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Abstract
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Keywords
monitor, compensation, time, mill, dead, strip, controller, pi, expert, hot, agc

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Research Article

An Expert PI Controller with Dead Time Compensation of Monitor AGC in Hot Strip Mill

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Hot strip rolling production is a high-speed process which requires high-speed control and communication system, but because of the long distance between the delivery stand of the finishing mill and the gauge meter, dead time occurs when strip is transported from the site of the actuator to another location where the gauge meter takes its reading, which seriously affects the thickness control effect. According to the process model which is developed based on the measured data, a filtered Smith predictor is applied to predict the thickness deviation of the finishing mill. At the same time, an expert PI controller based on feature information is proposed for the strip thinning during looper rising and coiler biting period and the strip thickening during the tension loss period of the strip tail end. As a result, the thickness accuracy has been improved by about 1.06% at a steady rolling speed and about 1.23% in acceleration and deceleration.

1. Introduction

Figure 1 shows the outline of a typical 1700 mm hot strip mill (HSM). Its purpose is to process cast steel slabs into steel strip. Hot rolling can achieve large dimensional changes in a single step; the slabs, of up to 35 t weight, are typically 250 mm thick and 10 m long, and the rolled strips are typically 2 mm thick and 1250 m long. This reduction in thickness is achieved by passing the piece through a series of rolling mill stands. Typically, at the first stand, the roughing mill (RM), the thickness of the hot slab (1240°C) is reduced by making several passes, forward and reverse, through the mill. At the end of this roughing process the piece will be 35 mm thick and 70 m long and its temperature will have dropped to 1050°C. Further reduction in thickness takes place in the six or seven close-coupled rolling finishing stands. The strip elongation is so great that the piece can straddle a region from the finishing mill (FM) approach tables to the coiler. During this part of the process, pieces normally have a final rolling temperature of 870°C followed by coiling at 600°C [1].

Thickness precision is one of the most important quality indexes in strip rolling process [2, 3]. Monitor automatic gauge control (AGC) based on hydraulic roll gap control system is widely used in modern strip rolling mills [4–7]. In monitor AGC system, gauge meter is used to measure strip gauge derivation, which is installed at the delivery side of the finishing mill. The strip thickness can be controlled by adjusting the roll gap. Because of restriction of mill structure and requirement of maintenance, the install location of gauge meter is far from the mill. As shown in Figure 2, the rolling mill produces steel strip at a speed of v, and gauge meter measures the strip thickness h. By comparing h with thickness reference h_0, thickness deviation Δh is obtained. Then the gap correction value of monitor AGC ΔS_M is calculated. At the same time, the gap correction value of other types of AGC ΔS_X is calculated too. ΔS_M and ΔS_X are subsequently added to the gap set value S_0 to get the target gap S_r. At last, hydraulic cylinders are used to modify the gap between a pair of working rolls that squeeze the material into the desired

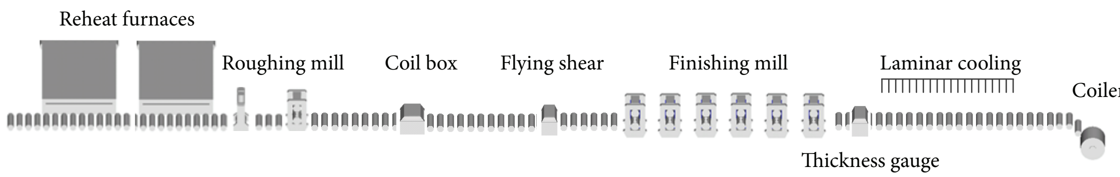

Figure 1: A typical hot strip mill layout.

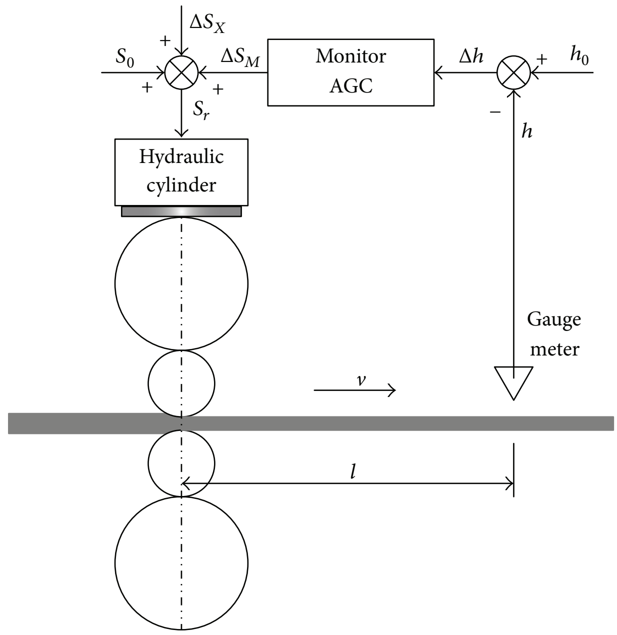

Figure 2: Simplified schematic diagram of monitor AGC.

thickness. The dead time τ in this process is caused by the distance l between the rolls and the gauge meter

$$\tau = \frac{l}{v}. \tag{1}$$

During that interval, the process does not respond to the controller's activity at all, and any attempt to manipulate the process variable before the dead time has elapsed inevitably fails.

According to control theory, the time delay in any feedback system reduces system stability and deteriorates dynamic characteristics, especially for the case of $\tau/T \geq 0.5$, where T is the time constant [8]. Because the inertia time constant T of the hydraulic system is generally less than 50 ms, the value of τ/T of the delivery stand is greater than 0.5 and those of the upstream stands are much greater.

Plants with a long time delay can often not be controlled effectively using a simple PID (Proportional, Integral, and Derivative) controller. The main reason for this is that the additional phase lag contributed by the time delay tends to destabilize the closed-loop system. The stability problem can be solved by decreasing the controller gain. However, in this case the response obtained is very sluggish [8, 9].

The Smith predictor (SP), shown in Figure 3, is well known as an effective dead time compensator for a stable process with long time delay [10]. The widespread application of the SP has been hindered by two problems. First, it is difficult to tune manually, because the practicing engineer is not very familiar with process modeling and it is a time-consuming manual task. Second, the predictor is sensitive to process parameter variations, as in any other advanced control technique. Hence the need for retuning the SP is more frequent than that for the PID controller [11, 12].

2. Filtered Smith Predictor (FSP)

The well-known SP is a dead time compensator (DTC) widely used in the industry in which a dead time nominal process model is used. Nevertheless, the main drawback of this algorithm is that dead time errors can destabilize the system. A robust solution is the FSP, in which a filter is included to attenuate the oscillation caused by delay mismatches [13]. The proposed controller is shown in Figure 4. It can be seen that the structure is the same as in the SP with an additional filter $F_r(s)$. Because of its characteristics, the FSP can be used to compute a controller taking into account the robustness, coping with unstable plants, improving the disturbance rejection properties, and decoupling the set-point and disturbance responses [14]. Therefore, all the drawbacks of the SP are considered in the design, using only one structure and, as will be shown, a unified design procedure.

In the structure $P_m(s) = G_m(s)e^{-\tau_m s}$ is a process model, $G_m(s)$ is the dead time-free model and $G_c(s)$ is the primary controller. In the nominal case ($P(s) = P_m(s)$) the closed-loop transfer function for set-point changes is the same for the SP and FSP:

$$H_r(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s) P_m(s)}{1 + G_c(s) G_m(s)}. \tag{2}$$

Note that the delay is eliminated from the characteristic equation and $F_r(s)$ does not affect $H_r(s)$. Assume that the real plant differs from the nominal case ($P_m(s) \neq P(s)$) and consider a family of plants $P(s) = G_p(s)e^{-\tau_p s}$ such that $P(s) = P_m(s)[1+\delta P(s)] = P_m(s)+\Delta P(s)$, and its characteristic equation is given by

$$1 + G_c(s) G_m(s) + G_c(s) G_m(s) P_m(s) \delta P(s) = 0. \tag{3}$$

The condition for closed-loop SP robustness is that, for all frequencies and all plants in the family, the distance between

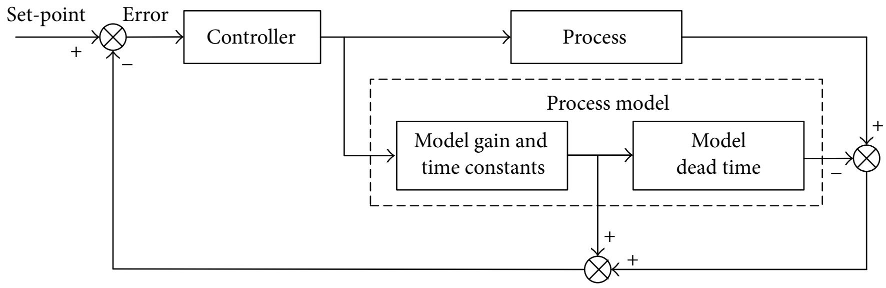

Figure 3: Smith predictor control scheme.

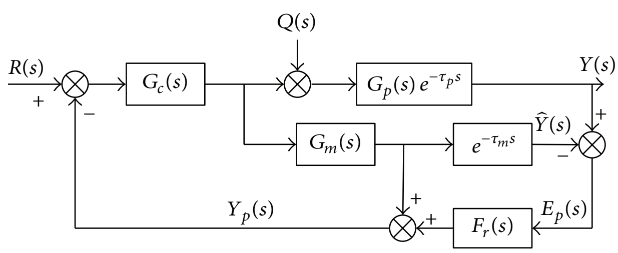

Figure 4: Structure of FSP.

$G_c(s)G_m(s)$ and the -1 point in the Nyquist diagram ($|1 + G_c(s)G_m(s)|$) is greater than $|G_c(s)\Delta P(s)|$. Thus, for the SP,

$$\overline{\delta P}(s) < \mathrm{d}P_{\mathrm{SP}}(s) = \frac{|1 + G_c(s)G_m(s)|}{|G_c(s)G_m(s)|}, \quad s = j\omega, \ \forall \omega > 0, \tag{4}$$

where j is the imaginary unit and ω is the frequency, and $\overline{\delta P}(\omega)$ is the multiplicative norm-bound uncertainty [15, 16].

Therefore, when the closed-loop transfer equation (2) is defined, $\mathrm{d}P_{\mathrm{SP}}(s)$ is also fixed and if $G_c(s)$ is chosen for a high performance then robustness will be poor. Thus, if $G_c(s)$ is not appropriately chosen, small uncertainties may destabilize the system.

The characteristic equation for $P(s)$ is then

$$1 + G_c(s)G_m(s) + G_c(s)G_m(s)P_m(s)F_r(s)\delta P(s) = 0. \tag{5}$$

Considering that the nominal system is stable, the robust stability condition for the FSP is

$$\overline{\delta P}(s) < \mathrm{d}P_{\mathrm{FSP}}(s) = \frac{|1 + G_c(s)G_m(s)|}{|G_c(s)G_m(s)F_r(s)|}, \quad s = j\omega, \ \forall \omega > 0. \tag{6}$$

If $F_r(s)$ is a low-pass filter, it can be used to improve the robustness of the system at the desired region of frequency [14]. Although $F_r(s)$ does not affect $H_r(s)$, it modifies the disturbance rejection response defined by

$$H_q(s) = \frac{Y(s)}{Q(s)} = P_m(s)\left[1 - \frac{G_c(s)P_m(s)F_r(s)}{1 + G_c(s)G_m(s)}\right]. \tag{7}$$

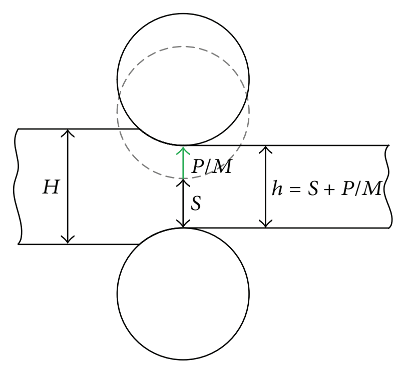

Figure 5: Roll force modeling principles.

Thus $F_r(s)$ must be tuned for a compromise between robustness and disturbance rejection performance.

Note that only $Y(s)/Q(s)$ and $\mathrm{d}P(\omega)$ are modified by the inclusion of the filter. That is, the filter $F_r(s)$ can be used to improve the robustness or the disturbance rejection capabilities of the system without affecting the nominal set-point response. Furthermore, $F_r(s)$ can be tuned to obtain an internal stable system when controlling unstable plants. Therefore, the proposed controller has enough degrees of freedom to obtain compromise between robustness and a desired set-point and disturbance rejection responses.

3. FSP for Monitor AGC

A typical and basic modeling task is that associated with setting up the roll gaps in a mill. The large deformation force P required to reduce the strip thickness from entry thickness H to exit thickness h causes the stand frame holding the rolls to stretch and mill rolls to bend and flatten. The result is the exit thickness as a function of force P. In simplified form this can be expressed as [1]

$$h = S + f(P), \tag{8}$$

where S is the unloaded roll gap and the term $f(P)$ is the mill stretch.

As shown in Figure 5, the normally used simplified thickness model of gauge meter equation or spring equation has the following form [17]:

$$h = S + \frac{P}{M}, \tag{9}$$

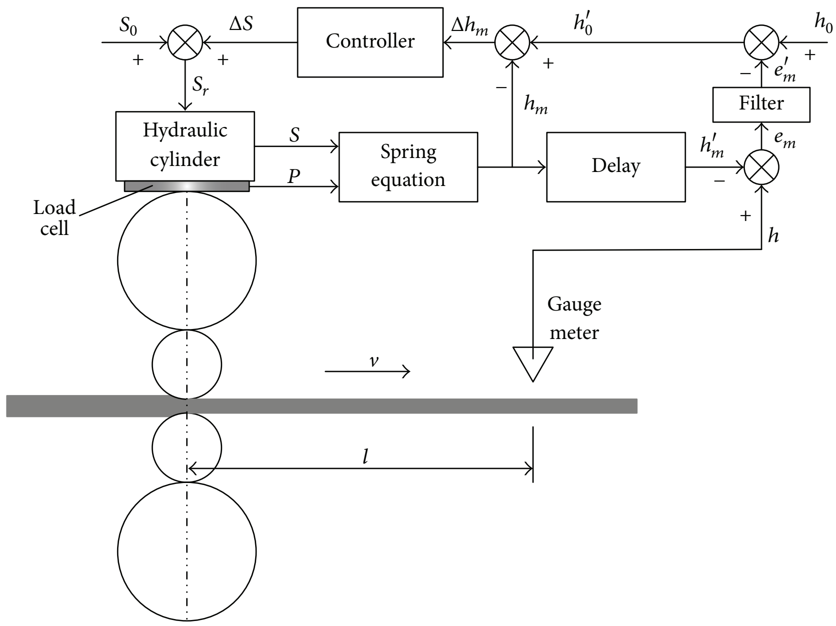

Figure 6: Monitor AGC system with SP.

where M is the mill modulus or stiffness coefficient and P/M is the approximate value of mill stretch.

Because of the inaccuracy of empirical formula and the measurement error, there is a deviation of the calculated thickness from the actual thickness. The delayed calculated thickness is compared with the measured thickness and the deviation e_m of the two is obtained to correct the deviation and improve the model accuracy. The monitor AGC system with SP is shown in Figure 6, where h_m is the calculated thickness and h'_m is the delayed calculated thickness.

As can be seen in Figure 6, the thickness deviation Δh_m can be calculated by the following formula:

$$\Delta h_m = \left(h'_m - h_m\right) - \left(h - h_0\right) = \left(h_m e^{-\tau s} - h_m\right) - \Delta h. \quad (10)$$

If the roll gap S_i remains unchanged, we have [7]

$$\Delta h_i = \frac{Q_i}{Q_i + M_i}\Delta H_i, \quad i = 1, 2, \ldots, 6, \quad (11)$$

where i refers to stand Fi, Δh_i and ΔH_i are the exit thickness and the entry thickness of stand Fi, respectively, M_i is the stiffness coefficient of stand Fi, and Q_i is the plastics coefficient of the rolled material in stand Fi.

Because the material flows passing through different stands are equal, the exit thickness of stand F$(i-1)$ is equal to the entry thickness of stand Fi with the dead time τ_{i-1}, which means that

$$H_i = h_{i-1} e^{-\tau_{i-1} s}, \quad i = 2, 3, \ldots, 6 \quad (12)$$

or

$$\Delta H_i = \Delta h_{i-1} e^{-\tau_{i-1} s}, \quad i = 2, 3, \ldots, 6. \quad (13)$$

Substituting (12) in (10) we get

$$\Delta h_i = \frac{Q_i}{Q_i + M_i}\Delta h_{i-1} e^{-\tau_{i-1} s}, \quad i = 2, 3, \ldots, 6. \quad (14)$$

If the thickness deviation Δh_m is relatively large, it will overload the delivery stand of the finishing mill and affect the crown and flatness of the strip, so Smith's method monitor AGC correction is distributed to upstream stand AGC to prevent the load unbalance [7]. At the same time, because the first few stands are too far to get good control effect, monitor AGC is only implemented to the last three stands of the finishing mill, as shown in Figure 7, where Δh_m is the exit thickness deviation to be eliminated; k_i $(i = 4, 5, 6)$ are the distribution coefficients of stand Fi and meet the condition of $0 < k_4 < k_5 < k_6 = 1$; M_i and Q_i $(i = 4, 5, 6)$ are the stiffness coefficients and plastic coefficients of stand Fi; τ_4, τ_5, and τ_6 are the dead time when material is transported from F4 to F5, F5 to F6, and F6 to gauge meter, respectively; Δh_{mi} $(i = 4, 5, 6)$ are the thickness deviation to be eliminated by stand Fi and its upstream stands; $\Delta h'_{mi}$ $(i = 4, 5)$ are the thickness modification of stand F$(i+1)$ influenced by thickness modification before stand F$(i+1)$; Δh_{Mi} $(i = 4, 5, 6)$ are the thickness deviation to be eliminated only by stand Fi; ΔS_{Mi} and ΔS_{Xi} $(i = 4, 5, 6)$ are the gap correction value of monitor AGC and other types of AGC of stand Fi; S_{0i} and S_{ri} are the gap set value and gap target value of stand Fi; M represents the motor of looper.

As shown in Figure 7, the thickness deviation to be eliminated only by stand Fi can be calculated from

$$\Delta h_{Mi} = \begin{cases} k_i \Delta h_m, & i = 4 \\ \Delta h_{mi} - \dfrac{Q_i}{Q_i + M_i} k_{i-1} \Delta h_m e^{-\tau_{i-1} s}, & i = 5, 6. \end{cases} \quad (15)$$

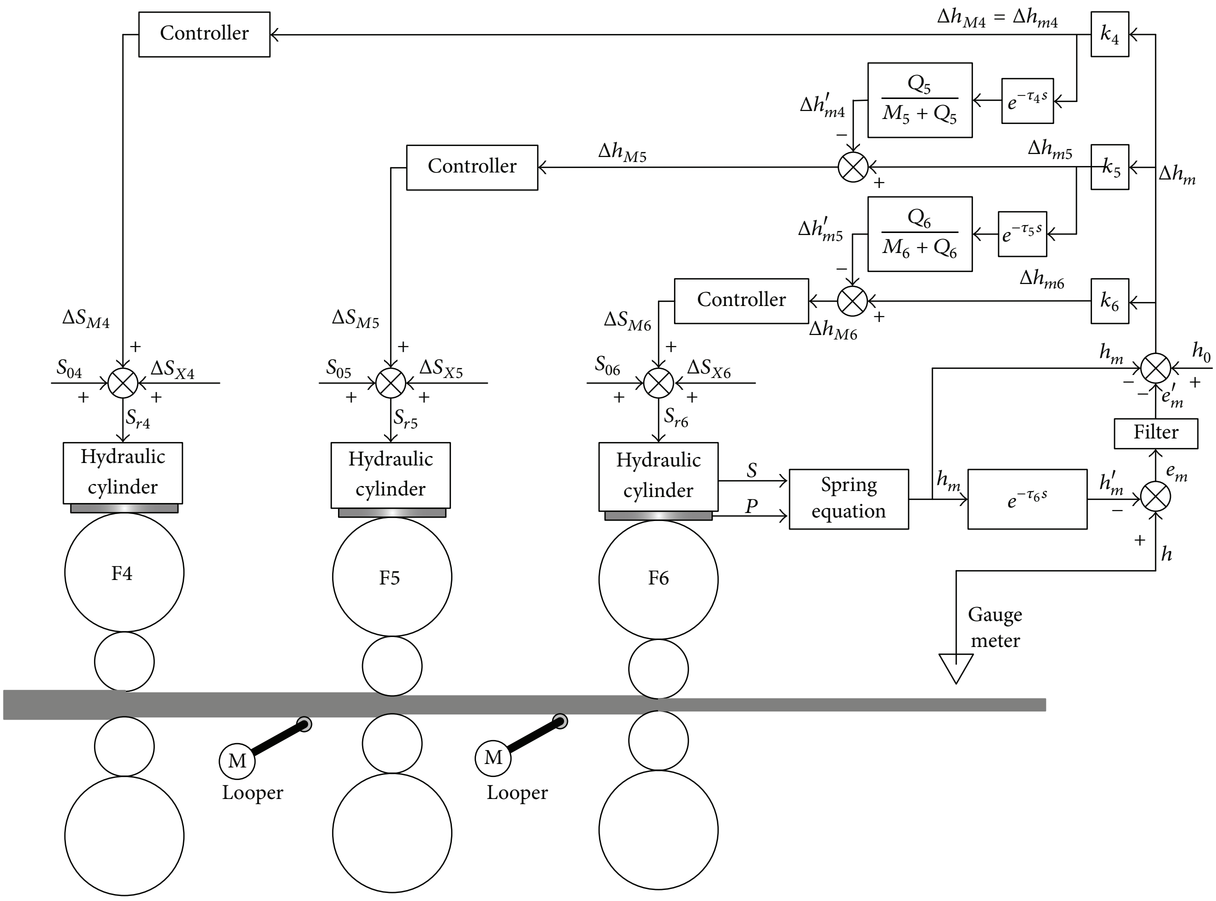

Figure 7: Schematic diagram of the complete monitor AGC system.

4. Expert PI Controller Design

The Proportional-Integral (PI) controller is adopted as the primary controller in monitor AGC. PI parameters k_p and k_i are expected to be modified appropriately based on the current status of the system to obtain a good dynamic performance in the actual control process. But the control algorithm purely based on the mathematical model is difficult to meet the requirements of the control system and get the satisfactory dynamic performance, especially in the case of parameter variations and load disturbances. The expert system adjusting control output based on feature information is proposed for the strip thinning during looper rising and coiler biting period and the strip thickening during the tension loss period of the strip tail end, as shown in Figure 8.

The expert PI controller is shown in Figure 9. The input basic information of the expert controller includes φ_1 = {Thickness set value}, φ_2 = {Thickness deviation e}, φ_3 = {Width set value}, φ_4 = {Speed mode}, φ_5 = {Looper rising period}, φ_6 = {Coiler biting period}, φ_7 = {Tension loss period of the strip tail end}, and φ_8 = {Steel grade}.

The main expert knowledge in the knowledge base is as follows:

(1) k_p and k_i are 0.6 and 0.15, respectively, when the thickness set value is less than 2.0 mm, 0.8 and 0.2 when the value is 2.0 to 5.0 mm, and 1.1 and 0.22 when the value is greater than 5.0 mm;

(2) k_p and k_i decrease 0.1 and 0.02, respectively, when the width set value is greater than 1450 mm;

(3) k_p decreases 0.2 and k_i increases 0.04 during speed-up rolling;

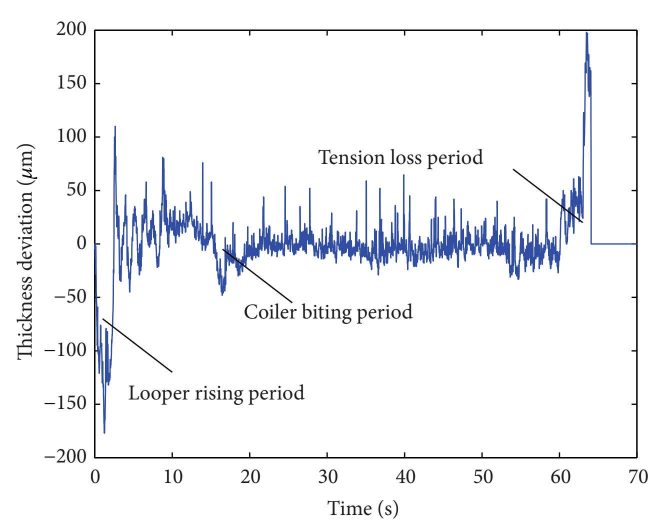

Figure 8: Thickness deviation of the old monitor AGC system.

Table 1: Thickness comparison at a steady rolling speed.

Category	h_0/mm	Ratio in corresponding range/%				
		$\lvert\Delta h\rvert \le 20\,\mu$m	$\lvert\Delta h\rvert \le 30\,\mu$m	$\lvert\Delta h\rvert \le 40\,\mu$m	$\lvert\Delta h\rvert \le 50\,\mu$m	$\lvert\Delta h\rvert \le 100\,\mu$m
New system	3.00	93.10	96.54	98.18	98.88	99.90
	4.00	90.33	93.98	96.70	98.08	99.79
	5.00	89.03	95.38	96.83	97.93	99.74
	6.00	85.46	93.82	96.02	97.04	99.58
Old system	3.00	90.89	96.07	97.62	98.05	99.89
	4.00	88.49	92.78	95.23	96.52	99.36
	5.00	87.80	94.75	95.42	96.89	99.54
	6.00	83.08	91.77	95.04	96.56	99.47

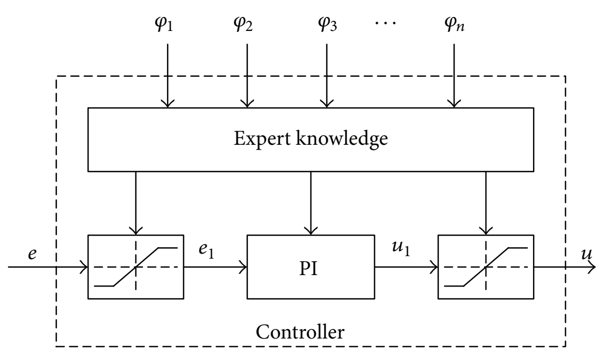

Figure 9: Expert PI controller.

(4) k_p and k_i increase 0.3 and 0.04, respectively, when SPCC steel is being rolled;

(5) e_1 decreases 100 μm and 30 μm on the basis of e during looper rising period and coiler biting period, respectively;

(6) e_1 gradually increases on the basis of e during tension loss period of the strip tail end;

(7) u reaches the preset maximum (or minimum) when e is greater than 150 μm (or less than −150 μm);

(8) k_p increases 0.2 and k_i decreases 0.02 when the absolute value of e is greater than 100 μm and less than or equal to 150 μm;

(9) k_p decreases 0.2 and k_i increases 0.02 when the absolute value of e is greater than 10 μm and less than or equal to 50 μm;

(10) k_p is 0 and k_i increases 0.04 when the absolute value of e is less than 10 μm.

5. Application Results

The monitor AGC tactics have been applied to the thickness control of a 1700 mm HSM and achieved good control effect. The control quality and the robustness of the system are very good, which proves the rationality of the system control principle. The system overcomes the subjective phenomenon of the instability of the manual operation, reduces the labor intensity of the operator, and improves the quality of the steel strip. Figure 10 is a measurement by X-ray gauge meter to the delivery thickness curve when the new monitor AGC system is working. As can be seen in Figure 8, the new AGC system achieves better thickness performance than the old AGC system.

We have collected statistics data for 2 months and conclude from the data analysis that the average thickness qualified rate of the AGC system with new monitor algorithm is generally higher than that of the AGC system with old algorithm. The application results of some main specifications are shown in Tables 1 and 2, where h_0 is the target thickness and Δh is the thickness deviation. Taking the steel strip with $h_0 = 4.0$ mm as an example, the ratio σ in corresponding range $|\Delta h| \le 30\,\mu$m at a steady rolling speed is calculated as follows:

$$\sigma = \frac{\text{Length of the strip rolled at a steady rolling speed with } |\Delta h| \le 30\,\mu\text{m}}{\text{Total length of the strip rolled at a steady rolling speed}}. \tag{16}$$

It can be calculated from Tables 1 and 2 that the average ratio of the new system and the old system is 94.76% and 95.82% at a steady rolling speed and 94.27% and 93.04% in acceleration and deceleration. As an important indicator, the ratio in corresponding range is generally used to represent the thickness precision. Therefore, it can be said that the thickness accuracy has been improved by about 1.06% at a steady rolling speed and about 1.23% in acceleration and deceleration.

6. Conclusion

This paper has presented a monitor AGC algorithm of expert PI controller with FSP which is suitable for the control of

Table 2: Thickness comparison in acceleration and deceleration.

Category	h_0/mm	Ratio in corresponding range/%				
		$\|\Delta h\| \leq 20\ \mu$m	$\|\Delta h\| \leq 30\ \mu$m	$\|\Delta h\| \leq 40\ \mu$m	$\|\Delta h\| \leq 50\ \mu$m	$\|\Delta h\| \leq 100\ \mu$m
New system	3.00	90.81	94.90	97.25	98.54	99.56
	4.00	87.90	91.26	94.86	97.51	99.79
	5.00	84.80	93.93	95.36	97.33	99.74
	6.00	79.89	91.62	94.66	96.19	99.58
Old system	3.00	87.44	94.52	97.05	97.44	99.89
	4.00	85.63	90.33	93.51	95.57	99.36
	5.00	83.17	94.08	93.46	96.01	99.54
	6.00	77.29	88.50	93.01	95.59	99.47

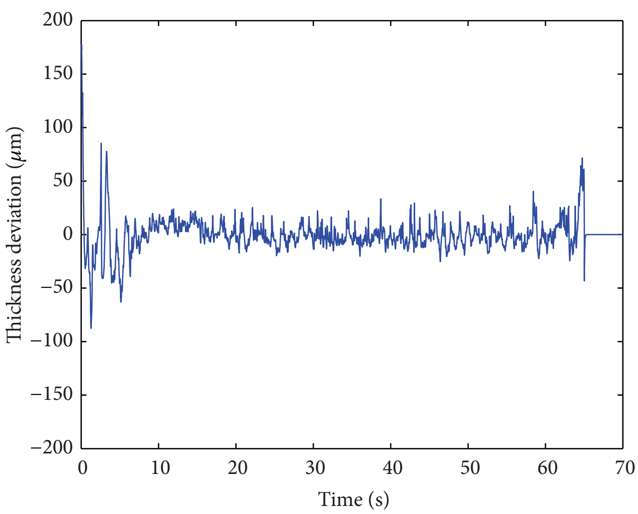

Figure 10: Thickness deviation of the new monitor AGC system.

processes with long dead time. Compared with a conventional algorithm it has the advantage of obtaining real-time thickness and improving robustness. Moreover, the discrete model of FSP control strategy is easy to implement and tune.

The disadvantage of new monitor AGC system is that the greater thickness deviation correction in downstream stands of FM causes the greater variation in strip shape quality resulting in excessive burden to the bending control system of work roll during thickness deviation correction, so the process automation system should adopt more accurate models and perform more exact setup calculations to overcome it.

Competing Interests

The authors declare that there are no competing interests regarding the publication of this paper.

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