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A new Model and Control of Coating Process at Galvanizing line

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Abstract: This paper proposes a new practical synthesis model for coating weight control and robust design method of feedback controller in galvanizing process. The model combines both long term and short term model. Long term model have a function of classification, averaging and learning based on real measured data. Short term model is differential model based on linear change of inputs and outputs. A set of practical controller and a robust design method of feedback controller is proposed so that it can attenuate quickly the errors caused by time-delay and modelling error. The proposed model with controller were applied to continuous galvanizing line(CGL) at Kwang Yang Steel Works. As the results, a good performance on the deviation control of coating weight was obtained at top of coil and also the uniform coating weight on the surface of strip was realized.

1. INTRODUCTION

After the concept of coating weight control was introduced to continuous galvanizing process, Butler [1970] proposed a coating weight model which is the sum of one-degree polynomials. However his model is based on absolute variables, thus it can not describe the coating process properly due to the nonlinearity existing in coating process. Thorton [1976] developed analytical coating weight models which can accurately describe the coating process. The model was well derived from several basic fluid equation, however it is so complicate that it has difficulty in realization at on-line real time control system. Edwards [1976] introduced simple exponential model which can be easily realized in the computer based control systems. This model was widely used in many coating weight control for its simplicity. Recently, Lacanette [2005] developed a numerical coating weight model, but it was not applicable to real control system, since dimensionless variables of the model made it difficult to realize on-line.

As to coating weight control, an adaptive control based on the linearized model is realized at coating process by Fenot [1992]. Modern nonlinear control algorithms, such as neural networks, fuzzy, are also applied coating weight control by Steven [1995], Yongzai [1997]. Also, there were much effort to reduce error of coating weight along the lateral direction of steel strip. Baxter [1988] handled this problem by low frequency feedback control based on average data. Chen [1995] handled this adaptively and Jacobs [1995] tried to solve the problem using the optimal control method.

In many previous researches, most of their solution are not easy to apply real process. Because real coating process is highly nonlinear and has time delay on its output feedback, thus it is very difficult to make accurate model and to get good performance on the control. Followings are the key issues to solve these problems.

- High accurate coating weight model is needed to attenuate coating weight error on the surface of coated strip.

- For fast and robust response, a easy and practical design method of feedback controller is needed regardless of time delay on output and modelling error.

In this paper, a new practical synthesis approach for coating weight control is proposed to attenuate the error of coating weight on steel strip in continuous galvanizing line.

2. MODELLING

At continuous galvanizing line as shown in Fig.1, each coil has its own target coating weight and it changes when coil changes. The amount of change may be wide or narrow. When there is change on target coating weight, control

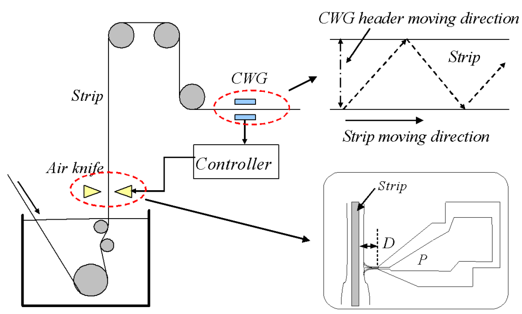


Fig. 1. Continuous galvanizing line

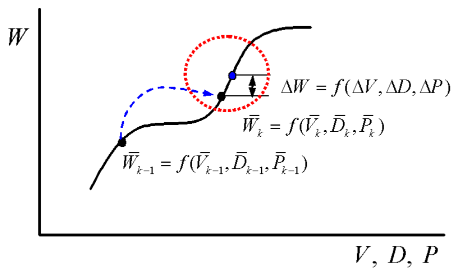


Fig. 2. Two types of change for coating weight

inputs, such as pressure of air knife and distance from nozzle to strip, has to be set to new values. Generally, when the weld point of two coils pass through air knife, there may be large change on target coating weight. At the moment, large change on pressure or distance has to be accompanied. After then, miner adjustment of pressure and distance follows. So it is useful to divide the adjusting process into two steps. Fig.2 shows the concept graphically. W is coating weight, P is pressure of air knife chamber, D is distance from air knife nozzle to strip and V is line speed. If the previous step is denoted by index $k-1$, current step is indexed as k. When weld point of two coils pass through air knife, there may be large change on coating weight from $\bar{W}_k - 1$ to $\bar{W}_k$. This is called as long term change. After then, if there exist the error in coating weight(ΔW), small change of distance and pressure will be enough to remove the difference in coating weight near to target value. The circle of Fig.2 is the vicinity of target value and in this region, the behavior of coating process is assumed as linear.

In time delayed system, the performance of control is affected by the accuracy of the model. The accurate model was derived analytically by Thorton [1976] in 1970. But in this research, Edwards' experimental model is used due to its simplicity described in Eq.(1),

$$W = KV^aD^bP^c, \tag{1}$$

where, a, b and c are parameters of model and has to be tuned by measured real data.

2.1 Long term model

Long term model is used to estimate coating weight for a coil of strip and the basic equation is Eq.(1). To get parameter of Eq.(1), simple regression method is widely used. However, the number of measured data are not distributed uniformly for whole range of coating weight in continuous galvanizing line. For some range of target coating weight, the number of measured data is small. These small data does not loose their importance at real coating process though the number is small. Thus, it should not be neglected and has to be considered with the same weight for whole range of target coating weight.

In this paper, the problem is solved by new approach considering long term estimation as shown in Fig.3. Here, VQ means vector quantization used for data classification. $W_1, ..., W_N$ are target coating weight classified by VQ. a_L, b_L and c_L are parameters of long term model. The measured data are averaged value for a coil and classified into several data sets, from Q_1 to Q_N. Each data set is

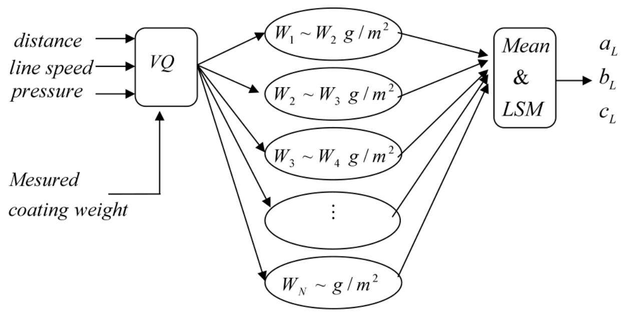


Fig. 3. Long term model and estimation method

divided according to its coating weight and has N numbers of data. The oldest data are replaced by newest data on the base of first in- first out(**FIFO**) rule. Let Q_{k_n} be the vector of measured data for a coil of strip, such as coating weight W_{k_n}, line speed V_{k_n}, distance and pressure D_{k_n}, then all data is represented as the matrix Q_k,

$$Q_k = \begin{bmatrix} Q_{k\_1} \\ Q_{k\_2} \\ \vdots \\ Q_{k\_n} \end{bmatrix} = \begin{bmatrix} W_{k\_1} & V_{k\_1} & D_{k\_1} & P_{k\_1} \\ W_{k\_2} & V_{k\_2} & D_{k\_2} & P_{k\_2} \\ \vdots & \vdots & \vdots & \vdots \\ W_{k\_n} & V_{k\_n} & D_{k\_n} & P_{k\_n} \end{bmatrix}. \tag{2}$$

If Eq.(1) is transformed to log space and apply average values of $\bar{Q}_k$, then it becomes

$$log\bar{W}_k = a_L \cdot log\bar{V}_k + b_L \cdot log\bar{D}_k + c_L \cdot log\bar{P}_k. \tag{3}$$

Assume that $K_L = 1$, then Eq.(3) is rewritten as following form.

$$w_k = a_L \cdot v_k + b_L \cdot d_k + c_L \cdot p_k \Rightarrow B_k = A_k \cdot x_k, \tag{4}$$

where,

$$B_k = \begin{bmatrix} \bar{Q}_{30\_1}(:,1) \\ \bar{Q}_{40\_2}(:,1) \\ \vdots \\ \bar{Q}_{max\_n}(:,1) \end{bmatrix}, A_k = \begin{bmatrix} \bar{Q}_{30\_1}(:,2\sim 4) \\ \bar{Q}_{40\_2}(:,2\sim 4) \\ \vdots \\ \bar{Q}_{max\_n}(:,2\sim 4) \end{bmatrix},$$

$$x_k = \begin{bmatrix} a_L \\ b_L \\ c_L \end{bmatrix} \tag{5}$$

Then, the parameter x_k can be estimated by least square method

2.2 Short term Model

Once the coating weight reach at inner region of circle as shown in Fig.2, it is possible to assume that the change of coating weight on the surface of strip is small with respect to the change of input variables such as distance, pressure and line speed, then coating process can be regarded as linear. Therefore the nonlinear coating weight control problem can be handled as linear control problem.

Short term model is described by change of variables instead of absolute variables. If Eq.(1) is differentiated with respect to W, then new short term model becomes

$$dW = \frac{\partial W}{\partial V}dV + \frac{\partial W}{\partial D}dD + \frac{\partial W}{\partial P}dP, \tag{6}$$

where

$$\frac{\partial W}{\partial V} = a_S \cdot \frac{W}{V}, \quad \frac{\partial W}{\partial D} = b_S \cdot \frac{W}{D}, \quad \frac{\partial W}{\partial P} = c_S \cdot \frac{W}{P}. \quad (7)$$

Let's replace dW, W, V, D, P as ΔW, $\bar{W}$, $\bar{V}$, $\bar{D}$, $\bar{P}$ for small interval time, then Eq.(6) can be rewritten as

$$\Delta W = a_S \cdot \frac{\bar{W}}{\bar{V}} \Delta V + b_S \cdot \frac{\bar{W}}{\bar{D}} \Delta D + c_S \cdot \frac{\bar{W}}{\bar{P}} \Delta P, \quad (8)$$

where $\bar{W}$, $\bar{V}$, $\bar{D}$ and $\bar{P}$ are average of coating weight, line speed, distance and pressure of air knife.

Let the differences of coating weight, line speed, distance and pressure from $l-1$ step to l step are ΔW_l , ΔV_l, ΔD_l, ΔP_l, respectively the differences from $l-2$ step to $l-1$ step are ΔW_{l-1}, ΔV_{l-1}, ΔD_{l-1}, ΔP_{l-1}. With the same manner, the initial value of each variable are ΔW_0 , ΔV_0, ΔD_0, ΔP_0. Then Eq.(8) can be rewritten as following form with the data at l-step.

$$\Delta W_l = a_S \cdot \frac{\bar{W}_l}{\bar{V}_l} \Delta V_l + b_S \cdot \frac{\bar{W}_l}{\bar{D}_l} \Delta D_l + c_S \cdot \frac{\bar{W}_l}{\bar{P}_l} \Delta P_l. \quad (9)$$

If Eq. (9) is represented as matrix form, then it becomes,

$$Z_l = H_l \theta_l, \quad (10)$$

where

$$Z_l = [\, \Delta W_l \;\; \Delta W_{l-1} \;\; \Delta W_{l-2} \,]^T ,$$

$$H_l = \begin{bmatrix} \frac{\bar{W}_l}{\bar{V}_l} \Delta V_l & \frac{\bar{W}_l}{\bar{D}_l} \Delta D_l & \frac{\bar{W}_l}{\bar{P}_l} \Delta P_l \\ \frac{\bar{W}_{l-1}}{\bar{V}_{l-1}} \Delta V_{l-1} & \frac{\bar{W}_{l-1}}{\bar{D}_{l-1}} \Delta D_{l-1} & \frac{\bar{W}_{l-1}}{\bar{P}_{l-1}} \Delta P_{l-1} \\ \frac{\bar{W}_{l-2}}{\bar{V}_{l-2}} \Delta V_{l-2} & \frac{\bar{W}_{l-2}}{\bar{D}_{l-2}} \Delta D_{l-2} & \frac{\bar{W}_{l-2}}{\bar{P}_{l-2}} \Delta P_{l-2} \end{bmatrix},$$

$$\theta_l = [\, a_S \;\; b_S \;\; c_S \,]^T .$$

Then, the parameters are estimated by recursive least square method at the book of Mendel [1987]. Finally, the short term model is depicted as

$$\Delta W_l = \hat{a}_S \cdot \frac{\bar{W}_l}{\bar{V}_l} \Delta V_l + \hat{b}_S \cdot \frac{\bar{W}_l}{\bar{D}_l} \Delta D_l + \hat{c}_S \cdot \frac{\bar{W}_l}{\bar{P}_l} \Delta P_l. \quad (11)$$

3. CONTROL

3.1 Preset control

Preset control is a kind of setup control based on model. When target coating weight is given, the distance from steel strip to nozzle of air knife and pressure at the chamber of air knife are determined by the use of inverse long term model.

First, when target coating weight changes and the distance $\bar{D}_{k-1}$ and $\bar{V}_{k-1}$ line speed of previous step's are constant, then the pressure control input is

$$P_{PRE} = e^{\left[\frac{1}{\hat{c}_L}\left(log(T_{cw}+\alpha) - \hat{a}_L log \bar{V}_{k-1} - \hat{b}_L log \bar{D}_{k-1}\right)\right]}, \quad (12)$$

where, $T_{cw}$is target coating weight and α is marginal value. When there is large change on target coating weight, it is difficult to adjust real coating weight to target value for whole change of coating weight by the change of pressure control input alone. Thus, the distance and pressure have to be changed simultaneously in that case.

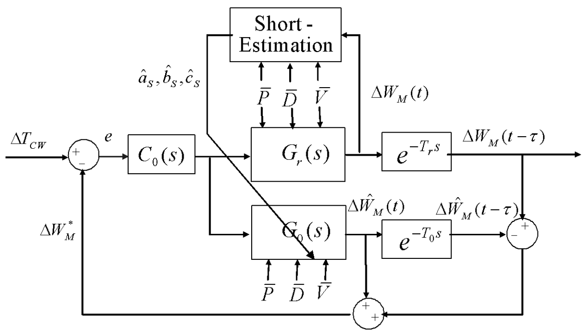


Fig. 4. Structure of feedback and skew controller

3.2 Feedback control(FBC)

In galvanizing line, usually, cold coating weight gauge (CWG) is located at 200 m downstream from air knife and can measure the zinc coating weight on the surface of steel strip as shown in Fig.1. The header of coating weight gauge move laterally, the trajectory of measured points on strip becomes dashed inclined line. The pressure control inputs of top and bottom side are calculated based on the short time model and applied to air knife. There are two criteria for selecting pressure control input. Pressures at both sides of air knife have to be the same and the distance at both air knives must be constant during the feedback control. Thus, the pressure control input which satisfies the two criteria are

$$e_p = \frac{2\Delta T_{cw} - (\Delta W_T + \Delta W_B)}{2} = \Delta T_{cw} - \Delta W_M, \quad (13)$$

$$P_{FBC} = \Delta P_T = \Delta P_B = \left[K_{f\_p} e_p + \frac{1}{K_{f\_i}} \int e_p dt \right], \quad (14)$$

where W_T and W_B are averages of top and bottom side during one scan. W_M is mean value of W_T and W_B. ΔP_T and ΔP_B are pressure changes of top and bottom side. K_{f_p} and K_{f_i} are the gains of feedback controller.

In this paper, we use Smith predictor to resolve time delay problem of control system as shown in Fig.4. The feedback of coating weight is

$$\Delta W_T^* = \Delta \hat{W}_M(t) + \Delta W_M(t-\tau) - \Delta \hat{W}(t-\tau), \quad (15)$$

where τ is time delay between air knife and **CWG**, $\Delta \hat{W}_M(t)$ is the estimated change of top coating weight when strip passes air knife. $\Delta \hat{W}_M(t-\tau)$is the estimated change of top coating weight when strip passes coating weight gauge. Thus, ΔW_M^* is the compensated coating weight.

3.3 Feed-forward control(FFC)

When line speed changes during the coating process, the coating weight on the surface of strip also changes. According to the change of line speed, distance or pressure has to

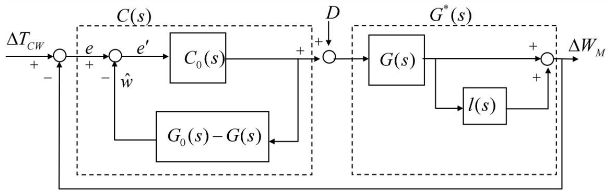


Fig. 5. Smith predictor for the nominal plant with multiplicative uncertainty

be set newly to maintain the coating weight constant. Let the variables of current step as V_1, D_1, P_1, W_1 and those of next step as V_2, D_2, P_2, W_2. When line speed changes from V_1 to V_2, coating weight will change from W_1 to W_2. But it is impossible to know what will be the next coating weight exactly. The coating weight can be estimated as $\hat{W}_2$,

$$\hat{W}_2 = W_1 + a_S \frac{W_1}{V_1} \Delta V + b_S \frac{W_1}{D_1} \Delta D + c_S \frac{W_1}{P_1} \Delta P. \quad (16)$$

Assume that there is no change on line speed and pressure, then the estimated distance control input is

$$D_{FFC} = D_1 + \frac{1}{b_S} \frac{P_1}{W_1} \left(\Delta W - a_S \frac{W_1}{V_1} \Delta V \right). \quad (17)$$

4. STABILITY AND DESIGN OF FEEDBACK CONTROLLER

For the quick convergence of response of feedback, the controller must have large gain. But, without any information for the upper bound of stability, it is difficult to set the gains high, because high gain can make the closed loop system unstable. Feedback control is operated based on short term model. Assume that there is no change on distance and line speed, then only the change of pressure can result in the change of coating weight. Eq. (8) is rewritten as

$$\Delta W = c \frac{\bar{W}}{\bar{P}} \Delta P', \quad (18)$$

where, $\Delta P'$ is the real change of pressure at the chamber of air knife. ΔP of Eq. (8) is the input of feedback controller. If we represent the transfer function of the change of coating weight with respect to the change of pressure as $G_0(s) = \Delta W(s)/\Delta P(s)'$, then, the nominal plant of coating weight has the form

$$G(s) = G_0(s) \cdot e^{-T_0 s}. \quad (19)$$

Smith predictor is a favorable solution to the time delay problemsPalmor [1994].

Fig.5 is the other form of Smith predictor. In this structure, time delay exists in nominal plant, $G(s)$. And $l(s)$ is multiplicative error of model of coating process. $C(s)$ is Smith predictor and consists of $C_0(s)$, the PI controller, and $G_0(s) - G(s)$, the inner feedback. Where $G_0(s)$ is the estimation model of coating weight without time delay. When the line speed and distance from strip to nozzle of air knife are constant, the modelling error can be written as

$$G^*(s) = G(s)(l + l(s)), \quad (20)$$

where $G^*(s)$ is real coating process and $l(s)$ is modelling error. Closed loop transfer function of Smith predictor is

$$C(s) = \frac{C_0(s)}{1 + C_0(s)(G_0(s) - G(s))}. \quad (21)$$

If $l(s) = 0$, that is, modelling error does not exist, the closed loop transfer function of closed loop control system is represented as

$$T_c(s) = \frac{C(s)G(s)}{1 + C(s)G(s)} = \frac{C_0(s)G(s)}{1 + C_0(s)G(s)}. \quad (22)$$

The criterion for robustness of closed loop transfer function is given by

$$\|l(j\omega)T_c(j\omega)\|_\infty < 1, \qquad \forall\omega. \quad (23)$$

From Eq.(19), $G(j\omega)e^{-jT_0\omega}$. Then the next inequality is valid.

$$\left| \frac{C_0(j\omega)G_0(j\omega)}{l + C_0(j\omega)G_0(j\omega)} \right| < \frac{1}{|l(j\omega)|}, \qquad \forall\omega. \quad (24)$$

If $|l(j\omega)|$, the multiplicative modelling error of nominal model in frequency space is determined, the feedback controller $C_0(s)$ can be designed so that has robust performance. How can $l(j\omega)$ of coating weight control system be drived? Real plant is represented as following two forms as shown in Fig.5.

$$G^*(s) = G(s)(1 + l(s)) = G_r(s)e^{T_r s}, \quad (25)$$

where $G_r(s)$ is real transfer function over the change of coating weight with respect to the change of pressure. T_r is real time delay. Assume that $T_0 - T_r \approx 0$, then $l(j\omega)$ can be expressed as

$$|l(j\omega)| = \frac{|G_r(j\omega) - G_0(j\omega)|}{|G_0(j\omega)|}, \qquad \forall\omega. \quad (26)$$

In this paper, $G_0(j\omega)$ and $|G_r(j\omega) - G_0(j\omega)|$ are derived from the results of experiments. $G_0(j\omega)$ is the transfer function of short term model and $G_0(j\omega)$ and $|G_r(j\omega) - G_0(j\omega)|$is norm of the difference between the measured change of coating weight and the estimated coating weight, with respect to the change of pressure at the chamber of air knife.

To design feedback controller, $C_0(s)$, $|l(j\omega)|_{max}$ at Eq.(26) have to be obtained from the real coating weight measured by coating weight gauge. The set up value of pressure change, $\Delta P(s)$ has the relation with the real pressure change, $\Delta P(s)'$. There is nonlinearity between $\Delta P(s)$ and $\Delta P(s)'$ in real process. But in this paper, it is assume that the system is 1-DOF(degree of freedom) linear system shown as follows.

$$\frac{\Delta P(s)'}{\Delta P(s)} = \frac{K}{T \cdot s + 1}. \quad (27)$$

Where T is time constant. K is a coefficient. Then $G_0(s)$ becomes

$$G_0(s) = \frac{\Delta W(s)}{\Delta P(s)} = \frac{Kc\bar{V}}{\bar{P}(Ts + 1)} \quad (28)$$

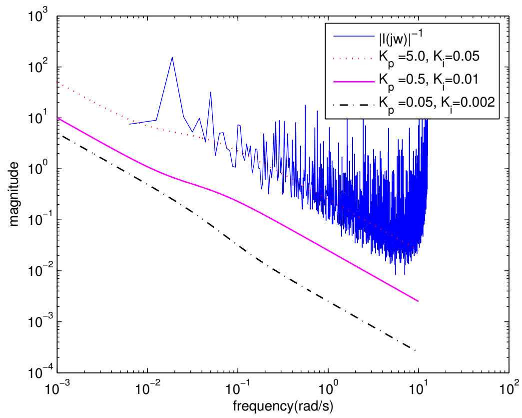


Fig. 6. Design of controller when pressure is actuator

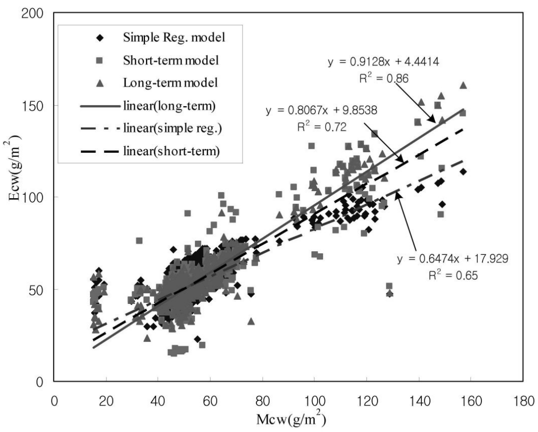


Fig. 7. Fitness of models

Let the controller as follows.

$$C_0(s) = \left(K_{f\_p} + \frac{1}{K_{f\_i} \cdot s} \right) E(s). \quad (29)$$

If Eq. (29) is applied to Eq. (24), it become

$$\left| \frac{\left(K_{f\_p} + \frac{1}{K_{f\_i} \cdot s} \right) \frac{Kc\bar{V}}{\bar{P}(Ts+1)}}{1 + \left(K_{f\_p} + \frac{1}{K_{f\_i} \cdot s} \right) \frac{Kc\bar{V}}{\bar{P}(Ts+1)}} \right| < |l(j\omega)|^{-1}_{max}. \quad (30)$$

Where T is time constant of pressure controller. Fig.6 shows the result of design of controller when three different gains of feedback controller are used. This figure shows the frequency response of feedback control system according to each gain. $|l(j\omega)|^{-1}$ is the minimum value that guarantees robustness of system. When the gains become bigger, the control system becomes unstable.

5. RESULT OF EXPERIMENT AND DISCUSSION

5.1 Evaluation of Models

In this paper, over 2000 numbers of measured data sets are used for long term estimation. At each set, target coating weight, measured coating weight, distances, pressures and line speed are contained for both air knives(top and bottom). Every data set has to be classified into several

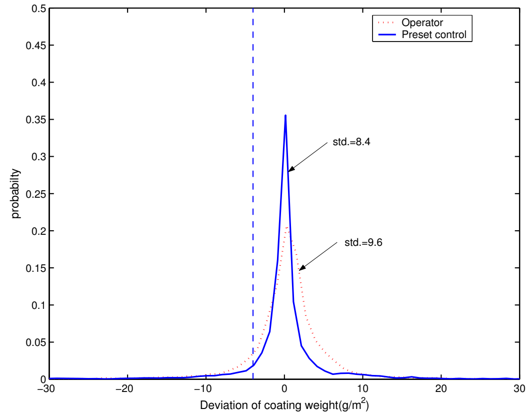


Fig. 8. Performance of preset control

data sets. All set of data are divided by 10 g/m^2 from 30 $\sim$ 150 g/m^2. Then the data of each set are averaged and least square method are applied to the averaged values. As the result, we can get the parameters of long term model, a_L, b_L and c_L became (0.6606, 0.2729, -0.4501).

Fig. 7 shows the fitness of **Mcw** vs **Ecw** for each coating weight model. **Mcw** means measured coating weight and **Ecw** stands for estimated coating weight. The fitness number of simple regression model is 0.65. Here, fitness number is square of the correlation coefficient. The fitness number of short term model used in long term estimation is 0.72, a little greater than simple regression case. In long term model, the fitness number reached to 0.86, which means more accurate than previous ones.

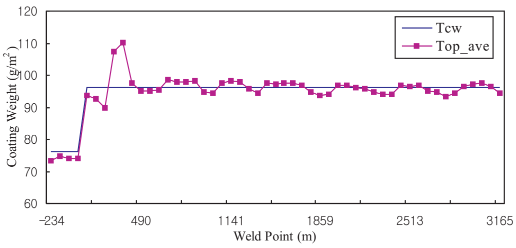
5.2 Result of Preset Control

In preset control, it is very important to avoid under coating on the surface of strip. Therefore, coating weight or thickness of layer have to be over the lower specification limit(**LSL**) and the target coating weights are given to operator or control system slightly over the ordered coating weight.

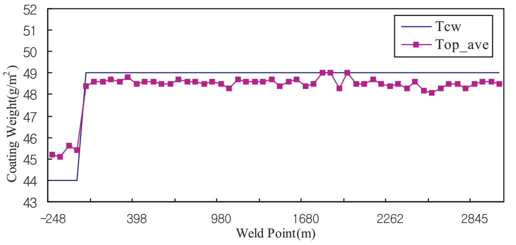
Fig. 8 is the result of preset control. In this figure, the measured and estimated coating weight are compared at the range of 50 $\sim$ 100 m from weld point. The dotted line is histogram of the difference of measured coating weight from target when the coating process was manipulated by operator manually. And the solid line is the histogram of the difference between the estimated coating weight and measured coating weight controlled by the result of preset control. In manual operation, there was 13% coating weight defect under low specification limit(**LSL**) denoted by a vertical dashed line, whereas, at the result by long term model, there was only 7% defect. The standard deviation for result of preset control is less than that for the result of manual operation.

5.3 Results of Feedback and Feed-forward control

When the a set of feedback gains designed based on result of previous chapters and feedback control algorithm were applied to continuous galvanizing line, Fig. 9 and Fig. 10 were obtained as the results.



(a) Feedback control with critical gain



(b)Good preset and no feedback control

Fig. 9. Result of feedback control

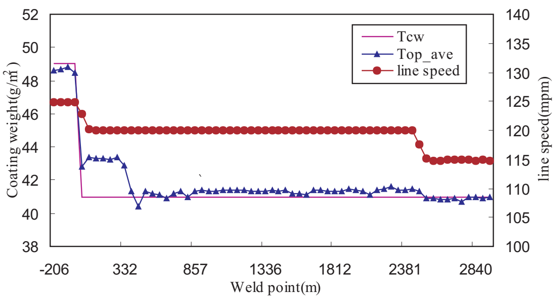


Fig. 10. Result of feedback and feed-forward control

These results were obtained at the conditions of same line speed and same distance from nozzle of top air knife and that of bottom's. During the test, material and dimension of strip remain unchanged. Fig. 9(a) shows the result of feedback control when the target coating weight changes from 76 g/m^2 to 96 g/m^2. In this test, the gains of feedback controller were set high enough to get quick response on their convergence to target coating weight. However, the measured coating weight of strip is oscillating periodically. This means that the gains of feedback controller were set to near the boundary of stability. Fig. 9(b) shows the results of feedback control when the target coating weight changes from 44 g/m^2 to 49 g/m^2. At top of coil in this figure, the measured coating weight by preset control is similar to target coating weight. In this case, it looks that no feedback control is applied during the coating process. The reason is, the result of preset control is good enough, thus feedback control does not work when the error between the measured coating weight and target coating weight remains within the range of -1 $\sim$ 1 g/m^2, so called as dead band.

Fig. 10 also shows the result of feedback and feed-forward control when there is a difference between target and measured coating weight at top of coil, beyond the dead band. After weld point pass through the coating weight gauge(**CWG**) located at 200 m downstream from air knife, feedback control works well. The measured coating weight converge to target one and then it remains with dead band. At near to 2500 m downstream, there is change on line speed from 120 mpm to 115 mpm. If there were no feed-forward control, this may result in change of coating weight on strip. However the coating weight do not change largely. This means that feed forward control was applied at this point and as the result there was no increase in coating weight error after then.

6. CONCLUSION

In this research, a new coating weight model and its robust control algorithm were proposed and evaluated at real galvanizing process. As a result, following results were obtained.

A set of practical synthesis model for galvanizing process was constructed by long term and short term model. Long term model have the function of the classification, averaging and least-square learning for measured data. Short term model is a new linear model based on the change of input and output variables and has the adaptive learning algorithm realized by recursive least-square method. By this linearized model, nonlinear coating weight control problem could be analyzed as a linear control problem. A systematic robust design method for feedback controller was also developed, though the coating process has time delay. As the result, lower deviation of coating weight on top of coil and uniform coating weight at galvanized steel sheet in the CGL at POSCO. It can be summarized as followings.

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