FLATNESS CONTROL OF STRIP IN CONTINUOUS HOT ROLLING PROCESSES

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Abstract

In order to improve the flatness of hot rolled strip in hot strip finishing mills, a novel segmented looper system is developed, which called the Flatness Sensing Inter-stand Looper (FlatSIL) system. The FlatSIL system measures the tension along the direction of the strip width by using segmented rolls, and the tension profile is calculated. Using the tension profile, the flatness control system of hot strip can be constructed. The new flatness control system works for the full strip length during strip rolling as far as the tension profile-measuring device and the work roll bender are on. To control the flatness of hot strip, self-tuning algorithm using the recursive least mean square method is applied to update PI gains. By the computer simulation and experiment, the performance of flatness control systems with the fixed and self-tuning PI gains is compared

1 Introduction

The flatness of hot strip is important in the hot rolled strip market. In order to keep the flatness of hot strip, a configuration of the roll gap between work-rolls is maintained to regular ratio together with the thickness of hot strip in the lateral direction. The tension of strip between stands should be also without a meandering of strip, and be kept the symmetric from the central shaft of the mill. It is, however, difficult to maintain an allowable flatness due to a lot of effective factors in continuous hot rolling processes.

Measurement methods for the strip flatness are the indirect measurement method to use a separated roll and the direct measurement method to use a laser sensor and image processing[1][2]. The indirect method usually uses the laser sensor and camera systems. The laser beam can only recognize goodness or badness of the flatness when the curve of hot strip is appeared, because the distance from sensor to a hot strip is converted to flatness. The direct method can measure the tension of strip precisely through separated rolls[3]. The coarse surrounding effects easily damage the detailed separate rolls, and the life cycle of sensor becomes short. Moreover, the bender that is a hydraulic actuator cannot control the detail tension of the hot strip.

In this paper, a novel inter-looper system, which called the Flatness Sensing Inter-stand Looper (FlatSIL) system, is developed[4] and the flatness control system is synthesized via the self-tuning PI control method. The FlatSIL system measures the tension and estimates the tension profile in the lateral direction. The estimated tension profile can be described as a quadratic equation, and the coefficient of the second order term represents the flatness of hot strip. Therefore, the FlatSIL system can monitor and control the flatness of hot strip during hot rolling processes[5]. Moreover, the FlatSIL system complements the direct and indirect measurement methods and extends the life cycle of measurement device. To show the effectiveness of the self-tuning PI flatness control using the FlatSIL system, computer simulation is executed and the proposed control system is applied to a hot rolling mill in POSCO.

2 Flatness sensing system

The inter-stand looper itself would have the same function as the traditional one from the viewpoint that the looper adjusts mass flow between two stands by changing the looper angle and maintains the strip tension constant. The FlatSIL system measures the tension of strip and converts to the profile of tension in the lateral direction. In order to setup the FlatSIL system, the traditional full-length looper roll is replaced by separated segment rolls with its own bearings. The FlatSIL system is consisted of five separated segment rolls that are three measuring segment rolls and two dummy ones. The concept of segmentation was to detect the tension profile across the strip width. The new design of reduced number of segments is to assure the longer life of the device under the severe environment of inter-stand space and easy maintenance.

Fig. 1 shows the configuration of the FlatSIL system. Each axis of the segmented roll is independently structured to its own bearings and each bearing assembly is connected by the pivoted angle to transfer the strip tension on the segmented roll to the load cell. The segmented rolls can be easily separated from the looper table by just unbolting the bearing shield covers of the roll shaft support. The level of each segment roll can be adjusted with an attached device. The load cells are capsulated by the housing block and cushioned by the shock absorbing pad for protecting from impact shock arising during the position resetting of the looper table between coils. The coolant water is supplied to the segmented roll and the load cell housing. A matter of point in the looper operation is the mass moment of inertia. The mechanical frame of the FlatSIL is designed by considering the base torque and the wear resistance of the segmented roll since the segmented roll is continuously contacted to running strip during rolling processes. The present segmented roll was thermal spray coated to increase wear resistance. The load acting on the segmented looper roll consists of the weight of strip, the bending force, the centrifugal force, and the inertia force as well as the strip tension.

Fig. 2 illustrates the load acting on the segmented roll separated by the radial force F_A and the tangential force F_L, θ_f is the looper angle and θ_o is the angle between the strip pass line and the load sensing direction of the segmented roll. For a simple approach, we consider static components of these forces with the assumption that the looper position is in a steady state. In the steady state, dynamic components of the force can be negligible. In order to calculate the strip tension from the measured load, the inertia effect is neglected and the geometric relation as shown in Fig. 2 is used to derive Eq. (1).

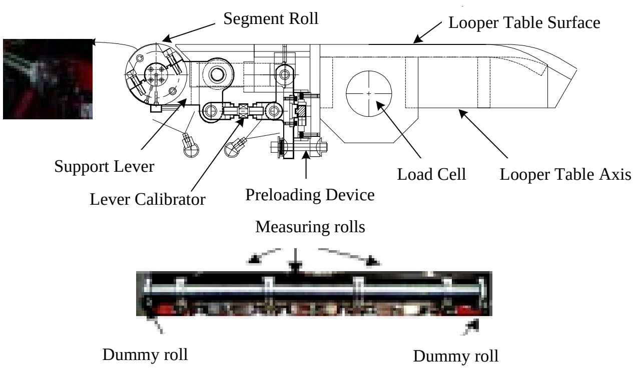

Fig. 1 Configuration of the FlatSIL system.

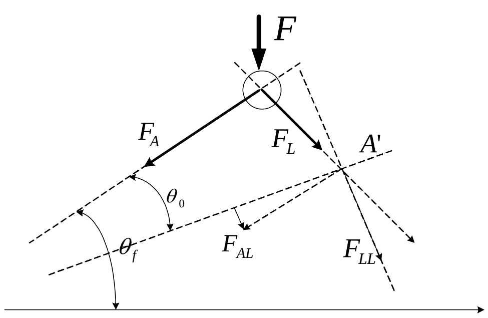

Fig. 2 Load acting on the segmented roll separated by the radial and tangential forces.

$$T = \frac{K_n \times F_{LC} - (K_j \sin\theta_f + K_k \sin\theta_f) \times (F_1 - F_2)}{W_{seg} \times h} \qquad (1)$$

where

T : Unit tension of the strip(N/mm),

K_n : Variable related to the looper angle,

F_{LC} : Weight of the strip on the load cell(N),

K_j, K_k : Constants related to the looper angle,

θ_f : Looper angle,

F_1 : Load of the strip bending and weight(N),

F_2 : Centrifugal force of strip(N),

W_{seg} : Strip width on the segmented roll (mm),

h : Exit thickness (mm).

The existing segmented looper rolls have seven to nine measuring segmented rolls and two dummy ones along the barrel width. In present, however, there is no good actuator except the work roll bender that controls the wave by a second order parabolic character and the exact wave index such as I-unit is not essential to control the wave pattern between stands. The three segmented measuring rolls are only adopted to get a wave pattern of hot strip between stands. Each segmented roll has the load cell at the position of both barrel ends, and the two load values acting on the individual segmented roll are used for calculating an average load value over the span of strip contact on the segmented roll. The position of strip over the looper roll in that case is informed by a width-meter installing behind the last stand. With three rolls, we can determine whether the pattern of tension profile is concave or convex. Based on the measured tension values we can formulate a basic correlation between the tension profile pattern and the strip wave. The limitation of the three-point curve fitting is justified here because the hot strip mill has only a symmetric control actuator of the work roll bender and the curve form of the tension profile is enough to determine the bending direction.

Fig. 3 shows a schematic diagram illustrating a tension profile formed on the strip based on the load values measured at segmented rolls. To express the tension profile of the dotted line, the tension value T_n across the strip width X_n is assumed as Eq. (2), where T_n and X_n are the normalized values by the set-up tension and the segmented roll length, respectively.

$$T_n = A_n + B_n X_n + C_n X_n^2 \qquad (2)$$

where

$$B_n = \frac{1}{X_{Rn} - X_{Ln}} \left(\frac{X_{Rn}}{X_{Ln}} \left(T_{n1} - T_{n2}\right) - \frac{X_{Ln}}{X_{Rn}} \left(T_{n3} - T_{n2}\right) \right),$$

$$C_n = \frac{1}{X_{Rn} - X_{Ln}}\left(-\frac{1}{X_{Ln}}\left(T_{n1} - T_{n2}\right) + \frac{1}{X_{Rn}}\left(T_{n3} - T_{n2}\right)\right),$$

$$T_{n1} = A_n + B_n X_{Ln} + C_n X_{Ln}^2,$$
$$T_{n2} = A_n,$$
$$T_{n3} = A_n + B_n X_{Rn} + C_n X_{Rn}^2,$$
$$X_{Ln} = -\frac{W_{seg2} + W_{seg1}}{2} \times \frac{1}{X_{L\max}},$$
$$X_{Rn} = \frac{W_{seg2} + W_{seg3}}{2} \times \frac{1}{X_{R\max}}.$$

B_n describes the linear component for skewing that means the level difference between strip sides, and C_n represents the difference of the normalized tensions between the strip center and sides. W_{seg1}, W_{seg2} and W_{seg3} are the lengths of hot strip on the segmented rolls. The normalized tension profile of strip can be expressed as a parabolic equation by the curve fitting with the three-point tension values on three segmented rolls. The normalized tension at each segmented roll is calculated over the strip width on each segmented roll. The normalized position of strip is informed from a width-meter installed behind the last stand. Then, the coefficients A_n, B_n and C_n in Eq. (2) represent the tension profile of strip. C_n represents the flatness character of strip and B_n represents the side wave character.

The important point to mention here is that the flatness coefficients in the present work can not be a presentation of the exact wave index such as I-unit since the tension values at both the end segmented rolls are not the value at the exact strip edge. But the coefficients are enough to indicate the strip wave pattern and the need to correct or not. Thus, we can predict the tension profile pattern by these coefficients and determine efforts for controlling the side wave and the flatness of strip based on coefficients of B_n and C_n, respectively.

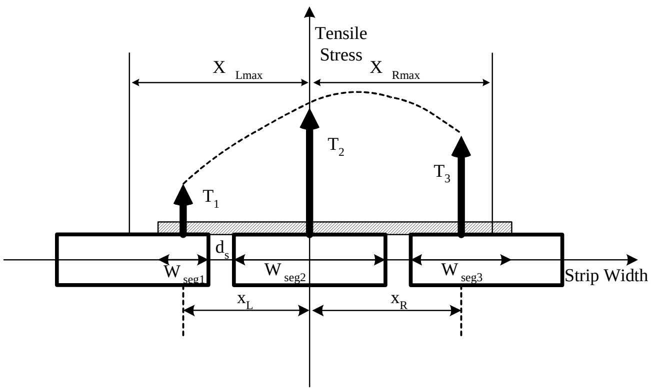

Fig. 3 Tension profile extracted from the load based on segmented rolls.

3 Self-tuning PI flatness control system

Fig. 4 shows the schematic of the self-tuning PI flatness control using the FlatSIL system. The coefficients of the quadratic equation, which are derived from the FlatSIL system, can be considered as tension indices. The coefficient B_n in Eq. (2) shows the linearity of the tension in the lateral direction, and the coefficient C_n shows the parabolic between the middle and each ends of hot strip. To improve the flatness property of hot strip, the coefficient C_n of the quadratic equation should be maintained zero. Thus, the coefficient C_n is considered for the flatness control of strip. It is related mainly with the hydraulic bender actuator. There is, however, not the dynamic model equation, which describes the relation between the bender and the coefficient C_n. Thus, the recursive least mean square (RLMS) with forgetting factor method is used for deriving the transfer function between the bender actuator and the coefficient C_n.

The system is assumed as a second order system with a finite zero. Then the ARMAX model is expressed as follows:

$$A(z^{-1})y(t) = B(z^{-1})u(t-1) + \xi(t) \tag{3}$$

where

$A(z^{-1}) = a_0 + a_1 z^{-1} + a_2 z^{-2}$, $B(z^{-1}) = b_0 + b_1 z^{-1}$,

$\xi(t)$ is the uncorrelated random noise.

The parameters in Eq. (3) are estimated by the RLMS with forgetting factor method.

$$\hat{\theta}(t) = \hat{\theta}(t-1) + L(t)\left[y(t) - \varphi^T(t)\hat{\theta}(t-1)\right] \tag{4}$$

where

$$L(t) = \frac{P(t-1)\varphi(t)}{\lambda_m + \varphi^T(t)P(t-1)\varphi(t)},$$

$$P(t) = \left[P(t-1) - \frac{P(t-1)\varphi(t)\varphi^T(t)P(t-1)}{\lambda_m + \varphi^T(t)P(t-1)\varphi(t)}\right] / \lambda_m,$$

$$\hat{\theta} = \left[a_0, a_1, a_2, b_0, b_1\right]^T,$$

$$\varphi = \left[y(t), y(t-1), y(t-2), u(t-1), u(t-2)\right]^T,$$

$0 < \lambda_m \le 1$ is the forgetting factor.

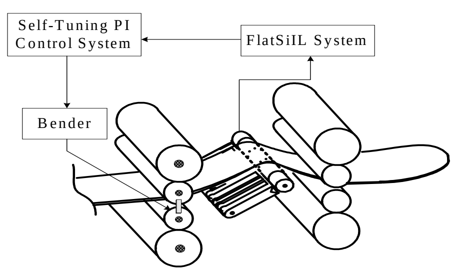

Fig. 4 Schematic of the self-tuning PI flatness control using the FlatSIL system.

And, the discrete PI control law is as follows:

$$\Delta u(t) = K_p \left[\{e(t) - e(t-1)\} + \frac{T_s}{T_i} e(t) \right] \tag{5}$$

where Δ denotes a differential operator defined by $\Delta = 1 - z^{-1}$, $e(t) = r(t) - y(t)$, K_p, T_i and T_s are the proportional gain, the reset time and the sampling period, respectively. And let $C(z^{-1})$ be considered as follows:

$$C(z^{-1}) = K_p(1 + \frac{T_s}{T_i}) - K_p z^{-1} \tag{6}$$

From Eqs (5) and (6), we can derive the following equation.

$$C(z^{-1})y(t) + \Delta u(t) - C(z^{-1})r(t) = 0 \tag{7}$$

To design the self-tuning PI controller based on the generalized minimum variance control, the cost function J is considered as follows:

$$J = E[\{P(z^{-1})y(t) + Q(z^{-1})\Delta u(t) - P(1)r(t)\}^2] \tag{8}$$

where

$P(z^{-1}) = p_0 + p_1 z^{-1} + p_2 z^{-2}$,

$Q(z^{-1}) = q_0 + q_1 z^{-1} + q_2 z^{-2}$.

The control input minimizing the cost function J is given by the following equation.[6]

$$F(z^{-1})y(t) + \{p_0 E(z^{-1})B(z^{-1}) + Q(z^{-1})\}\Delta u(t) - P(z^{-1})r(t) = 0 \tag{9}$$

where $E(z^{-1})$, $P(z^{-1})$ and $F(z^{-1})$ are given by solving the diophantine equation.[7][8]

$$P(z^{-1}) = \Delta p_0 A(z^{-1})E(z^{-1}) + z^{-1}F(z^{-1}), \tag{10}$$

where $E(z^{-1}) = 1, F(z^{-1}) = 1 + f_1 z^{-1} + f_2 z^{-2}$.
Subsituting Eq. (9) into Eq. (3) and using Eq. (10) the following equation can be derived.

$$y(t) = \frac{z^{-1}B(z^{-1})P(1)}{T(z^{-1})} r(t) + \frac{p_0 E(z^{-1})B(z^{-1}) + Q(z^{-1})}{T(z^{-1})} \xi(t) \tag{11}$$

where

$T(z^{-1}) = P(z^{-1})B(z^{-1}) + \Delta A(z^{-1})Q(z^{-1})$,
Consider the desired closed loop transfer function $T(z^{-1})$, the updating PI gains are as follows:

$$\begin{aligned} K_p &= -\frac{1}{\nu}(f_1 + 2f_2) \\ T_i &= -\frac{f_1 + 2f_2}{f_0 + f_1 + f_2} T_s \end{aligned} \tag{12}$$

where ν is a design parameter.

4 Simulation and implementation

To evaluate the FlatSIL system, the computer simulation is performed based on the estimated plant. As mentioned, the dynamics between the bender and the coefficient C_n in the tension profile equation is estimated by the RLS method which is based on the field data. The output of estimated plant and field data are shown Fig. 5 through Fig. 7. Figs are representative of each thickness and they are admittable for using a estimated plant. Based on the estimated plant, the computer simulation is performed to compare the performance the self-tuning PI and fixed PI gain controller. The simulation result is shown in Fig. 9. Except the transient response, the self tuning PI controller shows better performance.

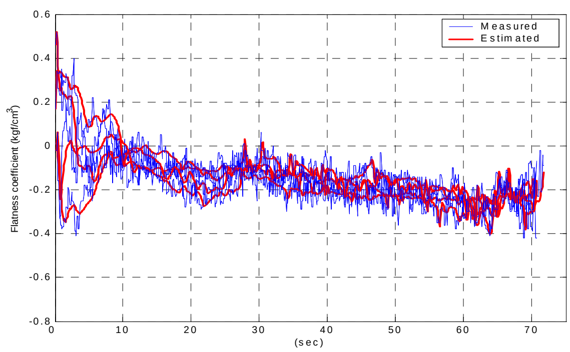

Fig. 5 Estimated flatness coefficients for the strip of 1.4t.

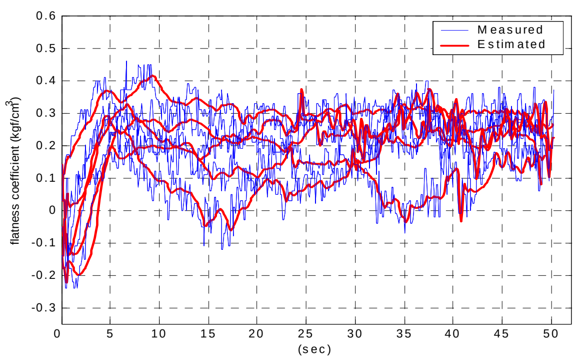

Fig. 6 Estimated flatness coefficients for the strip of 2.3t.

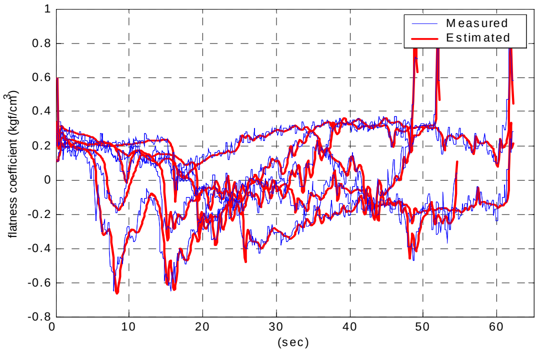

Fig. 7 Estimated flatness coefficients for the strip of 3.2t.

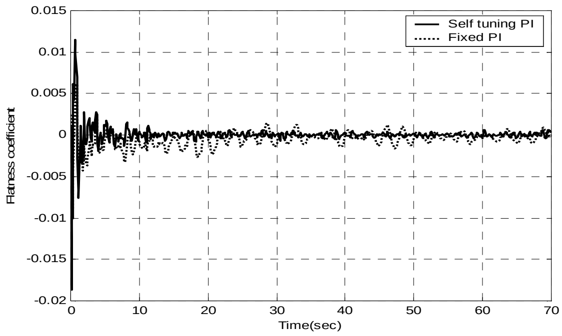

Fig. 8 Time response of flatness coefficient C_n for the fixed PI and self-tuning PI control systems.

In order to apply the FlatSIL system to a continuous hot rolling process, two FlatSIL systems were installed between #5 and #6 and between #6 and #7 work rolls. Fig. 9 shows the layout of the FlatSIL system.

The value of coefficient C_n is divided into 20 zones, which are divided into 3 parts again. They are called the edge wave, the dead flat and the center wave. The flatness control maintains the coefficient C_n in the dead flat. Fig. 10 shows the effect of the flatness control with/without the FlatSIL system. As shown in Fig. 10, the quality of flatness for the hot strip is improved using the FlatSIL system.

In order to improve the flatness control system with FlatSIL system, the self-tuning PI controller was implemented to a real system and results are shown in Fig. 11 through Fig. 14. Figs. 11 and 12 are for the fixed PI control system, and Figs. 13 and 14 are for the self-tuning PI control system. The self-tuning PI control system showed a better performance than the fixed PI control system. The results, however, at the #6 stand are worse than at the #5 stand in the fixed and self-tuning PI control systems simultaneously, because the hot strip becomes thinner after finishing the mill in the #5 stand.

Figs. 15 and 16 show the distribution of flatness coefficients for the fixed PI and self-tuning PI control systems during the hot rolling processes, respectively. In the case of the self-tuning PI control system, the range of distribution becomes narrower than the fixed PI control system. The standard deviations of the fixed and self-tuning PI control systems were 0.4056 and 0.2537, respectively. And, Fig. 17 shows the control inputs of the self-tuning PI control system in the #6 stand. The control inputs were saturated frequently, because the capacity of the bender is insufficient. To improve the performance of the self-tuning controller, the capacity of the bender should be increased.

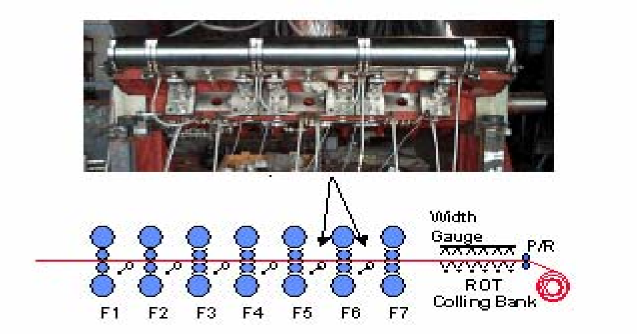

Fig. 9 Installment of the FlatSIL system.

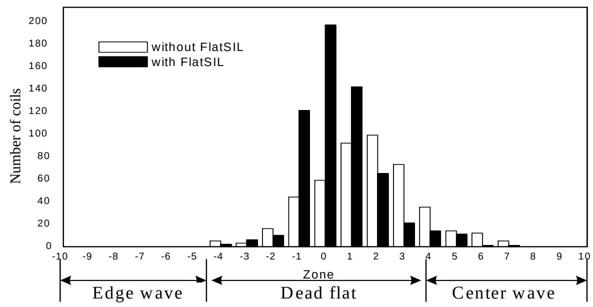

Fig. 10 Effect of the flatness control with/without the FlatSIL system.

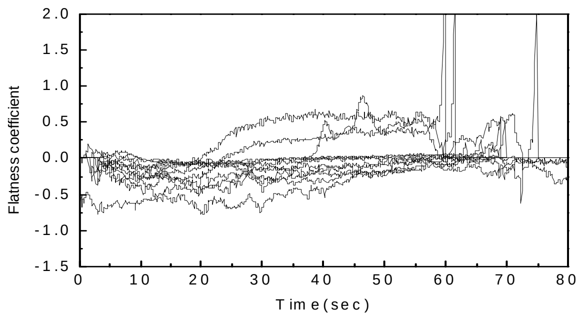

Fig. 11 Flatness coefficients in the #5 stand in case of the fixed PI control system.

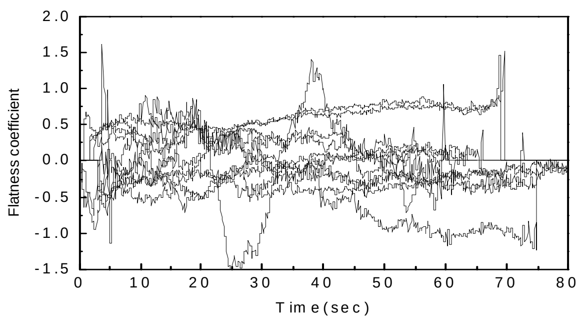

Fig.12 Flatness coefficients in the #6 stand in case of the fixed PI control system.

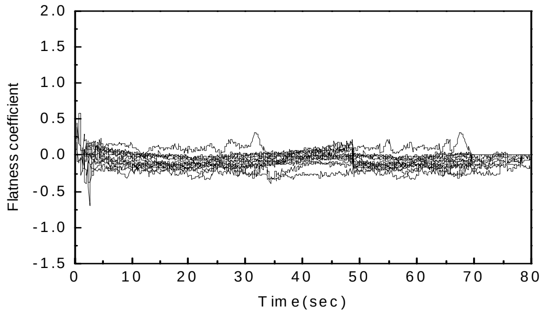

Fig. 13 Flatness coefficients in the #5 stand in case of the self-tuning PI control system.

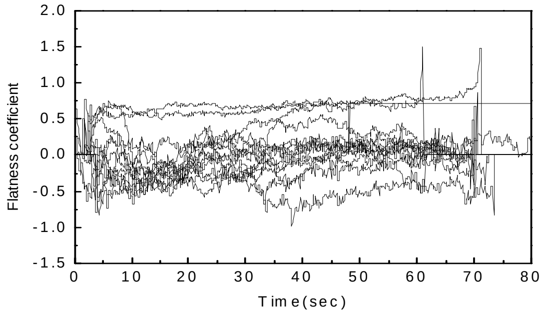

Fig. 14 Flatness coefficients in the #6 stand in case of the self-tuning PI control system.

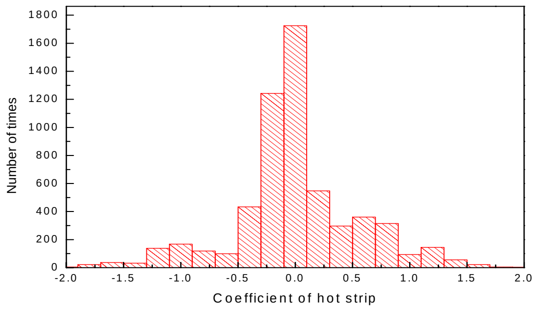

Fig. 15 Distribution of flatness coefficients in case of the fixed PI control system.

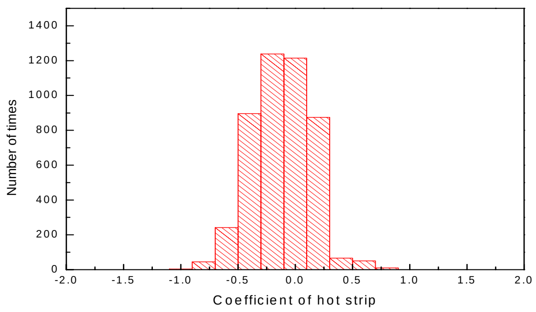

Fig. 16 Distribution of flatness coefficients in case of the self-tuning PI control system.

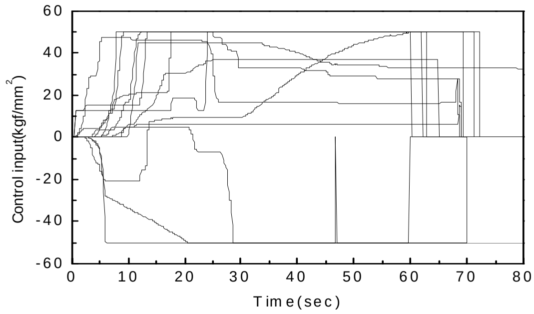

Fig. 17 Control input of the self tuning PI control system in the #6 stand.

5 Conclusion

In the paper, the novel inter-looper system called the FlatSIL system is developed, and the self-tuning PI flatness control with the FlatSIL system is designed. The FlatSIL system calculates the tension profile as a quadratic equation, and refers the flatness of hot strip through the coefficient of the second order term. And operators who work in the field can monitor the flatness of hot strip during hot rolling processes and can control the flatness of strip using the PI controller. The gains of PI controller are updated using the RLMS with forgetting factor method. Through implementing hot finishing mill processes, it is founded that the self-tuning PI flatness control with the FlatSIL system has desirable performance.

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