Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

NONLINEAR LOOPER-TENSION CONTROL FOR HOT STRIP FINISHING MILL USING FEEDBACK LINEARIZATION

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Abstract: This paper studies on the design of a nonlinear controller for the looper-tension system in hot strip finishing mills using a static state feedback linearization and an ILQ(Inverse Linear Quadratic) Optimal Control. Nonlinear dynamic equations of the looper-tension system are analytically linearized by a static feedback linearization algorithm with a compensator. A nonlinear controller is designed from the feedback linear model, which is composed of an ILQ controller and an input transformer. It is shown from a computer simulation that the nonlinear controller has good performances throughout the full strip part including top, middle and end parts of the strip.

1. INTRODUCTION

In the hot strip finishing mill, the looper-tension control system aims to balance a mass flow of the strip by adjusting an interstand strip tension and a looper angle to their target values, respectively. In a real process, the looper-tension system is controlled by each different control modes according to three parts of the strip: head, middle and tail parts. The reason is that the looper-tension system is nonlinear. The head and tail parts are respectively controlled by a looperless and a no-whip control modes, and the middle part is controlled by many linear feedback control mode, i.e. non-interactive PI control, LQ, ILQ, robust optimal control etc.[1]. Thus, using a static state feedback linearization and an ILQ optimal control techniques, this paper studies on the design of a nonlinear controller which can be applied to the head strip parts including the middle strip part.

2. SYSTEM DYNAMICS

By the Newton's second law and the Hooke's law, the looper-tension dynamics is described by the following equations:

$$J\frac{d^2\theta}{dt^2} = -F_1(\theta) - A_s\sigma_f F_3(\theta) - Z\frac{d\theta}{dt} + T_{lm} \tag{1}$$

$$\frac{d\sigma}{dt} = \frac{E}{L}\left\{\frac{\partial F_2(\theta)}{\partial\theta}\frac{d\theta}{dt} - (1+s_f)v_{\mathrm{Re}}\right\} \tag{2}$$

where $T_{lm} = \kappa_{lm} i_{lm}$ is a looper motor torque, $F_1(\theta)$ is the looper load torque by the looper weight, strip weight, and bending force, $F_2(\theta)$, $F_3(\theta)$ describe a geometric strip elongation including the extension due to the speed difference between two interstands, and an influence factor relative to the strip tension load, respectively.

In Eqs. (1) and (2), control inputs are a looper motor current(i_{lm}) and a speed difference(v_{Re}) of the strip considering a forward(or backward) slip ratio(s_f), and they are controlled by LCC(Looper Current Controller) and ASR(Automatic Speed Regulator), respectively. Thus we consider ASR and LCC as two actuators, which are described as the following first-order systems:

$$\begin{aligned}\frac{d}{dt}v_{\mathrm{Re}} &= -\frac{1}{T_{ASR}}v_{\mathrm{Re}} + \frac{1}{T_{ASR}}u_{ASR}\\ \frac{d}{dt}i_{lm} &= -\frac{1}{T_{LCC}}i_{lm} + \frac{1}{T_{LCC}}u_{LCC}\end{aligned} \tag{3}$$

where T_{ASR}, T_{LCC} are time constants of ASR and LCC, respectively.

3. FEEDBACK LINEARIZATION

A feedback linear model of the looper-tension system is obtained as follows[1]:

[STEP 1] Since the nonlinear model (1)-(3) has Kronecker's indices of $\rho_1 = 3,\quad \rho_2 = 2$, the system is linearizable by a static feedback.

Thus it is satisfied that (i) $\dim(\Delta_{\rho_{\max}-1}) = 5$ (ii) $\Delta_i : 0 \le i \le \rho_{\max} - 2$ are involutive of which dimensions are constant, where Δ_i denote invariant distributions. Note that the condition (i) guarantees the controllability of the system under state feedback or coordinate transformation. The condition (ii) means a necessary and sufficient condition for the existence of scalar seed functions $h_i(x)$, of which Lie derivative satisfies the following condition:

$$L_g L_f^l h_i(x) = 0 : 1 \le i \le 2,\quad 0 \le l \le \rho_i - 2 \tag{4}$$

[STEP 2] From Eq. (4), seed functions can be obtained as follows:

$$h_1(x) = \sigma_f = x_1,\quad h_2(x) = \theta = x_2 \tag{5}$$

Then, a coordinate transformation $z = S(x)$ is given by the following equation (6).

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10.3182/20080706-5-KR-1001.4145

$$z = S(x) \Rightarrow \begin{bmatrix} z_1 \\ z_2 \\ z_3 \\ z_4 \\ z_5 \end{bmatrix} = \begin{bmatrix} h_1(x) \\ L_f^1 h_1(x) \\ h_2(x) \\ L_f^1 h_2(x) \\ L_f^2 h_2(x) \end{bmatrix} = \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \\ f_5(x) \end{bmatrix} \quad (6)$$

[STEP 3] Thus, a state feedback control law u is obtained as

$$u = \alpha(x) + \beta(x)(-\Omega z + v) \quad (7)$$

where $\alpha(x)$, $\beta(x)$ are defined as

$$\alpha(x) = -\Gamma^{-1}(x)\eta(x), \qquad \beta(x) = \Gamma^{-1}(x)$$

$$\Omega = \begin{bmatrix} -\xi_0^1 & -\xi_1^1 & 0 & 0 & 0 \\ 0 & 0 & -\xi_0^2 & -\xi_1^2 & -\xi_2^2 \end{bmatrix}$$

$$\Gamma^{-1}(x) = \begin{bmatrix} \dfrac{\kappa_{lm}}{JT_{LCC}} & 0 \\ 0 & \dfrac{E(1+s_f)}{LT_{ASR}} \end{bmatrix}$$

$$\eta(x) = \begin{bmatrix} M_{11} & M_{12} & M_{13} & M_{14} & M_{15} \\ M_{21} & M_{22} & M_{23} & M_{24} & M_{25} \end{bmatrix} \begin{bmatrix} f_1(x) \\ f_2(x) \\ f_3(x) \\ f_4(x) \\ f_5(x) \end{bmatrix}$$

$$M_{11} = -\frac{E}{L}\frac{\partial s_f}{\partial \sigma_f} v_{Re}, \quad M_{12} = \frac{E}{L}\frac{\partial F_3(\theta)}{\partial \theta}\dot{\theta}, \quad M_{13} = \frac{E}{L}F_3(\theta),$$

$$M_{14} = \frac{E}{L}(1+s_f), \quad M_{15} = 0,$$

$$M_{21} = -\frac{A_3 F_3(\theta)}{J}, \quad M_{22} = -\frac{1}{J}\left(\frac{\partial F_1(\theta)}{\partial \theta} + A_3\sigma_f \frac{\partial F_3(\theta)}{\partial \theta}\right), \quad M_{23} = -\frac{Z}{J},$$

$$M_{24} = 0, \quad M_{25} = \frac{\kappa_{lm}}{J}$$

[STEP 4] The feedback linearization model is described as a Brunovsky block canonical form,

$$\frac{dz}{dt} = Az + Bv, \quad y = Cz \quad (8)$$

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 \\ -\xi_0^1 & -\xi_1^1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 1 \\ 0 & 0 & -\xi_0^2 & -\xi_1^2 & -\xi_2^2 \end{bmatrix},$$

$$B = [b_1 \mid b_2] = \begin{bmatrix} 0 & 0 \\ 1 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix}, \quad C = \begin{bmatrix} c_1 \\ - \\ c_2 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

4. ILQ NONLINEAR OPTIMAL CONTROL

An ILQ looper-tension controller for the plant given as in Eq. (8) is obtained by the following equation[2]:

$$v = \frac{K_I}{s}(r-y) - K_F z, \quad [K_F \quad K_I] = \Sigma[K_{F0} \quad K_{I0}]$$

where a gain tunning parameter Σ and normalized integral and state feedback control gains K_{I0}, K_{F0} are respectively obtained as follows:

$$\Sigma = \begin{bmatrix} \sigma_1 & 0 \\ 0 & \sigma_2 \end{bmatrix}$$

$$K_{I0} = \begin{bmatrix} K_{I011} & 0 \\ 0 & K_{I022} \end{bmatrix},$$

$$K_{F0} = \begin{bmatrix} K_{F011} & K_{F012} & 0 & 0 & 0 \\ 0 & 0 & K_{F023} & K_{F024} & K_{F025} \end{bmatrix}$$

$$K_{I011} = -\omega_1^2, \quad K_{I011} = -\omega_2^3,$$

$$K_{F011} = -2\omega_1, \quad K_{F012} = 1,$$

$$K_{F023} = 3\omega_2^2, \quad K_{F024} = -3\omega_2, \quad K_{F025} = 1$$

where $\omega_i, i = 1,2$ are target time constants of the control system. Figure 1 shows that the ILQ controller based on the feedback linear model has good command following performances than that of the linear model using Talyor's series.

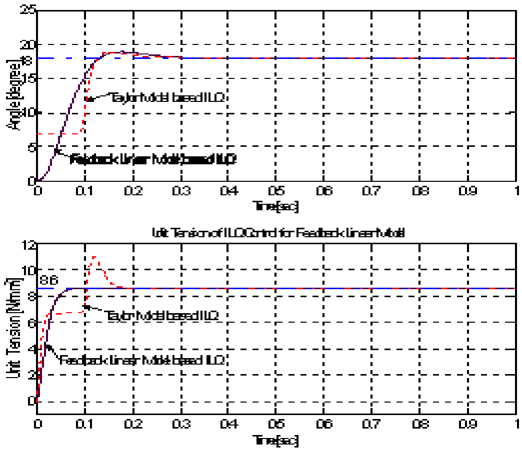

Fig. 1. Strip tension and looper angle

5. CONCLUSION

This paper proposed a new linear model using a static feedback linearization technique. Furthermore , an ILQ looper-tension controller with a nonlinear structure is designed. It is shown that the proposed controller is useful to control the tension of the head strip part in the hot strip mill process.

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