INTEGRATED QUALITY CONTROL FOR LOOPER SYSTEM BY ADAPTIVE TECHNIQUE

Akira KITAMURA *, Hideki ASADA and Masami KONISHI*****

** Faculty of Engineering, Tottori University, Japan*
***Kakogawa Works, Kobe Steel, Ltd.*
**** Faculty of Engineering, Okayama University, Japan*

Abstract: This paper describes the integrated quality control in consideration of equipment diagnosis and control of looper height in hot strip rolling. In the integrated platform, deterioration of the induction motor is recognized quantitatively and tendency management of the deterioration is carried out. Simultaneously, the looper height control in consideration of the material quality change and degree of deterioration is performed. The motor deterioration by breakage of the rotor bar is adaptively estimated from change of the rotor bar resistance. The change of material quality and the deterioration condition are regarded as change of the damping coefficient of the looper dynamic model. The adaptive type robust control is applied to the looper height control. The validity is verified by numerical simulation.

Keywords: Steel manufacture, Looper control system, Hot rolling, Induction motor, Equipment diagnosis, Adaptive algorithm, Robust control, Parameter estimation

1. INTRODUCTION

In order to maintain the quality of steel products, it is necessary to operate equipments for stability and even if the material quality changes, it is required that the control system guarantees robust stability. The deterioration of the equipment and change of the material quality have a bad influence on the product quality. However, it may be difficult to judge it from operation data which of them is for the cause. Then, a platform which consists of automatic maintenance technique and advanced control system is needed to be developed.

This paper focuses on the looper control system in hot rolling. There are already many researches about looper control (Kotera, et al., 1979). So, the new platform which consists of the deterioration diagnosis technique for the mill motor and the looper control system corresponding to the quality change of the rolling material is proposed.

First, it is analyzed about the bad influence that deterioration of the motor and change of the material quality give the product quality. Next, a concept of the totalized control platform where the highly precise control system is integrated with equipment diagnosis technique is introduced. Moreover, in order to calculate the deterioration degree of rotor bar, an estimation method based on the mathematical model of induction motor is explained and a looper control algorithm by the adaptive type robust control based on the dynamical model of looper height control is described.

2. DYNAMICAL MODEL

2.1 Looper dynamical model

In the hot strip mill, tension of the rolling direction given to strip is reduced by an installing looper between rolling mills and making a loop form of rolled material. The tension deviation changes the looper height. The looper height is detected at a looper rotation angle and the tension is kept by a constant value by controlling the angle in a fixed value. The looper control system is shown in Fig. 1. Here, an induction motor is often used as the mill motor. The motor speed follows a targeted value by feedback control. In the steady state, the load torque which acts on the looper from rolling material balances with the looper generation torque.

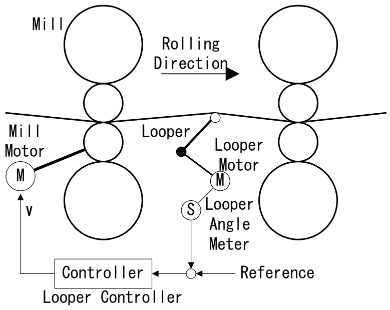


Fig.1. Outline of looper control system

By feed back of the measured rotation angle to the speed control system of the upstream rolling mill, the tension between stands is controlled to the targeted value. The block diagram of the looper control system is shown in Fig. 2.

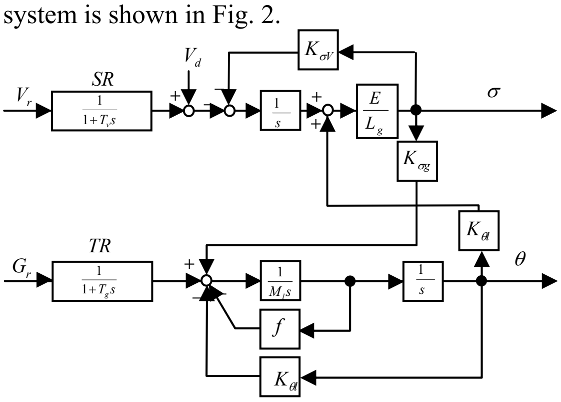


Fig.2. Block diagram of looper control

Notations used in this figure are summarized as follows; V_r :targeted value of rolling speed, G_r :targeted value of looper motor torque, T_g :time constant of rolling speed regulator, V :strip speed, G_M :looper torque, M_l :moment of inertia of looper, E :Young's modulus(the influence of friction is included in E in equivalent), L_g :distance between stands, f :sacrifice selling of friction, $K_{\bullet\bullet}$:various kinds of influence coefficients, *SR* :rolling speed regulator, *TR* :looper torque regulator σ :strip tension, θ :looper roll rotation angle

Moreover, it is known that the looper height dynamics can be approximated to a following second order lag and dead time system by actual data analysis (Fujisaki, et al., 1991).

$$\frac{Y(s)}{U(s)} = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2}\exp(-Ls) = P(s)\exp(-Ls) \quad (1)$$

Where, $Y(s)$ is Laplace transform of the looper angle, $U(s)$ is Laplace transform of corrected velocity of the mill motor, s is the Laplace operator, ω_n is the resonant frequency, ξ is the damping coefficient, and L is the dead time.

2.2 Dynamical model of induction motor

The induction motor is often used as mill motor of a rolling mill and breakage of the rotor bar becomes a cause and the performance of a motor deteriorates.

Usually, the frequency analysis method is used for diagnosing the rotor bar deterioration (McCully, et al., 1997). However, since the quantitative diagnosis cannot be performed by this method, the opportunity of suitable repair may be overlooked. Then, the quantitative diagnostic method based on the expression model of the motor is proposed. A mathematical model is derived from the physical characteristic of stator and the rotor of the induction motor. Figure3 shows outline of the induction motor and the geometrical position between the stator and the rotor and parameters which constitute them.

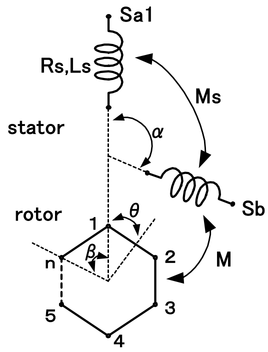


Fig.3. Outline of induction motor

Notations used in this figure are summarized as follows; R_s : resistance of each stator, L_s : inductance of each stator, M : mutual inductance between each stator and rotor, M_s : mutual inductance between stators, α : phase angle of stator and β: electric phase angle of rotor bar θ: electric phase angle between phase winding of stator S_{a1} and first loop of the rotor.

The equilibrium equations for voltages of induction motor can be laid out as follows:

$$\begin{pmatrix} V_s \\ 0 \end{pmatrix} = \begin{pmatrix} Z_{ss} & Z_{sr} \\ Z_{rs} & Z_{rr} \end{pmatrix}\begin{pmatrix} I_s \\ I_r \end{pmatrix} = Z\begin{pmatrix} I_s \\ I_r \end{pmatrix} \quad (2)$$

V_s and I_s express the voltage vector of a stator(3×1), and the current vector of a stator(3×1), respectively. Moreover, I_r expresses a rotor current vector (3×1). Furthermore, Z_{ss} , Z_{sr} , Z_{rs} , and Z_{rr} express an impedance matrix. In equation (2), the following formula is obtained by leaving the clause containing a differentiation part to the left side, and shifting the other clause to the right-hand side.

$$A\dot{X} = BX + U \quad (3)$$

Here, $X = \begin{pmatrix} I_s \\ I_r \end{pmatrix}$, $U = \begin{pmatrix} V_s \\ 0 \end{pmatrix}$, Matrix A is a portion which includes a differentiation clause among the impedance processions Z . Moreover, the partial matrix B expresses the remaining portion.

3. EQUIPMENT DETERIORATION AND MATERIAL QUALITY CHANGE

The looper height deviation causes the thickness and width variation. Moreover, it gives the bad influence to the product quality.

The deterioration by the breakage of the rotor bar of a motor is equivalent to increase of the resistance. Moreover, the increase of resistance leads to the aggravation of response of the rolling speed regulator (*SR* in Fig.2). On the other hand, equation (1) and Fig.2 show that the change of Young's modulus is equal to the change of damping coefficient and resonance frequency of the secondary delay system. Especially, the damping coefficient deviation has a great influence on the stability of the control system.

In the following, the influence which response of the speed regulator and change of Young's modulus have on looper height is considered.

At first, in the case of no deterioration, when the rolling speed regulator *SR* is approximated by a first order lag, the time constant is 0.05 [s]. The simulation result is shown in Fig.4.

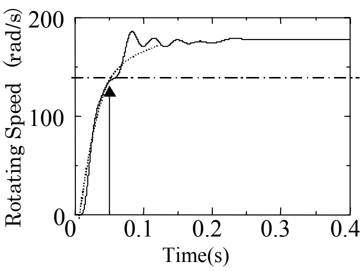
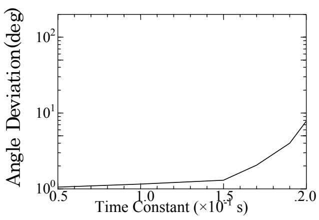


Fig.4. Response of the rolling speed regulator without deterioration

When Young's modulus is set to 8000[kg/mm^2], the relation between response (an equivalent for the time constant) of the rolling speed regulator and amplitude of the height deviation is shown in Fg.5

Fig.5. Deterioration of rotor bar and looper height



If the time constant of the rolling speed regulator becomes 0.15[s] or more, the looper height change will increase and it will have the bad influence on the products quality.

Next, the relation between change of the Young's modulus and amplitude of the looper height change is shown in Fig.6.

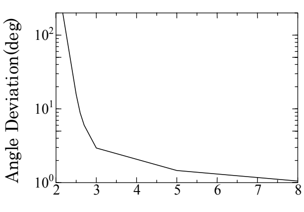


Fig.6. Young's modulus and looper height

The system will be unstable if Young's modulus becomes 3000[kg/mm^2] or less.

Next, the simulation has been performed with the conditions that the time constant of a motor is set in 0.15[s] and the equivalent Young's modulus is set in 5000. The result is shown in Fig.7.

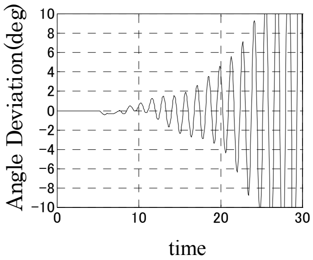


Fig.7. Simulation result in the case of Young's modulus: 5000[kg/mm^2] Time constant of a motor: 0.15[s]

When Young's modulus becomes small and the motor rotor bar deteriorates, the stability of the system cannot be secured in a usual feedback control for the looper height.

4. INTEGRATED QUALITY CONTROL SYSTEM

The integrated quality control system consists of the deterioration diagnosis of the motor rotor bar and the adaptive robust control of the looper height. The concept of the totalized system is shown in Fig.8.

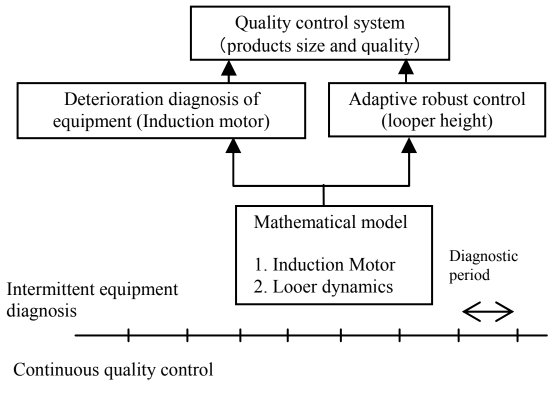


Fig.8. Concept of integrated quality control system

About the motor rotor bar deterioration, a tendency management is performed by intermittent equipment diagnosis. When the degree (value of resistance) of deterioration exceeds the threshold value set up beforehand, repair of the motor rotor bar is carried out. On the other hand, looper height is continuously controlled. The control system is characterized by estimating the change of the damping coefficient which is a parameter related to both change of the material quality and degree of the motor rotor deterioration.

The estimated values of the two rotor bars resistance are shown in Fig.9. The vertical axis shows the ratio between the initial resistance R_0 and the present resistance R_b. The horizontal axis shows the number of the diagnosis, which is periodically carried out.

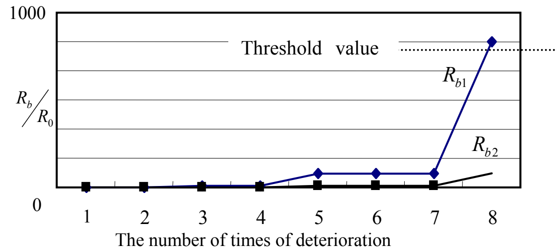


Fig.9. Trend management of the deterioration

As shown in the figure, R_{b1} exceeds the boundary value at the eighth diagnosis occasion. Therefore this result shows the induction motor should be repaired. Once this on-line diagnosis system is constructed, the rotor deterioration is automatically recognized before the occurrence of a serious trouble.

5. ESTIMATION OF ROTOR BAR RESISTANCE

5.1 Diagnosis system

The deterioration state of the induction motor is estimated from change of the rotor bar resistance. the diagnosis system using following estimation method of the rotor bar resistance is proposed. The value of the rotor bar resistance is estimated using the stator currents and the input power voltages. The block diagram of estimation is shown in Fig.10.

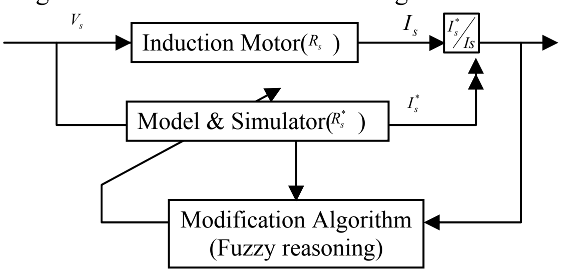


Fig.10. Block diagram of adaptive estimation

The input voltage V_s is used to estimate the stator current I_s^* by the mathematical model of the induction motor, assuming the value of rotor bars resistance R_b^*. Then, the estimated stator current I_s^* is compared with the measured stator current I_s. The rotor bars resistance is modified reflecting the difference between I_s^* and I_s in the estimation of the stator current. After iteration of these steps, the value of R_b^* converges to its real value R_b.

5.2 Estimation Algorithm

When the same input V_s is given to the induction motor and to the simulator in Fig.5, the following equation (4) can be obtained (Asada, et al., 2001).

$$R_b = R_b^* \times \left(\frac{I_s^*}{I_s} \right) \qquad (4)$$

Therefore, if the following equation (5) holds, R_b of the motor can be estimated from equation (6).

$$I_s^* = I_s \quad (5) \qquad R_b^* = R_b \quad (6)$$

Next, new variable D is defined as follows:

$$D = \frac{I_s^*}{I_s} \qquad (7)$$

In the algorithm, estimated value of R_b^* at $(m+1)$ th sampling is calculated from R_b^* and D at m th sampling as the following equation

$$R_b^*(m+1) = R_b^*(m) \times D(m)^{u(m)} \qquad (8)$$

Here, $u(m)$ is the enforced factor for fast convergence as given in equation (9).

$$u(m) = \begin{cases} -k \ (k > 0) & if \quad F(m) < D(m-1) < 1 \\ & \qquad or \quad 1 < D(m-1) < D(m) \\ k & \qquad else \end{cases}$$

(10)

The parameter k has an effect on trend of the convergence. It is effective to change the parameter k depending on the value of ratio D. To design the control factor u, X and ΔX are defined as follows:

$$X_j(m) = \ln D_j(m) \qquad (11)$$

$$\Delta X(m) = \ln D_j(m) - \ln D_j(m-1) \qquad (12)$$

The control factor u is defined as follows:

$$u_j(m) = k \cdot sign\left(u_j(m-1)\right) \qquad (13)$$

$$sign(input) = \begin{cases} -1 & (input < 0) \\ 1 & (else) \end{cases}$$

Even if the deterioration arises in two or more stators the resistance change can be estimated by the same technique.

5.3 Application of Fuzzy reasoning

Fuzzy rules used to determine the parameter k are represented by 5x5 cells as shown in table 1.

Table 1. Fuzzy logic for parameter k

		ΔX_j				
		NB	NS	M	PS	PB
X_j	NB	$-k_{11}$	$-k_{12}$	k_{13}	k_{14}	k_{15}
	NS	$-k_{21}$	$-k_{22}$	k_{23}	k_{24}	k_{25}
	M	k_{31}	k_{32}	k_{33}	k_{34}	k_{35}
	PS	k_{41}	k_{42}	k_{43}	$-k_{44}$	$-k_{45}$
	PB	k_{51}	k_{52}	k_{53}	$-k_{54}$	$-k_{55}$

As shown in this table, the value of k is changed by its sign according to the fuzzy rules. Where, P,M,N,S,B means positive, medium, negative, small and big. The stability of the algorithm is attained from existence of the dead band for both variables and control of the modification factor z. In case of estimating the values of two R_bs , R_{bx} and R_{by}, the identification is carried out as follows:

$$D_j(m) = \frac{I_{sj}^*(m)}{I_{sj}(m)} \qquad (14)$$

$$R_{bx}(m+1) = R_{bx}(m) \times \overline{D}_a(m)^{z_1 \times u_1(m)} \times \overline{D}_b(m)^{z_2 \times u_2(m)} \qquad (15)$$

$$R_{by}(m+1) = R_{by}(m) \times \overline{D}_a(m)^{z_2 \times u_1(m)} \times \overline{D}_b(m)^{z_1 \times u_2(m)} \qquad (16)$$

where x,y∈ {1,2,..,6},x≠ y ,$\overline{D}$ means the average of D. As for the variables in equation (15),(16), m is number of the calculation. $u_1(m)$, $u_2(m)$ are the control factors stabilizing the convergence of the algorithm determined by the fuzzy reasoning.

5.3 Numerical simulation

In the case of two stators, the effect of proposed algorithm is verified by numerical simulation. The estimation result is shown in Fig.11. As shown in the figure, the R_{b1} and R_{b2} values successfully converge to their real values (R_{b1} =335Ω, R_{b2} =670Ω) after several hundred iterations.

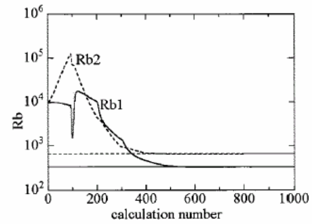


Fig.11. Estimation result of R_{b1} and R_{b2}

6. ADAPTIVE AND ROBUAT CINTROL FOR LOOPER HEIGHT

6.1 Control system

Robust control of looper is designed supposing the case where the model error is the largest (Fujisaki, et al., 1991). Even with the largest error, the value varies with the rolling situation every hour. So, the adaptive type robust control characterized by estimating the model error recursively and correcting the parameter for guaranteeing the robust stability is proposed. The block diagram of the control system is shown in Fig.12.

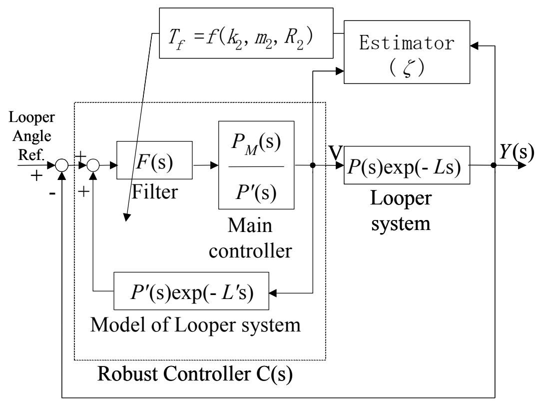


Fig.12 Block diagram of adaptive robust controller

The structure of controller is based on *Internal Model Control*. Here, $C(s)$ is the controller and $P(s)e^{-Ls}$ is the true characteristic of looper dynamics. $F(s)$ is the transfer function of the filter for robust control, $P_M(s)$ is the transfer function of the reference model and $P'(s)e^{-L's}$ is the looper height model. $C(s)$ can be laid out as follows:

$$C(s) = \frac{F(s)P_M(s)}{P'(s)\left\{1 - F(s)P_M(s)e^{-L's}\right\}} \qquad (17)$$

In Fig.4, the characteristics which should be designed are $F(s)$ and $P_M(s)$. $P_M(s)$ is designed to the second order lag. In order to maintain the system stability even under the change of the material characteristics, $F(s)$ is designed so that the looper height control system can guarantee robust stability.

6.2 Robust stability problem

The complementary sensitivity function T(s) can be expressed as follows:

$$T(s) = \frac{F(s)P_M(s)P(s)e^{-Ls}}{P'(s)\left\{1 - F(s)P_M(s)e^{-L's}\right\} + F(s)P_M(s)P(s)e^{-Ls}} \qquad (4)$$

T(s) is designed to be sufficiently small at the frequency of the worst disturbance. In order to satisfy this condition, the characteristics F(s) is to be designed sufficiently small in the frequency domain of low damping comparatively.

With this background, the adaptive looper height robust control accompanying estimation of the damping coefficient is proposed. The adaptive control system is expected to guarantee the stability of the system and a high degree of accuracy even if the looper characteristics $P(s)e^{-Ls}$ is changed. So, the recursive estimation of damping coefficient ξ is employed. It is important that the damping coefficient deviation originates in change of resistance R_b and Young's modulus E. The reference model P_M(s) is designed to have the second order lag element, and the filter F(s) is designed to have the first order lag element as follows:

$$P_M(s) = \frac{\omega_M^2}{s^2 + 2\zeta_M \omega_M s + \omega_M^2} \qquad (5)$$

$$F(s) = \frac{1}{1 + T_f s} \qquad (6)$$

Where ω_M and ξ_M are designed to satisfy the specification for response of the looper angle.

The problem is the design of the time constant T_f of the filter F(s) to guarantee the system stability. Specifications are described in equation (7) and (8).

$$\left| T(s) \right| < \beta(\omega) \qquad (7)$$

$$\beta(\omega) < \frac{1}{\left| \Delta\{\xi(R_b, E), \omega\} \right|} \qquad (8)$$

Where Δ is the additive uncertainty of the looper height model based on deterioration of the equipment and change of the material quality. It can be expressed as follows (Asada, et al., 2002):

$$P(s)e^{-Ls} = P'(s)e^{-L's} + \Delta\{\xi(R_b, E), \omega\} \qquad (9)$$

In equation (9), $P(s)e^{-Ls}$ shows the dynamics of the actual plant. Arrangement of the above mentioned equations obtains the following inequality:

$$k_2\{\xi(R_b, E)\} < T_f < k_1\{\xi(R_b, E)\} \quad (k_1 < k_2) \qquad (10)$$

The time constant T_f can be designed to satisfy the following equation :

$$T_f = k_2 + \varepsilon_1 \quad (\varepsilon_1 > 0) \qquad (11)$$

As far as T_f satisfies equation (11), the looper control system remains stable even if the rolling characteristics change.

6.3 Sensitivity Reduction Problem

In order to reduce the influence of the disturbance at low frequency, F(s) is designed such that the sensitivity function S(s) is small in low frequency domain comparatively. The sensitivity function S(s) can be expressed as follows:

$$S(s) = \frac{P'(s)\left\{1 - F(s)P_M(s)e^{-Ls}\right\}}{P'(s)\left\{1 - F(s)P_M(s)e^{-L's}\right\} + F(s)P_M(s)P(s)e^{-Ls}} \quad (12)$$

If the time constant T_f of the filter F(s) is designed to satisfy equation (13), the influence of the disturbance can be reduced below the value of $\alpha(\omega)$.

$$\left| S(s) \right| < \alpha(\omega) \quad \forall\omega \quad (13)$$

The α -function (Saeki, et al., 1998) as given in equation (14) to reduce the plant gain in low frequency domain. The equation (14) is the small value M_u at low frequency and increases monotonously to the large value M_L at high frequency.

$$\alpha(\omega) = \left| \frac{3.699M_L + 2.0256M_u s + M_u s^2}{3.699 + 3.0156s + s^2} \right| \quad (14)$$

T_f can be given by m_1 and m_2 ($m_1 < m_2$) and it is designed to satisfy the following inequality:

$$\begin{aligned} &0 < T_f < m_2\{\xi(R_b, E)\} \quad (\alpha < 1) \\ &m_2\{\xi(R_b, E) < T_f \quad (\alpha \geq 1) \end{aligned} \quad (15)$$

The time constant T_f is designed so that equations (11) and (15) should be satisfied. Thus, the looper system can be designed as being adaptive to disturbances satisfying both the robustness and a high accuracy of control performance.

6.4 Simulation analysis

When the damping coefficient changes in correspondence with the deviation of the resistance of a motor and Young's modulus of material, the change of the time constant T_f is shown in Fig.13.

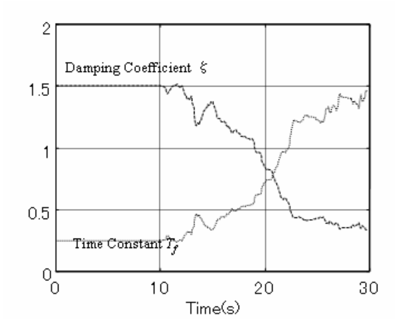


Fig.13. Estimated damping coefficient and time constant of filter

When the looper height dynamics becomes under damping, it is confirmed that the time constant T_f will be increased and the stability of system is secured.

The simulation result of the height control by the adaptive robust control to propose is shown in Fig.14 as compared with the result depended on the conventional robust control technique.

It is clear that the proposed control algorithm is filling both of demands which are restraint of the disturbance and high responsibility as compared with the conventional method.

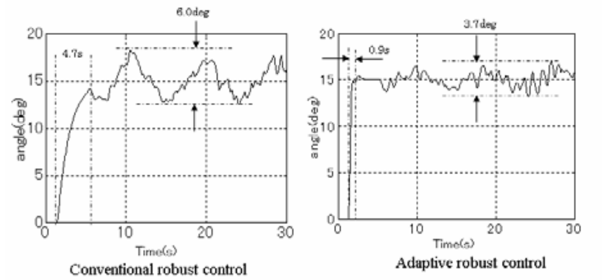


Fig.14. Simulation results of looper height control by adaptive control technique

7. CONCLUSION

The integration system consists of the deterioration diagnosis of the motor rotor bar and the adaptive control system of looper height. In this system, the quantitative diagnostic method based on the expression model of a motor and the adaptive robust control method using the estimation of the looper height characteristic have been developed. The characteristic of the integrated system is to make it possible to maintain quality of the product in a high rank, even if deterioration of the motor rotor bar and change of the materials quality are caused at the same time. The usefulness of this system is verified by the simulation.

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