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Explicit Model Predictive Controller Design for Thickness and Tension Control in a Cold Rolling Mill

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Abstract: This paper addresses modeling of a cold rolling mill and controller design based on explicit model predictive control(explicit MPC). The control objectives are to track the exit thickness to the reference with high accuracy with minimized strip tension deviation. In the simulation, good control is obtained when the disturbance entering the system is small enough. However, the thickness shows the offset from the reference in case of acceleration, because the approximation error of the linearized model increases and it is different from the model in the design of the controller. In order to compensate for the control offset, an additional integral logic using the estimation error of exit thickness is proposed. The validity of this approach was verified by simulation and offset free control was achieved.

Keywords: process control, process models, predictive control, optimal control, multi-input/multi-output system, steel industry.

1. INTRODUCTION

In a cold strip mill, as shown in Fig. 1, the preceding strip and the receding strip are welded together and it is rolled continuously. The exit thickness of each of the rolling stands should be controlled with high accuracy. It is also necessary to minimize strip tension deviations during thickness control in order to prevent rolling trouble such as strip breakage. These variables are controlled by adjusting the roll gap and the roll speed. At the welding point, the roll gap and the roll speed are synchronized to achieve the thickness change. These actions are executed by feed forward control. When the welding point is not passing through the mill, feedback control is used for thickness and tension control.

This paper deals with thickness and tension control problem during normal operation for two adjacent rolling stands in a rolling mill, as depicted in Fig. 2.

Model Predictive Control (MPC) is well known for its control performance and ability to account for the constraints of the plant. Therefore it has been regarded as a practical solution and is widespread in the process industry. For example, an application of nonlinear MPC to a cold rolling mill is reported by Ozaki et al. (2009) and it shows good results under acceleration and deceleration conditions. However it requires online optimization and the implementation cost related to the optimization software and high performance computer tends to be high. Furthermore, the time of solving an optimization problem possibly exceeds the sampling period. Consequently, the applications are limited.

In explicit MPC(Bemporad et al. (2000)), the optimization problem in the MPC for the linear time-invariant system such as a quadratic programming problem is converted into a multi-parametric programming problem, and then the solution is obtained as a piecewise affine function of the state of the plant in offline. Hence it does not require online optimization and can potentially reduce the implementation cost and overcome the limitation of normal MPC. Therefore, explicit MPC is applied in this paper.

The outline of this paper is as follows. In section 2, the state space model of a cold rolling mill is presented. In section 3, the design procedure of the explicit MPC is given. Next, the simulation results and controller modifications for improving the tracking performance of the thickness are shown in section 4.

2. DYNAMICAL MODEL OF A ROLLING MILL

In this section, a nonlinear dynamical model of a cold rolling mill and its linear state space model are described.

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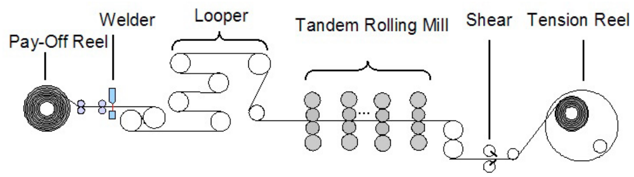

Fig. 1. Layout of a Continuous Cold Rolling Mill

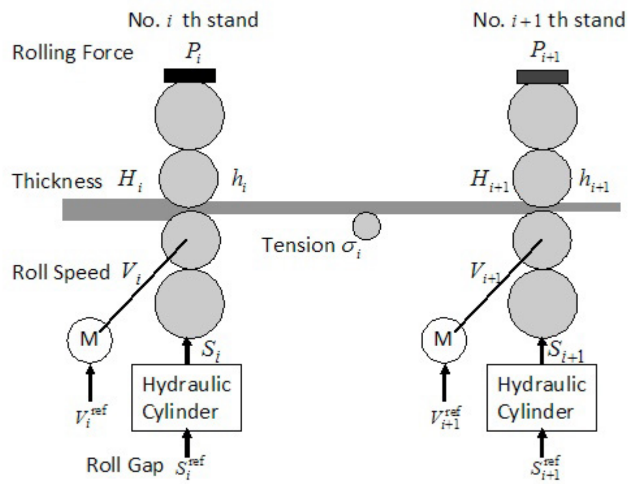

Fig. 2. Adjacent Rolling Stands in a Rolling Mill

2.1 *Rolling Models and Actuator Models*

The model consists of rolling models and actuator models. Each model is shown below. Here, the variables in the models are presented in Table 1. Note that the suffix i denotes the i th stand.

- Rolling Force Model

$$P_i = w(k_i - 0.7\sigma_{i-1} - 0.3\sigma_i) \times \left(1.08 + 1.79 r_i \mu_i \sqrt{\frac{R'_i}{H_i}} - 1.02 r_i\right) \times \sqrt{R'(H_i - h_i)} \times 1000. \quad (1)$$

where,

$$R'_i = R_i\left(1 + \frac{16(1-\nu^2)}{E_s \pi} \frac{P_i}{w(H_i - h_i)}\right),$$

$$r_i = \frac{H_i - h_i}{H_i}.$$

- Forward Slip Model

$$f_i = \tan^2\left(\frac{1}{2}\tan^{-1}\left(\sqrt{\frac{H_i - h_i}{h_i}}\right) - \frac{1}{4\mu_i}\log\left(\frac{H_i}{h_i}\frac{k_{i-1}(1-\sigma_i)}{k_i(1-\sigma_{i-1})}\right)\right). \quad (2)$$

- Friction Model

$$\mu_i = \mu_a \exp(-\mu_b \times V_i) + \mu_c. \quad (3)$$

- Deformation Resistance Model

$$k_i = 1.15 l \left(m + 1.15 \log\left(\frac{H_0}{h_i}\right)\right)^n. \quad (4)$$

- Strip Tension Model

$$\frac{d\sigma_i}{dt} = \frac{E_s}{L}\left(\frac{h_{i+1}}{H_{i+1}}(1 + f_{i+1})V_{i+1} - (1 + f_i)V_i\right). \quad (5)$$

- Thickness Model

$$h_i = S_i + \frac{P_i}{M_i}. \quad (6)$$

- Transport Delay Model

$$H_{i+1} = h_i \exp\left(-\frac{L}{(1 + f_i)V_i}s\right). \quad (7)$$

- Roll Speed Model

$$V_i(s) = \frac{1}{T_v s + 1} V_i^{\mathrm{ref}}. \quad (8)$$

- Roll Gap Model

$$S_i(s) = \frac{1}{T_s s + 1} S_i^{\mathrm{ref}}. \quad (9)$$

The rolling force model given in (1) and forward slip model given in (2) are reported by Misaka (1967). The friction coefficient between strip and work roll is dependent on the roll speed and it is modeled as (3). The deformation resistance model given in (4) is based on the effectiveness of strain hardening. Strip tension results from the elastic deformation of the strip. Therefore, it is proportional to the difference of the strip velocity between the exit of i th stand and the entry of $i + 1$ th stand. It is modeled as (5). The thickness model shown in (6) indicates that it is determined by the roll gap S_i and elastic deformation of the work roll, which is represented as P_i/M_i. The exit thickness of the i th stand is transported to the $i + 1$ th stand. Thus this system includes time delay. This relationship is represented in (7).

The actuators of the mill are electric motors and hydraulic cylinders. The former are for controlling the roll speed, and latter for controlling the roll gap position. The motors are controlled by the Automatic Speed Regulator(ASR) and the hydraulic cylinders are controlled by the position control system. Thanks to these minor feedback control, these actuators can be modeled as first order transfer function described in (8) and (9).

2.2 *Linear State Space Model*

The linear state space model is derived from the nonlinear model shown above. First, total derivative of the thickness model is expressed as

$$\Delta h_i = \Delta S_i + \Delta P_i / M_i. \quad (10)$$

where,

$$\Delta P_i = \frac{\partial P_i}{\partial h_i}\Delta h_i + \frac{\partial P_i}{\partial H_i}\Delta H_i + \frac{\partial P_i}{\partial \sigma_{i-1}}\Delta\sigma_{i-1} + \frac{\partial P_i}{\partial \sigma_i}\Delta\sigma_i + \frac{\partial P_i}{\partial V_i}\Delta V_i. \quad (11)$$

By substituting (11) for (10), the thickness model is linearized as

$$\Delta h_i = \frac{1}{M_i + Q_i}\left(M_i \Delta S_i + \frac{\partial P_i}{\partial H_i}\Delta H_i + \frac{\partial P_i}{\partial \sigma_{i-1}}\Delta\sigma_{i-1} + \frac{\partial P_i}{\partial \sigma_i}\Delta\sigma_i + \frac{\partial P_i}{\partial V_i}\Delta V_i\right). \quad (12)$$