controllers because it reduces dependence on model inaccuracies and external disturbances. So there has been much research to develop this SMC, and there are many remarkable achievements [13-16]. In [17], the authors used a SMC to bring the synchronizing error of the induction motors to zero. In the study [18], the authors introduced a decentralized structure using one SMC for speed and two SMC for tension. Research contributions [19] have introduced a powerful SMC with the addition of an extended state observer to the traditional SMC. However, this method still needs to consider the uncertainty component, namely the moment of inertia.

To overcome these inadequacies, the research team has developed a sliding mode controller integrated moment of inertia observer. The simulation results of the web handling systems show that the system operates steadily and with good quality, thereby demonstrating the robustness and superiority of the proposed controller. The remainder of this paper is divided into four parts. Part two presents the modeling of the web handling systems for controller design. The third section is devoted to designing a sliding mode controller integrated moment of inertia observer. An integral part of developing a controller is the proof of system stability, also mentioned in the third part based on Lyapunov theory. The simulation results of the system are shown in part four. The final part is the conclusion and suggestions for future controller development.

2. MATHEMATICAL MODEL FOR WEB HANDLING SYSTEMS

The main components of web handling systems to be considered include an unwinding roll, an active guide roll, and a rewinding roll, as shown in Fig. 1.

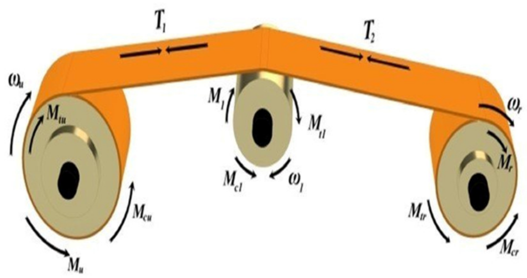

Fig. 1. Model of two-span web handling systems

The study [13] is based on three primary laws of physics: the Law of Conservation of Mass, Hooke's Law, and Coulomb's Law, and mathematical transformations. The model of a two-span nonlinear web handling systems is then given, but this paper does not consider disturbances.

$$\begin{cases} \dfrac{dT_1}{dt} = c_1\omega_1 + c_2\omega_u + c_3T_1\omega_1 \\ J_u\dfrac{d\omega_u}{dt} = c_4T_1 + c_5\omega_u + c_6\omega_u^2 - M_u \\ J_1\dfrac{d\omega_1}{dt} = c_7\omega_1 + c_8T_2 + c_9T_1 + M_1 \\ \dfrac{dT_2}{dt} = c_{10}\omega_r + c_{11}T_2\omega_r + c_{12}T_1\omega_1 + c_{13}\omega_1 \\ J_r\dfrac{d\omega_r}{dt} = c_{14}T_2 + c_{15}\omega_r + c_{16}\omega_r^2 + M_r \end{cases} \tag{1}$$

with

$$\begin{cases} c_1 = \dfrac{ESR_1}{L_1}; c_2 = \dfrac{R_u(T_{ud} - ES)}{L_1}; c_3 = \dfrac{-R_1}{L_1} \\ c_4 = R_u; c_5 = -b_{f_u}; c_6 = aw\rho R_u^3 \\ c_7 = -b_{f_1}; c_8 = R_1; c_9 = -R_1 \\ M_{cu} = b_{f_u}\omega_u; M_{c1} = b_{f_1}\omega_1; M_{cr} = b_{f_r}\omega_r \\ M_{tu} = T_1R_u \\ M_{t1} = (T_2 - T_1)R_1 \\ M_{tr} = T_2R_r \\ c_{10} = \dfrac{ESR_1}{L_2}; c_{11} = \dfrac{-R_r}{L_2}; c_{12} = \dfrac{R_1}{L_2}; c_{13} = -\dfrac{ESR_r}{L_2} \\ c_{14} = -R_r; c_{15} = -b_{f_r}; c_{16} = -aw\rho R_r^3 \end{cases} \tag{2}$$

where T_1, T_2 are the tensions on the respective materials segments over time; ω_u, ω_1, ω_r are angular velocities of the unwinding roll, active guide roll, and rewinding roll, respectively; T_{ud} is the reference tension of unwinding roll; L_1, L_2 are the length of two spans web materials; E is Young's elastic modulus; S is the cross-sectional area of materials span; b_{f_u}, b_{f1}, b_{f_r} are the drag coefficient between the bearing and the corresponding rolls; a is materials span's thickness; w is the width of materials span; ρ is the density of materials span after deformation; M_{tu}, M_{t1}, and M_{tr} denote the torques of the tension force acting on the unwinder roll, active guild roll, and rewinder roll; M_{cu}, M_{c1}, and M_{cr} represent the torque due to the frictional force acting on the unwinder roll, active guild roll, and rewinder roll shaft. R_u, R_1, R_r and J_u, J_1, J_r are the radius and the respective moments of inertia of the unwinding roll, active guide roll, and rewinding roll, respectively. Significantly, the consideration of the variation is to be expressed in equation (3).

$$\begin{aligned} & R_u = R_{u0} - \frac{\theta_u a}{2\pi}; R_r = R_{r0} + \frac{\theta_r a}{2\pi} \\ & J_u = J_{u0} + \pi\rho w\frac{R_u^4 - R_{u0}^4}{2} \\ & J_r = J_{r0} + \pi\rho w\frac{R_r^4 - R_{r0}^4}{2} \end{aligned} \tag{3}$$

The variable components R_u, R_1, R_r and J_u, J_1, J_r cause uncertainties for the model, so the sliding mode control integrated moment of inertia observer is presented in the next section to deal with the uncertainties.

3. A SLIDING MODE CONTROLLER INTEGRATED MOMENT OF INERTIA OBSERVER APPROACH OF MULTI-SPAN WEB HANDLING SYSTEMS

In this section, we propose a nonlinear control structure for the multi-span web handling systems, as shown in Fig. 2. The input of the system is the reference signal ω_{1d} and $\mathbf{T}_d = [T_{1d}, T_{2d}]^T$. They are fed to the controllers designed according to the cascade control strategy. The outer controllers rely on SMC to control the tension $\mathbf{T} = [T_1, T_2]^T$, generating the virtual set signals $\boldsymbol{\omega}_d = [\omega_{ud}, \omega_{rd}]^T$ for the inner controllers and moment of inertia observer. The inner controllers are also based on SMC but have an additional component $\hat{\mathbf{J}} = \left[\hat{J}_1, \hat{J}_u, \hat{J}_r\right]^T$, which is an observer of the moment of inertia $\mathbf{J} = \left[J_1, J_u, J_r\right]^T$ provided by moment of inertia observer to control the speed $\boldsymbol{\omega} = \left[\omega_1, \omega_u, \omega_r\right]^T$ of the whole system by generating a control torque $\mathbf{M} = \left[M_1, M_u, M_r\right]^T$ for the motor. Assume that the responses of the system $\mathbf{T} = \left[T_1, T_2\right]^T$, $\boldsymbol{\omega} = \left[\omega_1, \omega_u, \omega_r\right]^T$ are completely measurable, feedback to the controllers and the moment of inertia observer.

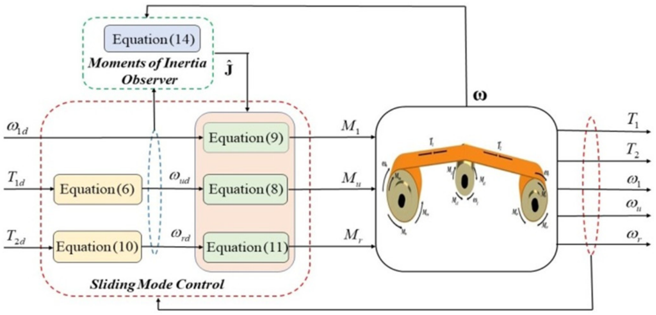

Fig. 2. The control structure based on the Sliding Mode Control Integrated Moment of Inertia Observer

The controller aims to automatically adjust the regulators in the control circuit when the parameters of the controlled process is change over time. Select the sliding surface as equation (4).

$$s_u = \omega_u - \omega_{ud}, s_r = \omega_r - \omega_{rd}, s_1 = \omega_1 - \omega_{1d}$$
$$s_{T_1} = T_1 - T_{1d}, s_{T_2} = T_2 - T_{2d} \tag{4}$$

Taking the derivative of equation (5), we get

$$\frac{ds_u}{dt} = \frac{d\omega_u}{dt} - \frac{d\omega_{ud}}{dt}, \frac{ds_r}{dt} = \frac{d\omega_r}{dt} - \frac{d\omega_{rd}}{dt},$$
$$\frac{ds_1}{dt} = \frac{d\omega_1}{dt} - \frac{d\omega_{1d}}{dt}, \frac{ds_{T_1}}{dt} = \frac{dT_1}{dt} - \frac{dT_{1d}}{dt}, \tag{5}$$
$$\frac{ds_{T_2}}{dt} = \frac{dT_2}{dt} - \frac{dT_{2d}}{dt}$$

Since the input is less than the output, we need to divide the system into three subsystem parts to make it easier to control tension and speed. First of all, the paper considers the dynamic equation of the first span and the dynamic equation of the unwinding roll. The virtual control signal ω_{ud} includes two components: ω_{udeq} which oversees driving the sliding surface $\left(\frac{ds_{T_1}}{dt}\right)$ to zero and ω_{udsw} leads the system state toward the sling surface. The virtual control signal can be rewritten as

$$\omega_{ud} = \omega_{udeq} + \omega_{udsw} = \frac{1}{c_2}\begin{pmatrix} -c_1\omega_1 - c_3T_1\omega_1 + \frac{dT_{1d}}{dt} \\ -k_1 \operatorname{sgn}(s_{T_1}) - k_2 s_{T_1} \end{pmatrix} \tag{6}$$

The controller M_u is selected $M_u = M_{u1} + M_{u2} + M_{u\alpha}$, with $M_{u\alpha}$ is the adaptive compensation, M_{u1} which oversees driving the sliding surface (ds_u/dt) to zero, M_{u2} which leads the system state toward the sling surface, and $\hat{J}_u$ is an estimate of J_u.

$$\begin{cases} M_{u1} = c_4T_1 + c_5\omega_u + c_6\omega_u^2 \\ M_{u\alpha} = -\hat{J}_u \frac{d\omega_{ud}}{dt} \\ M_{u2} = k_{u1}\operatorname{sgn}(s_u) + k_{u2}s_u \end{cases} \tag{7}$$

Therefore, the driving moment is summarized as equation (8)

$$M_u = c_4T_1 + c_5\omega_u + c_6\omega_u^2 + k_{u1}\operatorname{sgn}(s_u) + k_{u2}s_u - \hat{J}_u\frac{d\omega_{ud}}{dt} \tag{8}$$

Similarly, the controller M_1 is selected as $M_1 = M_{11} + M_{12} + M_{1\alpha}$

$$M_1 = -c_7\omega_1 - c_8T_2 - c_9T_1 - k_{11}\operatorname{sgn}(s_1) - k_{12}s_1 + \hat{J}_1\frac{d\omega_{1d}}{dt} \tag{9}$$

Finally, we consider the dynamic equation of the two-span and the dynamic equation of the rewinding roll, the control signal ω_{rd} can be rewritten as

$$\omega_{rd} = \frac{1}{c_{10} + c_{11}T_2}\begin{pmatrix} -c_{12}T_1\omega_1 - c_{13}\omega_1 \\ +\frac{dT_{2d}}{dt} - k_1'\operatorname{sgn}(s_{T_2}) - k_2's_{T_2} \end{pmatrix} \tag{10}$$

The control signal M_r is selected as $M_r = M_{r1} + M_{r2} + M_{r\alpha}$

$$M_r = -c_{14}T_2 - c_{15}\omega_r - c_{16}\omega_r^2 - k_{r1}\operatorname{sgn}(s_r) - k_{r2}s_r + \hat{J}_r\frac{d\omega_{rd}}{dt} \tag{11}$$

To summarize we will have two virtual control signals ω_{ud} and ω_{rd} for tension T_1 and T_2; three controllers M_u, M_1, M_r for speed ω_u, ω_1 and ω_r.

$$\begin{cases} \omega_{ud} = \frac{1}{c_2}\begin{pmatrix} -c_1\omega_1 - c_3T_1\omega_1 \\ +\frac{dT_{1d}}{dt} - k_1\operatorname{sgn}(s_{T_1}) - k_2s_{T_1} \end{pmatrix} \\ M_u = c_4T_1 + c_5\omega_u + c_6\omega_u^2 + k_{u1}\operatorname{sgn}(s_u) \\ \quad + k_{u2}s_u - \hat{J}_u\frac{d\omega_{ud}}{dt} \\ M_1 = -c_7\omega_1 - c_8T_2 - c_9T_2 - k_{11}\operatorname{sgn}(s_1) \\ \quad - k_{12}s_1 + \hat{J}_1\frac{d\omega_{1d}}{dt} \\ \omega_{rd} = \frac{1}{c_{10} + c_{11}T_2}\begin{pmatrix} -c_{11}T_2\omega_r - c_{12}T_1\omega_1 - c_{13}\omega_1 \\ +\frac{dT_{2d}}{dt} - k_1'\operatorname{sgn}(s_{T_2}) - k_2's_{T_2} \end{pmatrix} \\ M_r = -c_{14}T_2 - c_{15}\omega_r - c_{16}\omega_r^2 - k_{r1}\operatorname{sgn}(s_r) \\ \quad - k_{r2}s_r + \hat{J}_r\frac{d\omega_{rd}}{dt} \end{cases} \tag{12}$$

To determine the stability of the system, we consider the following Lyapunov function as

$$V=\frac{1}{2}s_{T_1}^2+\frac{1}{2}s_{T_2}^2+\frac{1}{2}J_1s_1^2+\frac{1}{2\gamma}\tilde{J}_1^2+\frac{1}{2}J_us_u^2+\frac{1}{2\gamma}\tilde{J}_u^2+\frac{1}{2}J_rs_r^2+\frac{1}{2\gamma}\tilde{J}_r^2 \quad (13)$$

where $\tilde{J}_u=\hat{J}_u-J_u$, $\tilde{J}_1=\hat{J}_1-J_1$, $\tilde{J}_r=\hat{J}_r-J_r$, $\gamma>0$ and select the moment of inertia observer as

$$\begin{cases}\frac{d\hat{J}_u}{dt}=-\gamma\frac{d\omega_{ud}}{dt}s_u\\ \frac{d\hat{J}_1}{dt}=-\gamma\frac{d\omega_{1d}}{dt}s_1\\ \frac{d\hat{J}_r}{dt}=-\gamma\frac{d\omega_{rd}}{dt}s_r\end{cases} \quad (14)$$

Taking the time derivative (14), $\frac{dV}{dt}$ has the formula

$$\begin{aligned}\frac{dV}{dt}&=s_{T_1}(\frac{dT_1}{dt}-\frac{dT_{1d}}{dt})+s_{T_2}(\frac{dT_2}{dt}-\frac{dT_{2d}}{dt})\\&+s_1(J_1\frac{d\omega_1}{dt}-J_1\frac{d\omega_{1d}}{dt})+\frac{1}{\gamma}\tilde{J}_1\frac{d\hat{J}_1}{dt}\\&+s_u(J_u\frac{d\omega_u}{dt}-J_u\frac{d\omega_{ud}}{dt})+\frac{1}{\gamma}\tilde{J}_u\frac{d\hat{J}_u}{dt}\\&+s_r(J_r\frac{d\omega_r}{dt}-J_r\frac{d\omega_{rd}}{dt})+\frac{1}{\gamma}\tilde{J}_r\frac{d\hat{J}_r}{dt}\end{aligned} \quad (15)$$

Substituting equations (12) and (14) into (15), we get

$$\begin{aligned}\frac{dV}{dt}&=-k_1|s_{T_1}|-k_2s_{T_1}^2-k_1'|s_{T_2}|-k_2's_{T_2}^2\\&-k_{11}|s_1|-k_{12}s_1^2-k_{u1}|s_u|-k_{u2}s_u^2\\&-k_{r1}|s_r|-k_{r1}-k_{r2}s_r^2\end{aligned} \quad (16)$$

The control parameters are chosen as: k_1, k_2, k_1', k_2', k_{11}, k_{12}, k_{u1}, k_{u2}, k_{r1}, $k_{r2}>0$; it can be concluded $\frac{dV}{dt}<0$.

The chattering occurs when the control signal has to change the sign of the value with high-frequency in the saturated region to keep the state on the sliding surface s = 0. Therefore, to reduce this chattering phenomenon, we propose a function in continuous form and only meaningfully to reduce the frequency of the sign change of the control signal however, the amplitude of the oscillation keeps stably, defined as equation (17)

$$sat(x)=\begin{cases}1 & \text{khi } x>1\\ -1 & \text{khi } x<-1\\ x & \text{khi } -1<x<1\end{cases} \quad (17)$$

4. SIMULATION RESULTS

In this part, the performance of the proposed controller is demonstrated through simulations. The parameters of the web handling systems utilized in the simulation can be listed as follows: R_{u0} = 0.04m, R_{r0} = 0.01m, b_{fr} = 0.00002533Nms, J^1 = 0.007kgm², R_1 = 0.015m, J_{u0} = 0.007kgm², b_{fu} = 0.00002533Nms, b_{f1} = 0.00002533Nms, L_1 = 0.5m, L_2 = 0.5m, E = 2.5 x 10^9N/m², ρ = 800kg/m³, a = 0.02m, S = 0.002m², J_{r0} = 0.007kgm², w = 1m. The controller parameters are calculated as: k_{u1} = k_{u2} = 300, k_{11} = k_{12} = 700, k_{r1} = k_{r2} = 800, k_1 = k_2 = 50, k_1' = k_2' = 30, γ = 600. Simulation conditional and parameters are set up with zero initial conditions, trapezoidal signals of reference angular velocities, and the prescribed reference web tension is 10 (N). As we mentioned, the sliding mode controller integrated moment of inertia observer has an observer component to help estimate the moment of inertia. Fig 3, Fig 4, and Fig 5 describe the moment inertia of unwinding roll, active guide roll, and rewinding roll response, respectively.

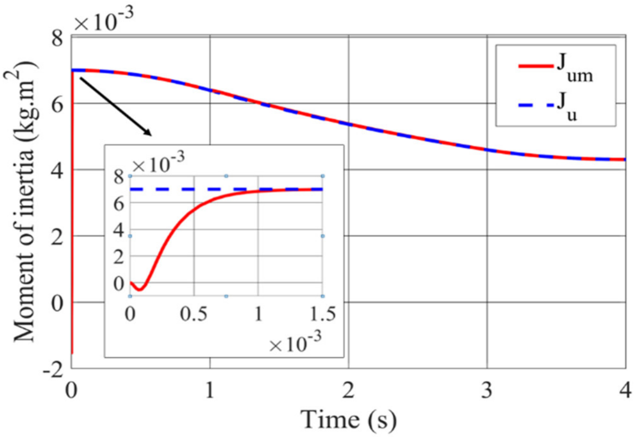

Fig. 3. Moment of inertia of unwinding response

The error response of the moment of inertia between the observed value and the actual value of the unwinding roll, active guide roll, and rewinding roll is 0.048%, 0.0016%, and 0.062%, respectively. Generally, the moment of inertia of the active guide tends to be constant due to the radius is always permanent; the moment of inertia of the unwinder tends to increase because the radius is decreasing, conversely, and the moment of inertia of the rewinder tends to decrease due to the increasing radius.

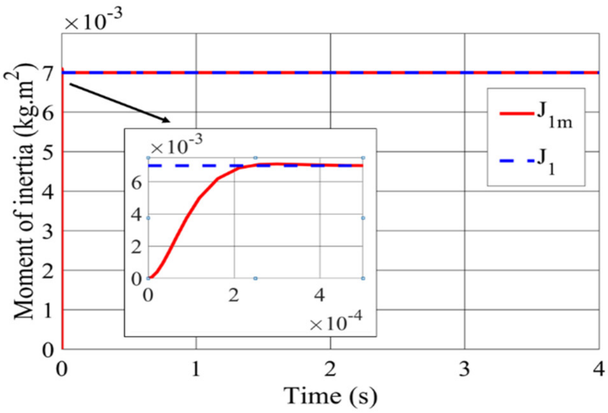

Fig. 4. Moment of inertia of active guide response

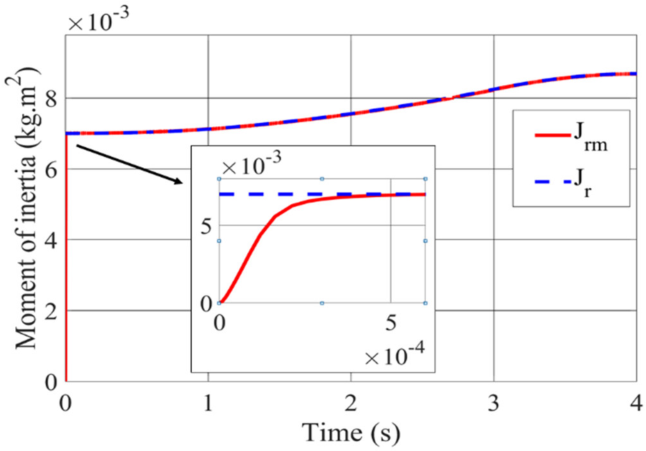

Fig. 5. Moment of inertia of rewinding response

The observed value gradually increases and sticks to the actual value with the response time of unwinder roll, active guide roll and rewinder roll are 1.1ms, 0.23ms and 0.5ms respectively. This demonstrates the outstanding durability and quality of the sliding mode controller that adapts to the variation of moment of inertia.

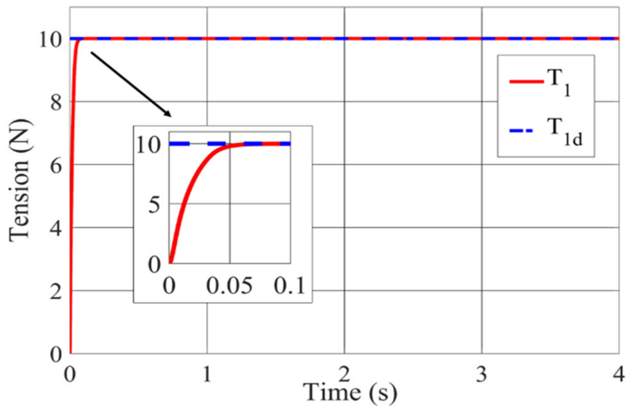

Fig. 6. The first tension response

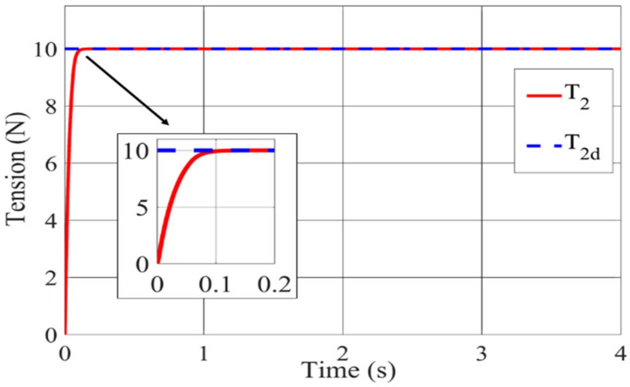

Fig. 7. The second tension response

Besides, the response time and the error response to the desired tension value on the first span is 0.055s, 0.0004% in Fig. 6 and on the second span is 0.13s, 0.00008% in Fig. 7. This proves the controller's output performance is amazing, and the stability of the system is verified.

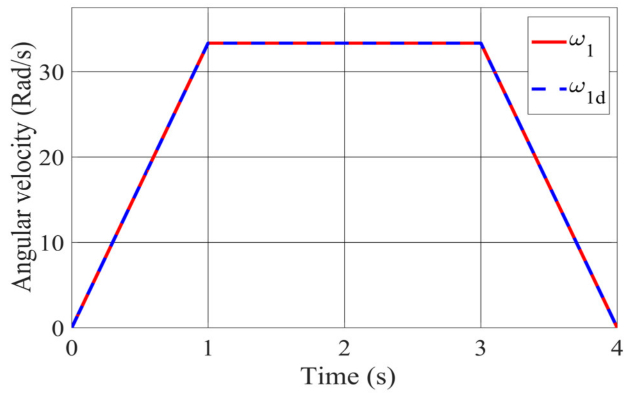

Fig. 8. Angular velocity of active guide response

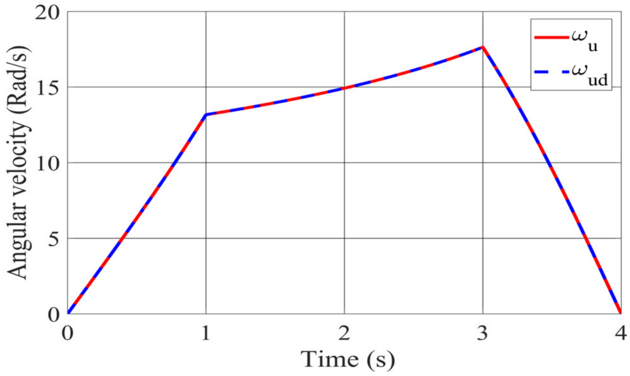

Fig. 9. Angular velocity of unwinding response

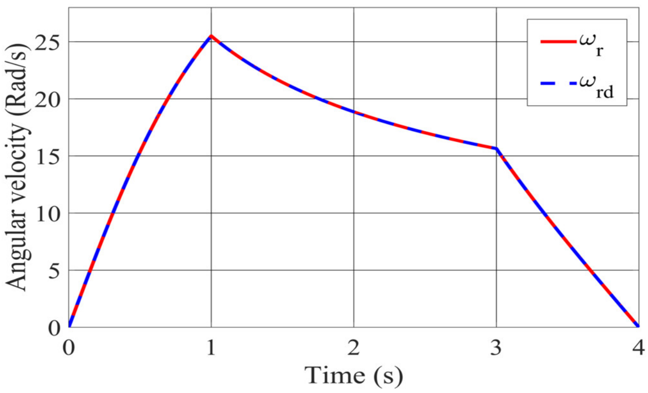

Fig. 10. Angular velocity of rewinding response

In addition, the response of the actual angular velocity to the defined trajectories in the shape of a trapezoid is given in Fig. 8, Fig. 9, and Fig. 10. Because the angular velocity (ω) is an internal control loop, the fast response time less than 1ms and the percentage error is small and negligible about 0.00008% of all 3 rolls compared to the response time of the external control loop, tension (T). The simulation results show the correctness and advantage of the algorithm using the sliding mode controller integrated moment of inertia observer. Moreover, the saturation function in equation 17 is used, which greatly reduces the chattering phenomenon compared to the traditional controller. Besides, the controller proposes to overcome the explosion of terms. As a result, the life of the actuators is enhanced, and the product quality is also improved.

5. CONCLUSION

The paper has succeeded in building a sliding mode controller integrated moment of inertia observer based on the backstepping technique, sliding mode control to deal with the moment of inertia. The stability of the controlled system is proven using Lyapunov's stability theory. The simulation results have verified the performance and superior response of the controllers. However, depending on the whole model information is a huge drawback of the proposed controller because several model parameters cannot be measured in fact. Future work is to develop a controller with an extended state observer and an uncertainty estimation component for the sliding mode controller integrated moment of inertia observer, and experimental verification of the control will be conducted.

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