Online Automatic Gauge Controller Tuning Method by using Neuro-Fuzzy Model in a Hot Rolling Plant

Sunghoo Choi, YoungKow Lee, SangWoo Kim* and SungChul Hong**

*Division of Electrical and Computer Engineering, Pohang University of Science and Technology, Pohang 790-784, Korea
(Tel: +82-54-279-5018; Fax: +82-54-279-5018; Email:csh425,dudry,swkim@postech.ac.kr)
**Technical Research Labratory, POSCO, Pohang, Korea
(Email:schong1@posco.co.kr)

Abstract: The gauge control of the finishing mill is very important because more and more accurately sized hot rolled coils are demanded by customers recently. Because the mill constant and the plasticity coefficient vary with the specifications of the mill, the classification of steel, the strip width, the strip thickness and the slab temperature, the variation of these parameters should be considered in the automatic gauge control system(AGC). Generally, the AGC gain is used to minimize the effect of the uncertain parameters. In a practical field, operators set the AGC gain as a constant value calculated by FSU (Finishing-mill Set-Up model) and it is not changed during the operating time. In this paper, the thickness data signals that occupy different frequency bands are respectively extracted by adaptive filters and then the main cause of the thickness variation is analyzed. Additionally, the AGC gain is adaptively tuned to reduce this variation using the online tuning model. Especially ANFIS(Adaptive-Neuro-based Fuzzy Interface System) which unifies both fuzzy logics and neural networks, is used for this gain adjustment system because fuzzy logics use the professionals' experiences about the uncertainty and the nonlinearity of the system. Simulation is performed by using POSCO's data and the results show that proposed on-line gain adjustment algorithm has a good performance.

Keywords: Fuzzy system, Automatic Gauge Control, Automatic Gain Tuning.

1. Introduction

In the hot strip mill process in the iron and steel industry, heated slabs are rolled to the required strip thickness and width. To make a hot rolled coil, a roughing mill and finishing mill are used. Slabs are rolled roughly in the roughing mill because they are hard to be rolled to a required thickness at one time. And then the strip passes through the finishing mill. At this time, an Automatic Gauge Control(AGC) system plays an important role in making an accurate sized hot rolled coil.

The AGC system adjusts the exit thickness by controlling the roll gap to reduce the exit thickness variations and by considering the mill constant and the plasticity coefficient additionally. The mill constant varies with the strip width and the specification of the mill. The plasticity coefficient varies with the classification of steel, the strip thickness and the slab temperature. Fortunately the variation of the mill constant is very small. That of the plasticity coefficient, however, is higher than expected and it affects the quality of the product. The plasticity coefficient is hard to be measured as well as to be found the weight of the parameters. Therefore the plasticity coefficient is set to a constant drawn from the theory of metal and the experience of the field. Because there is a deviation between the real plasticity and this estimated plasticity, the control amount based on this estimated plasticity is not desirable.

To overcome the above mentioned drawbacks, a AGC gain is used in the practical field. If the mill constant and the plasticity coefficient could be measured exactly, the AGC gain is always one. However, it is usually set between 0.6 and 0.8. The control amount of the AGC system may either excess or lack because of the plastic coefficient variation caused by the strip temperature variation, if the AGC gain is set to a constant by considering the entry thickness of slabs only. Because of uncertainty and nonlinearity about the temperature distribution of the strip and time delay between the stands, it is not easy to control the exit thickness accurately with the predetermined constant gain, so that the online gain tuning method is necessary.

This paper introduces a new online gain tuning method using adaptive filters which separates the exit thickness signal into some components, and shows the relation of a AGC gain and thickness variation. Finally, a new online gain tuning system implemented by a adaptive fuzzy model is proposed. An ANFIS (Adaptive-Neuro-based Fuzzy Interface System) which can unify both fuzzy logics and neural networks is used for this system because fuzzy logics use the professionals' experiences about the uncertainty and the nonlinearity of the system and neural networks have a learning ability that adjust the membership function effectively.

This paper is organized as follows: Section 2 briefly introduces the structure of AGC System. In Section 3, a adaptive filter used to analyze the thickness data is described. In Section 4, The ANFIS is introduced briefly. In Section 5, a proposed on-line gain tuning model and its strategy are described. In Section 6, Simulation results and analysis are described.

2. The Structure of Automatic Gauge Control System

A roll gap and roll speed is adjusted to roll the strip into the required exit thickness in the hot strip mill process. The roll force AGC(RFAGC) controls the roll force to adjust the roll

---

This paper is supported by Brain Korea 21 Program.

gap and the tension AGC controls the roll speed. And the monitoring AGC controls the roll gap by calculating deviation between the exit thickness and the required thickness. In a finishing mill process, the RFAGC and monitoring AGC is used basically. When a strip enters to the roll for the first time, the instantaneous roll force measured by the RFAGC change abruptly. After 0.9 1.5 seconds, the change becomes stable. That point of time is called to be "lock-on time". After memorizing the estimated thickness calculated from the roll force at lock-on time, the roll gap is controlled to reduce error between the estimated exit thickness and the memorized thickness. The estimated thickness is calculated by the following equation:

$$h_0 = S_o + \frac{F_0}{M}, \triangle h = S - S_0 + \frac{F - F_0}{M}, \qquad (1)$$

where h is the exit thickness, S is the roll gap value, F is the roll force, M is the mill constant, α is the AGC gain, h_0 is the fiducial thickness at lock-on time, F_0 is the fiducial roll force at lock-on time, S_0 is the fiducial roll gap at lock-on time. The movement amount of the roll is followed by:

$$\triangle S = -\frac{M + Q}{M} \triangle h. \qquad (2)$$

Equation 2 is modified by multiplying a RFAGC gain G_{rf}:

$$\triangle S = -\frac{M + Q}{M} \triangle h \times G_{rf}. \qquad (3)$$

The RFAGC system ensures the thickness variation of a strip to be reduced, but does not ensure the required exit thickness. So monitoring AGC which measures and calculates error between the exit thickness and the required thickness is added in the finishing mill process. The Monitor AGC controls the roll gap to reduce the error mentioned above. The difference ($\triangle h_m$) between the exit thickness and the required thickness is followed by:

$$\triangle h_m = \triangle h_{mon} \frac{T_0}{T_d} \triangle G_{mon}, \qquad (4)$$

where T_0 is the time allotted each stand, T_d is the time delay of the strip-traveling. Because the RFAGC controls the roll gap by measuring the roll force, it has the critical defect that the effect of the roll eccentricity is not distinguished well. Considering this phenomenon, G_{rf} is set to $0.6 \sim 0.8$. And then there remains a thickness variation which was not eliminated in the RFAGC. To compensate this defect, feed forward AGC(FFAGC) which estimate skid mark caused by the strip temperature variation is needed. In short, the RFAGC, FFAGC and monitoring AGC is needed to ensure the required exit thickness. The final movement amount($\triangle S$) is calculated by following equations:

$$\triangle h = \triangle h_{rf} + \triangle h_m + \triangle h_{ff}, \qquad (5)$$

$$\triangle S = -\frac{M + Q}{M}((G_{RF} \triangle h_{rf} + \triangle h_m) * \alpha + \triangle h_{ff} * \beta), \qquad (6)$$

where α is the AGC gain which is needed to resolve the problem that there is a deviation between the real plasticity and the constant plasticity. The AGC gain(α) is used as a constant in the practical field by considering the classification of steel and the strip thickness; which can be known in advance; among classification of steel, a strip thickness, a strip temperature and a roll eccentricity. Above equation, β is the FFAGC gain. β is set in advance to offset the thickness variation which is not eliminated in RFAGC. Since FFAGC does not form closed loop, it reduces stability. Generally β is fixed to a small constant.

Table 1. Modified ALE algorithm

$$\begin{aligned}
w_k &= cos\theta_k && (7)\\
y_k &= (1 + s_k)w_k y_{k-1} - s_k y_{k-2} \\
&\quad +(1 - s_k)(w_k u_k - u_{k-1}) && (8)\\
y_{f,k+1} &= a y_{f,k} + (1 - a)u_{k+1} && (9)\\
r_{k+1} &= u_{k+1} - y_{f,k+1} && (10)\\
e_k &= r_{k+1} - y_{k+1}; && (11)\\
\alpha_k &= (1 + s_k)w_k\alpha_{k-1} - s_k\alpha_{k-2} \\
&\quad -sin\theta_k[(1 + s_k)y_{k-1} + (1 - s_k)u_k] && (12)\\
\theta_{k+1} &= \theta_k + \mu_\theta \frac{e_k\alpha_k}{1 + e_k\alpha_k} && (13)\\
\beta_k &= (1 + s_k)w_k\beta_{k-1} \\
&\quad -s_k\beta_{k-2} - (w_k e_{k-1} - e_{k-2}) && (14)\\
s_{k+1} &= s_k + \mu_s[\frac{1}{(1 - s_k)^2}y_k^2 + \frac{1 + s_k}{1 - s_k}y_k\beta_k] && (15)
\end{aligned}$$

Because the AGC gain(α) is determined by not considering the effect of the strip temperature, low quality of the hot rolled coil may be produced. To find the solution to this problem, a variation of the plasticity coefficient should be compensated according to the strip temperature variation. That is to say, the AGC gain(α) should be adjusted automatically according to the strip temperature variation. Although a thermometer and thickness gauge used to get information about the traveling strip, the temperature distribution inside the strip cannot be measured. And the roll eccentricity due to the abrasion and distortion decreases the capability of the RFAGC system by generating arbitrary roll force. The variation of the plasticity coefficient and the information about the roll eccentricity play a key role in determining the AGC gain(α), so it is difficult to produce accurate sized hot rolled coil by the constant AGC gain.

3. The Analysis of Thickness Signal

3.1. Adaptive Filter

A general adaptive line enhancer (ALE) is used to enhance the sinusoids corrupted by noise, and to estimate and track the unknown frequencies of the sinusoids. We use a notch filter type ALE to estimate the skid mark. Some advantages of notch filtering are an easy control of bandwidth, a theoretically infinite null, and the capability of tracking sinusoidal frequencies, which can then be retrieved or eliminated. Digital notch filtering has been used with various adaptive algorithms. Generally, gradient-based algorithms have been used in IIR adaptive Line enhancement filtering

Table 2. The RFAGC gain according to the exit thickness

the exit thickness9	F4 RFAGC gain	F5 RFAGC gain	F6 RFAGC gain	F7 RFAGC gain
1∼3mm	0	0.658	0.578	0.703
3∼6mm	0.485	0.573	0.493	0.602
6∼9mm	0.71	0.71	0.63	0.74
9∼12mm	0.437	0.608	0.522	0.6

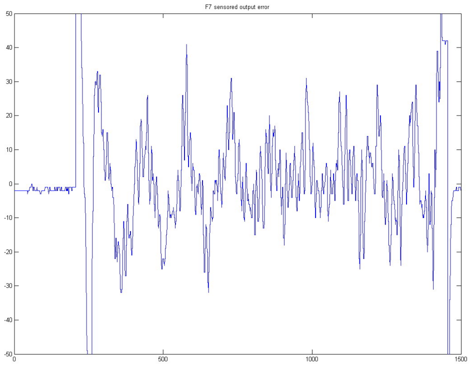

Fig. 1. The exit thickness variation.

applications. In the filtering problem of the skid mark, an input signal is the exit thickness of the previous stand. The signal has many frequency components. It is needed to reject the offset that degenerates the exact estimation of the skid mark. We use the IIR type low pass filter to reduce the effect of offset in the ALE algorithm. This filter is designed using the plant data as the required exit thickness. Table 1 shows the modified ALE algorithm. Equations (9), (10) and (11) are modified to reduce the offset. A normalize algorithm is used to enhance the performance in equation (13).

The thickness variation caused by a skid mark and a roll eccentricity are separated by using the filter designed above. The exit thickness data is shown in Fig. 1. The skid mark component and the roll eccentricity component is shown in Fig. 2 and 3. Two components are the useful inputs of the RFAGC to adjust the AGC gain. By using the modified notch filter mentioned before, each component can be extracted with no DC offset. Generally, most of the component are skid marks early on strip and the latter half of it is the component of the roll eccentricity. It is because of the traveling speed of a strip is high in the last half. If the AGC gain is adjusted properly rather than remained constant in one strip, the exit thickness variation can be reduced from a tendency above.

3.2. Signal Analysis

A analyzing method is needed to obtain how much each component affects the exit thickness variation. First of all, to meet the criterion of the limited thickness variation of POSCO. The maximum value of the exit thickness variation should restricted. So we can find the range of fluctuation by checking the MAX-MIN of each component. Fig. 4 and 5 show the result of the max-min algorithm. Because a signal

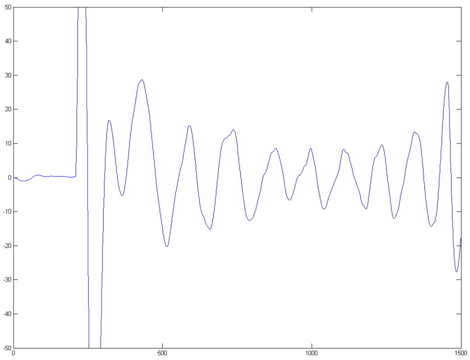

Fig. 2. The skid mark component.

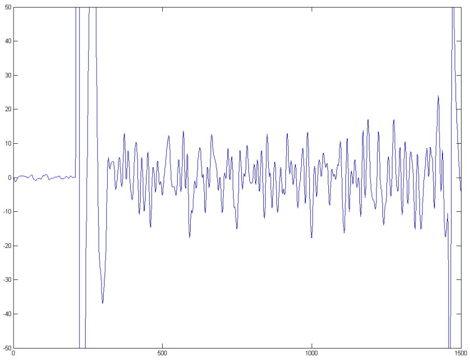

Fig. 3. The roll eccentricity component.

has maximum and minimum value when it has more than one period, the MAX-MIN method is applied partially to a low frequency signal like the thickness variation caused by the skid mark.

3.3. Result of the AGC Gain(α)

In this paper, the RFAGC(G_{rf}) gain is not directly adjusted, but adjusted by controlling the AGC gain which is multiplied to the RFAGC gain. This control mechanism is used in the practical field. Table 2 shows a tendency about the RFAGC gain settings according to the exit thickness. A plate less than 3mm has a high gain after F5 stand because of no operation at F4 stand. A plate more than 9mm has a relatively high gain at F4 and F5 stand because the exit thickness is thick. The AGC gain of each stand, however, is not simply determined by the exit thickness. It is mentioned above. In this section, how the skid mark component and the roll eccentricity component change according to the RFAGC gain is described. So two plates data which have the same classification of steel and the exit thickness but have the different RFAGC gain are compared.In Fig. 7 and 9, low frequency component caused by the skid mark appear less compared to Fig. 6 and 8 while the high frequency component does not, conversely. As a result, to reduce the exit thickness variation, the AGC gain is set in the direction that the component which affect the exit thickness variation relatively large is reduced.

4. Adaptive Neuro-Fuzzy Inference System

Suppose we want to apply fuzzy inference to a system for which we already have a collection of input/output data that we would like to use for modeling, model-following, or some similar scenario. We don't necessarily have a predetermined model structure based on characteristics of variables in your system. There will be some modeling situations in which we can't just look at the data and discern what the membership functions should look like. Rather than choosing the parameters associated with a given membership function arbitrarily, these parameters could be chosen so as to tailor the membership functions to the input/output data in order to account for these types of variations in the data values. This is where the so-called neuro-adaptive learning techniques incorporated into anfis in the Fuzzy Logic Toolbox can help.

5. Online AGC Gain Tuning Model

5.1. Tuning Strategy

In this section, we describe a method which adjusts the AGC gain(α) obtained by fuzzy model. As mentioned above, the RFAGC gain(G_{rf}) is proportional to the thickness variation of the skid mark component and inversely proportional to the thickness variation of the roll eccentricity component. At first the RFAGC gain is determined by the FSU. If the variation of the roll eccentricity component increases in the exit thickness variation, ANFIS reduces the AGC gain. Since the variation of the skid mark component can be reduced by determining a proper FFAGC gain, after setting the AGC gain by analyzing the variation of the skid mark component, the FFAGC gain is determined to reduce the remaining variation of the roll eccentricity component. Two components can be reduced simultaneously by doing above steps.

A fuzzy model which adjusts the AGC gain at first for a strip to get the proper roll eccentricity and then adjusts the FFAGC gain by using the AGC gain and the thickness variation is proposed in this section. The stability is guaranteed by restricting the AGC gain and data which have the smallest range of fluctuation in the field used in the fuzzy model learning. Because of the lack of data, the model learning is done by using data which have the same exit thickness. Especially, researches about sheets and plates more than 9mm are needed additionally because their model does not have generality.

5.2. Gain Tuning Model

Input and output data which come out before and after the stand are used as input for the fuzzy system. To get the information about the thickness variation, the magnitude of the mean squared each component are used as an input for the fuzzy system after being divided into two components. The fast AGC gain change during the traveling time of a plate has no meaning due to the response delay caused by an oil pressure cylinder. So the mean-squared component are passed through the LPF. The data which have the exit thickness of 3 4mm are used to model ANFIS and fuzzy model is implemented by MATLAB. The output values of model have ±0.1 and fuzzy model has three inputs. ANFIS is modeled given 5763 sets of input/output data. The training options are following. Training epoch number is 10, training error goal is 0, initial step size is 0.01, step size decrease rate is 0.9, step size increase rate is 1.1. The trained ANFIS model tested by using another 2572 input/output data.

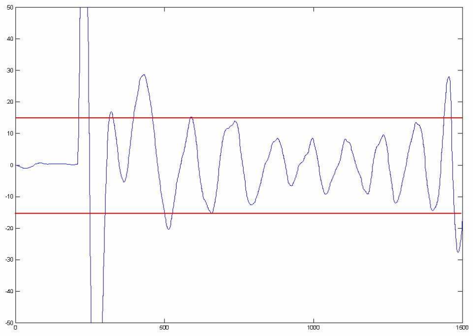

Fig. 4. MAX-MIN estimation of the skid mark component.

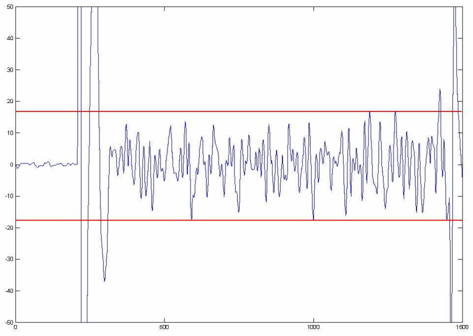

Fig. 5. MAX-MIN estimation of the roll eccentricity component.

6. Simulation

6.1. Simulation Model

To prove the effectiveness of the on-line AGC gain adjustment, we simulated using two stands only. The model was constructed by MATLAB Simulink. The output of F5 stand is determined by the inputs which are the practical field data. And then, the F6 stand and F7 stand are used in simulation. In addition, the RFAGC and the Monitoring AGC are implemented. Each stand is implemented using the I/O relationship described in this paper. Fig. 10 shows the entire MATLAB Simulink.

In Fig. 11, the exit thickness is determined by using the variation of the entry thickness estimated from the roll force(F). Fig. 12 shows the ANFIS which determines the AGC gain. An input signal passes through the lock-on block and the signal difference passes through the lock-on block after the lock-on time. In filter block, the skid mark and the roll eccentricity component are filtered.

6.2. Simulation Result

This simulation was performed using the data from the POSCO. The exit thickness is 3.25mm and most of the produced hot rolled coils have this size. The initial roll gap value

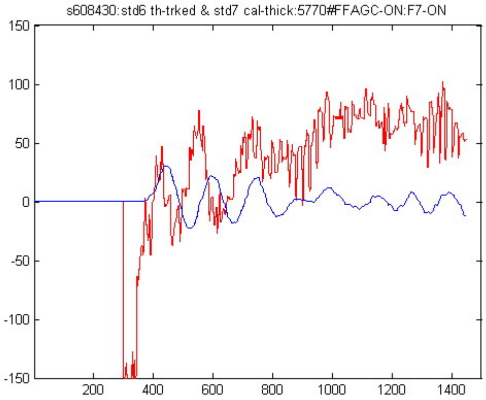

Fig. 6. The exit thickness of 5770 mm , G_{rf} is 0.49, F6 stand.

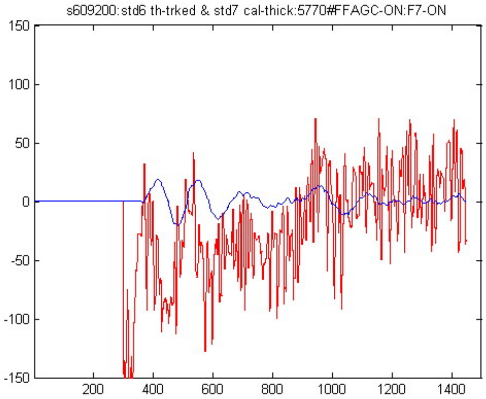

Fig. 7. The exit thickness of 5770 mm , G_{rf} is 0.65, F6 stand.

of the practical field is used as that of the simulation model. The mill constant is 463, 417 and the plasticity coefficient is 256, 342. The lock-on time is set to 177th sample as used in practical field. The simulation results are compared among the conventional system using the AGC gain as a constant, the system using on-line gain adjustment algorithm by the ANFIS and the system combined FFAGC finally. The AGC gain(α) is a constant used in practical field. The thickness variation of the 6th stand shows the DC component because it is less affected from Monitoring AGC.

6.2.1 The RFAGC gain change

Let us analyze the decrease of the skid mark and the increase of the roll eccentricity as the change of the RFAGC gain in this section. The constant RFAGC gain(G_{rf}) is used and the exit thickness is compared. When the RFAGC gain(G_{rf}) is set to 0.63, it does not affect seriously. In case the G_{rf} is set to likely 1, the output thickness variation almost never appear. However the effect caused by the roll eccentricity appear. This situation appear remarkably when G_{rf} is set to 1 exactly. To facilitate comparing performances, G_{rf} is set to the maximum value(0.8) used in the practical field.

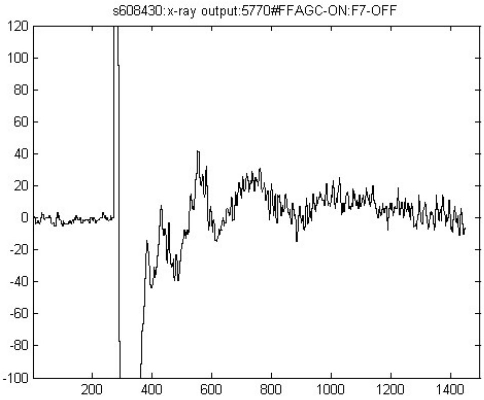

Fig. 8. The exit thickness of 5770 mm , G_{rf} is 0.49, F7 stand.

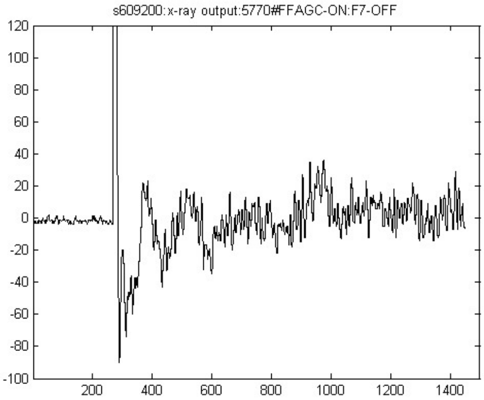

Fig. 9. The exit thickness of 5770 mm , G_{rf} is 0.65, F7 stand.

6.2.2 The FFAGC gain change

The value of G_{rf} is 0.8 as mentioned before. Because two stands are used in this simulation, there is only one output variation of the stand that depends on FFAGC. The exit thickness could have the large range of fluctuation due to the excessive FFAGC gain. Therefore the proper FFAGC gain adjustment is needed. In case a proper control amount of the FFAGC applied to the next stand with a proper delay time, the exit thickness variation may decrease. In this paper, we set the FFAGC gain according to the G_{rf}.

6.2.3 Performance Analysis

An on-line AGC gain adjustment algorithm adjusts the value of the α and it decreases the output thickness variation. However this method causes a DC offset to the exit thickness. This means that the role of the Monitoring AGC is important. In this paper, the ANFIS finds the optimal α by measuring the variation of the skid mark component and the roll eccentricity component. Fig. 13 shows the variation of the α of F7 stand. The ANFIS increases α by analyzing the data whose component is mostly skid mark. Considering the decreased skid mark, the ANFIS decreases α because of the roll eccentricity. And the exit thickness variation is shown in Fig. 14.

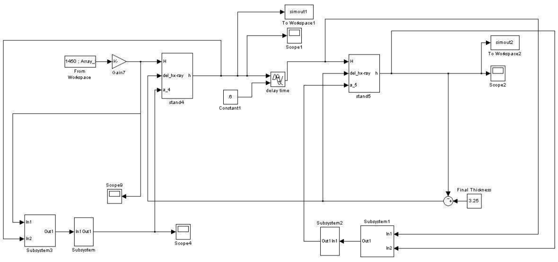

Fig. 10. Block diagram of the MATLAB simulator.

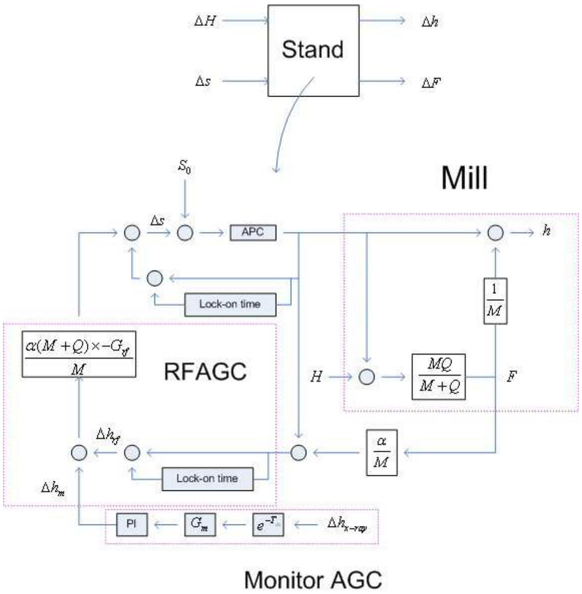

Fig. 11. The structure of a stand.

7. Conclusion

This paper proposed a new on-line gain tuning method in the finishing mill of a hot rolling plant. This method separates a thickness signal into the skid mark component and the roll eccentricity component by using adaptive filter. And then the current AGC gain was evaluated by analyzing the relationship between two signals according to the AGC gain. This criterion brought a new online gain tuning algorithm implemented by the ANFIS. It showed better performance on reducing the exit thickness variation in simulation which was demonstrated by the data from the second hot rolling plant in POSCO.

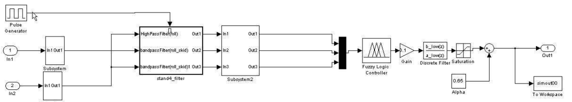

Fig. 12. The implemented stand model.

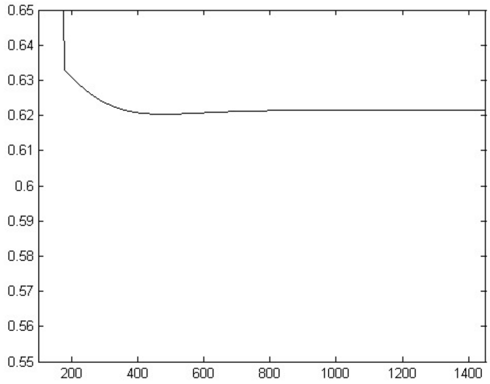

Fig. 13. The optimal α.

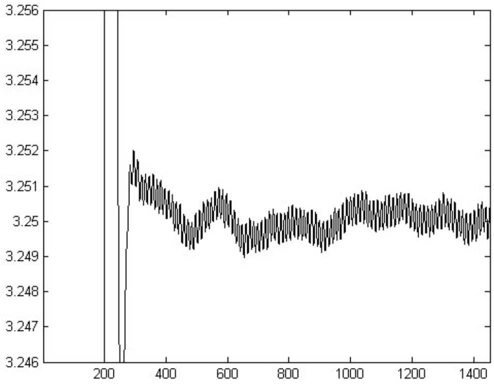

Fig. 14. The final exit thickness variation.

References

[1] V. B. Ginzburg, *High-Quality Steel Rolling, Theory and Practice*, Marcel Dekker, 1993.

[2] G. W. Rigler, et al., "*Improved rolling mill automation by means of advanced control techniques and dynamic simulation*," *IEEE Trans. Industrial Application*, vol. 32, no. 3, May/June 1986.

[3] G. Keintzel, M. Schoisswohl, P. Vorstandlechner, K. Aistleitner, and R. Schneeweis, "Advanced control methods in rolling applications," *IEEE Industry Applications Conference*, vol. 3, pp. 2263–2269, 1998.

[4] C. B. Rorabaugh, *Digital Filter Designer's Handbook*, McGraw-Hill inc, New York, 1993.

[5] B. Farhang-Boroujeny, "*An IIR adaptive line enhancer with controlled bandwidth*," *IEEE Trans. Signal Processing*, vol. 45, no. 2, Feb. 1997.

[6] Hideki Asada, Akira Kitamura, Satoshi Nishino and Masami Konishi, "*Adaptive and Robust Control Method with Estimation of Rolling Characteristics for Looper Angle Control at Host Strip Mill*," *ISIJ International*, vol. 43, no. 3, pp. 358–365, 2003.

[7] Gerald Hearns and Michael J. Grimble, "*Robust Multivariable Control for Hot Strip Mills*," *ISIJ International*, vol. 40, no. 10, pp. 995–1002, 2000.