Sliding Mode Control for Two-input and Two-output (TITO) Looper Systems

Chi Yu, Hongwei Wang and Yuanwei Jing

***Abstract*—A robust sliding mode controller is designed for looper systems in hot strip mills in order to solve the problem of tension and height decoupling control. The original uncertain looper system was first transformed into a standard form for facilitating the design of the controller. Then based on the transformed system, an improved sliding mode control strategy is proposed. This kind of control action has robust performance, which is suitable for complex looper systems. For the particular mode, the corresponding sliding mode reaching condition of the controller is obtained, and gives the proof of stability. The design control strategy of sliding mode control for looper systems is introduced to decouple the system and improve control effect. At last, simulation results show that the proposed scheme can get well performance under various conditional.**

Key words: Sliding Mode Control; Two-input Two-output (TITO); Looper Systems; Decoupling Control

I. Introduction

HOT strip mills (HSMs) are very complex processes. Recently, with increasing pressure of competition and the tighter market, some researches are looking for some new control methods to improve quality and production. A hot strip mill, a heated slab is rolled in roughing mills and finishing trains, and the rolled strip is cooled down. In the roughing mill, the reheated slabs are reduced to the desired width. The resulting sheet bar is then transported to the finishing mill, where it is further reduced to the final thickness. The resulting strip is then coiled to form the finished coil of steel strip [1].

In the finishing mill, to achieve the required reduction, final qualities and tolerances, several passes of rolling are executed by tandem rolling. Tension control is the key to the successful mill operations and to the successful operation of subsystems controlling product qualities such as gage, width and mechanical properties [2]. The loopers are placed between each rolling stands to fulfill an important tension control, looper tension control is important in hot strip mills because they affect the strip quality as well as strip threading.

Looper system has an important role on regulating the mass flow of the strip by accumulating and controlling the strip tension which influences the width of the strip. Moreover, design robust controller is the difficult problem from the interaction between looper angle and strip tension. Many researchers have proposed and applied a variety of control schemes to this control problem such as PID control[3], intelligent control[4], optimal control[5] and sliding mode control[6], [7] in the looper control system, but nevertheless, the increasingly strict market demand for strip quality requires further improvements in this control area.

Recently, many customers of steel makers have severely requested to keep the product quality higher. Therefore, it is necessary to renew the present control systems. One of our challenges is to refresh looper control systems to get better tension control performance, sliding mode control is a robust performance well known for its ability to withstand external disturbance and parameters uncertainties, it is suitable to a two-input and two-output multivariable looper system, and many advanced control algorithms based on this control structure have been applied and shown to give improved control performance. Although several control schemes have been proposed for uncertain system in [8], [9], very few of these schemes are applicable to looper system.

To solve the above-mentioned problems simultaneously, we design a robust sliding mode controller in this paper. The scheme can be applied to uncertain looper systems with disturbance. The original uncertain looper system was first transformed into a standard form for designing the controller. Then based on the transformed system, by using Ackermann functional approach and equivalent control law method, a robust controller is developed for tension control, and gives the proof of stability. We have shown that the proposed scheme have reliable asymptotic stability and robust in various scenarios, and can accurately track the desired value, ensuring proper product quality and strip threading.

The research is organized as follows. The looper system dynamic model is discussed in Section Ⅱ. Section Ⅲ presents a robust controller for a class of uncertain looper system. A sliding mode reaching condition is given. Section Ⅳ shows the results of simulation to demonstrate the performance of the proposed control schemes. Finally, we conclude our brief work in Section Ⅴ.

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II. PROBLEM FORMULATION

The mathematical mode for TITO looper system is proposed of some parts. A more complete dynamic model structure is given [7]. Also taking into account the speed controller in the field looper is always at the saturation point actually, that only the current loop plays a major role. The system state equation and output equation can be written as

$$\begin{cases} \dot{x}(t) = Ax(t) + Bu(t) + Df(t) \\ y(t) = Cx(t) \end{cases} \tag{1}$$

where $x(t) \in R^n$, $y(t) \in R^P$ and $u(t) \in R^m$ represent the system state, output and control input, A, B, C are the system state matrix, control input matrix and output matrix, $f(t)$ is the disturbance for the system,

$$A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix},\ B = \begin{bmatrix} B_1 \\ B_2 \end{bmatrix},\ C = \begin{bmatrix} C_1 & C_2 \end{bmatrix}, D = \begin{bmatrix} D_1 \\ D_2 \end{bmatrix}.$$

In process of designing controller, we introduce the following assumptions imposed on system (1).

Assumption 1: the pair (A, B) is controller, the input matrix B has full rank;

Assumption 2: the disturbance $f(t)$ satisfy norm bounded, exist a positive constant β, get $\|f(t)\| \le \beta$;

The equation (1) simplified analysis will bring great convenience for designing sliding mode variable structure controller, so we do a transformation for $x(t)$ as follows:

$$z(t) = Tx(t) \tag{2}$$

where

$$T = \begin{bmatrix} I_{n-m} & -B_1 B_2^{-1} \\ 0 & B_2^{-1} \end{bmatrix} \tag{3}$$

So equation (1) can be rewritten as follows:

$$\begin{cases} \dot{z}(t) = TAT^{-1}z(t) + TBu(t) + TDf(t) \\ y(t) = CT^{-1}z(t) \end{cases} \tag{4}$$

where

$$TAT^{-1} = \begin{bmatrix} \bar{A}_{11} & \bar{A}_{12} \\ \bar{A}_{21} & \bar{A}_{22} \end{bmatrix},\ TB = \begin{bmatrix} 0 \\ I_m \end{bmatrix},\ TD = \begin{bmatrix} \bar{D}_1 \\ \bar{D}_2 \end{bmatrix}.$$

That is

$$z_1(t) = \bar{A}_{11} z_1(t) + \bar{A}_{12} z_2(t) + \bar{D}_1 f(t) \tag{5}$$

$$z_2(t) = \bar{A}_{21} z_1(t) + \bar{A}_{22} z_2(t) + I_m u(t) + \bar{D}_2 f(t) \tag{6}$$

In what follows we will carry out the design a robust sliding mode controller for looper systems based on LMI methods which is robust to variations of parameter uncertainties.

III. DESIGN OF ROBUST CONTROLLER

Since looper systems are more complex, a more practical approach is to design a robust sliding mode controller, which is capable of achieving asymptotic stability performance. Sliding mode control (SMC) makes systems very robust with respect to parameter perturbation and external disturbances. Switching converters constitute an important case of sliding mode system and different sliding mode strategies to control this class of circuits have been reported in the last years. The design of these strategies is performed in two steps. In the first step, we choose among different sliding surface that one which provides the desired asymptotic behavior when the converter dynamics is forced to evolve over it. In the second step, sliding surface is designed.

A. Design Sliding Surface Using LMI

Without loss of generality, a sliding surface functions according to the state estimation is defined as

$$s = Mz(t) = \begin{bmatrix} M_1 & I_m \end{bmatrix} \begin{bmatrix} z_1(t) \\ z_2(t) \end{bmatrix} \tag{7}$$

where $M_1 \in R^{m\times(n-m)}$, $I_m \in R^{m\times m}$ is unit matrix.

In sliding mode, it will regard $z_2(t)$ as virtual input control of subsystem (11), designing state feedback:

$$z_2(t) = -M_1 z_1(t) \tag{8}$$

By substituting Eq. (8) into Eq. (5), we obtain as follow:

$$\dot{z}_1(t) = (\bar{A}_{11} - \bar{A}_{12} M_1) z_1(t) + \bar{D}_1 f(t) \tag{9}$$

where uncertainties $f(t)$ satisfied unmatched condition, but $f(t)$ is affected on the state of the system, when the system is stable when the interference is zero for practical looper system in the paper. The pair (A, B) is controller, so $(\bar{A}_{11}, \bar{A}_{12})$ is controllable, we will recur to pole assignment method to find out the matrix M_1 , which can make the system stabilization.

B. Designing Sliding Mode Control Law

In the previous section, the designed sliding mode surface can guarantee the asymptotic stability of the system in terms of LMI; next, we need find feedback control law u to drive state trajectories of the system onto the sliding surface. The designed control law can satisfy the reaching condition.

Theorem 2: For uncertain systems (5) and (6), sliding mode function (7) is selected; sliding mode control law is chosen as follow.

$$\begin{aligned} u &= u_N + u_m \\ u_m &= -\big[M_1 \bar{A}_{11} z_1 + M_1 \bar{A}_{12} z_2 + \bar{A}_{21} z_1 + \bar{A}_{22} z_2 + \\ &\qquad \varepsilon_1 \operatorname{sgn}(s) + \varepsilon_2 s \big] \\ u_N &= -(\|M_1 \bar{D}_1\| + \|\bar{D}_2\|) \beta \operatorname{sgn}(s) \end{aligned} \tag{10}$$

where ε_1 and ε_2 are both greater than zero, which is able to satisfy reaching condition $s^T \dot{s} < 0$ for system with any state, if and only if $s=0$, $s^T\dot{s}=0$. The system will reach to sliding mode surface.

Proof: By substituting equation (10) into sliding mode reaching condition:

$$\begin{aligned} s^T\dot{s} &= s^T\left[M_1\bar{A}_{11}z_1 + M_2\bar{A}_{12}z_2 + \bar{A}_{21}z_1 + \bar{A}_{22}z_2 + \right. \\ &\quad \left. +u(t) + M_1\bar{D}_1 f(t) + \bar{D}_2 f(t)\right] \\ &= s^T\left[u_N(t) + M_1\bar{D}_1 f(t) + \bar{D}_2 f(t) - \right. \\ &\quad \left. \varepsilon_1 \operatorname{sgn}(s) - \varepsilon_2 s\right] \\ &\le \|s^T\|\left(\|M_1\bar{D}_1\|\beta + \|\bar{D}_2\|\beta\right) + s^T B_2 u_N(t) + \\ &\quad s^T\left(-\varepsilon_1 \operatorname{sgn}(s) - \varepsilon_2 s\right) \\ &\le s^T\left(-\varepsilon_1 \operatorname{sgn}(s) - \varepsilon_2 s\right) \\ &\le 0 \end{aligned}$$

Sliding mode reaching condition is satisfied.

In a word, the control law (10) can compensate for the disadvantageous effect of disturbance, which can drive system state trajectories to arrive at the switch band in limit time. Also, the control law can guarantee that the looper system satisfies the sliding mode reaching condition. This completes the proof.

IV. Simulation Results

In this section, the dynamic simulation model was designed according to the previous sections and following the standard literature on rolling mills. Model parameters were obtained based on [7].

The looper height and tension control system are seen as two separate systems to design controller. If we study a looper height system, tension coupling is known as a perturbation, and study a tension system, looper height is known as a perturbation. So we design sliding mode controller for two systems, respectively, the purpose of decoupling is come true.

By ignoring the small higher order terms items, combined with engineering practice, the establishment of the following type state equations are give.

$$\begin{bmatrix}\dot{x}_1\\ \dot{x}_2\end{bmatrix} = \begin{bmatrix}0 & 1\\ -2.045 & -2.8507\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} + \begin{bmatrix}26043\\ -34057\end{bmatrix}u_1 + \begin{bmatrix}0\\ 1\end{bmatrix}f_1 \tag{11}$$

$$y_1 = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}x_1\\ x_2\end{bmatrix} \tag{12}$$

$$\begin{bmatrix}\dot{x}_3\\ \dot{x}_4\end{bmatrix} = \begin{bmatrix}0 & 1\\ -16.0772 & -11.9212\end{bmatrix}\begin{bmatrix}x_3\\ x_4\end{bmatrix} + \begin{bmatrix}-140.4546\\ 1457.7\end{bmatrix}u_2 + \begin{bmatrix}0\\ 1\end{bmatrix}f_2 \tag{13}$$

$$y_2 = \begin{bmatrix}1 & 0\end{bmatrix}\begin{bmatrix}x_3\\ x_4\end{bmatrix} \tag{14}$$

where $f_1=-7.7279x_3$, $f_2=2.7572\dot{x}_1$, x_1 and x_3 represent looper angle variation $\Delta\theta$ and strip tensile stress variation $\Delta\tau_3$, $\beta=10$, $\Delta\theta=5\sin(4t)^{\circ}$, $\Delta\tau_3=1Mpa$.

We do a transformation for $x(t)$ using Eq.(4), we choose the sliding mode function (7), equation (9)and control law(10), employing the method of pole placement, using Ackermann formula and the same pole value, finally we obtain sliding mode surface function and control law. For alleviating chattering phenomena caused by the sliding mode control, we will introduce an approximation

$$\operatorname{sgn}(s) = \frac{s}{|s|+\mu}$$

where $\mu = 0.01$.

In this simulation, we will draw the designed sliding mode controller about the performance and surface function under the variations of network looper system parameters. The simulation results are showed in Fig.1, Fig. 2 and Fig3.

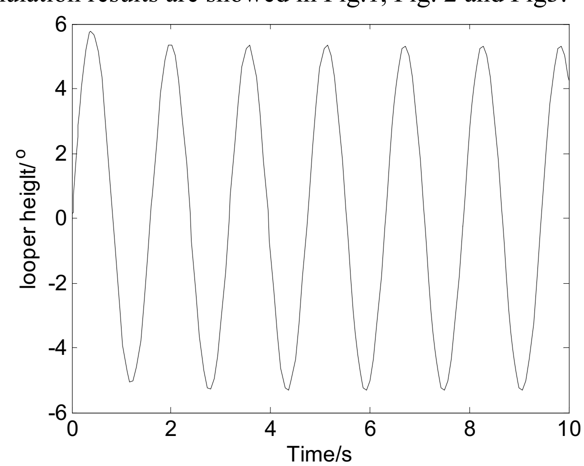

Fig. 1 The looper height response curves

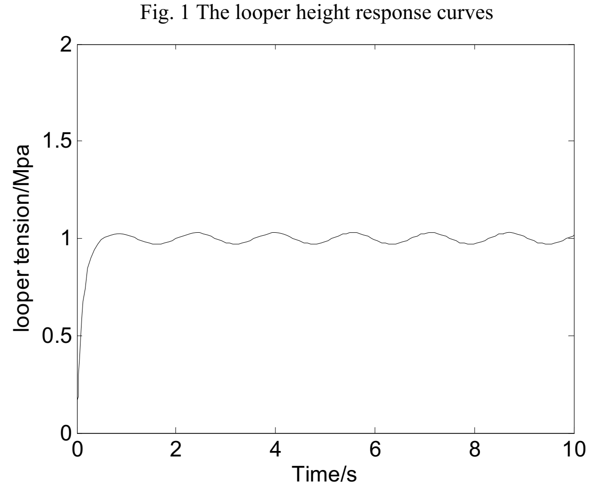

Fig.2 The looper tension response curves

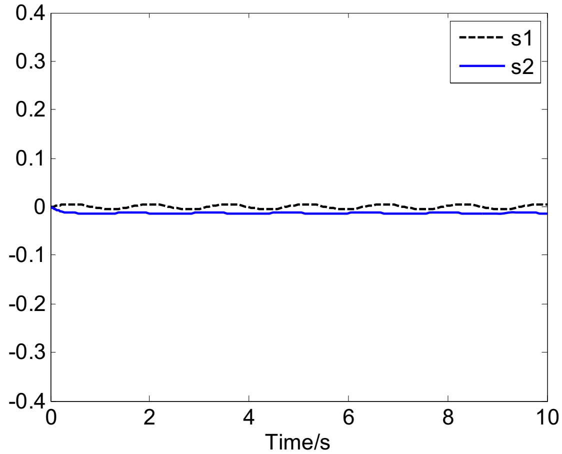

Fig.3 The variation curves of sliding mode surface function

We can see that the design controller can obtain fast and stability responses for the looper height from Fig. 1. Fig. 2 gives the trajectory of the looper tension state. We can obtain the system states are asymptotically stable. Simulation results are given to illustrate the feasibility of the presented method. At last, sliding mode surface function curves are given under the design controller from Fig.3.

V. CONCLUSIONS

For a class of uncertain looper system of hot strip rolling mill, a robust sliding mode controller is designed by using the Ackermann functional approach and equivalent control law method. Under the conditions that parameters uncertainties and disturbance exist in systems, robust controller was designed, which made looper systems good characteristics such as perfect robust stabilization and strong disturbance attenuation, it has good decoupling effect, and gives the proof of stability. At last, simulation results comparing with traditional sliding mode controller are presented to illustrate the validity of the proposed method.

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