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ON MATHEMATICAL MODEL FOR HOT TANDEM MILL WITH AUTOMATIC CONTROL SYSTEM

制御系を含むホットタンデムミルの数式モデルについて

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1. Introduction

Recently, studies on the characteristics of hot tandem mill have developed and many useful results have been obtained.

In these studies, it was common to approach this problem through simulation by a digital computer.

However, this technique requires much complexity of repeated computation and much store capacity of a digital computer. Therefore, we can not avoid many difficulties when we study on the optimum control system for hot tandem mill theoretically.

In this paper, we propose a new mathematical model which enables us to study not only on the characteristics of hot tandem mill but also on the problem of the optimum control system for hot tandem mill theoretically.

Further, this model is suitable for studies on the transient properties of practical systems.

In the following, we describe this new mathematical model and offer an used example of this model.

2. Fundamental equations

The system we consider is the one illustrated in Fig. 1. Rolling parameters are presented on Table 1.

The fundamental equations of this system are given as follows:

First, for single stand we consider

(1) Out-going strip thickness:

$$h_i = Sr_i + \frac{P_i}{K_i} \qquad (1)$$

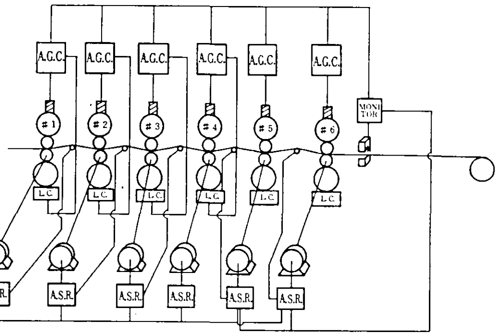

Fig. 1 6 stands hot tandem mill with automatic control system.

Table 1 Notations

H	incoming strip thickness
h	outgoing strip thickness
P	rolling force
T	rolling temperature
G	rolling torque
V	rolling speed
f	forward slip ratio
ϵ	backward slip ratio
vf	outgoing strip speed
vb	incoming strip speed
B	strip width
L	distance between stands
Sr	roll gap setting
K	mill modulus

(2) Rolling force:

$$P_i = f_{(1)}(P_i, H_i, h_i, T_i, V_i, B) \qquad (2)$$

(3) In-coming and out-going strip velocities:

$$vf_i = f_{(2)}(P_i, H_i, h_i, T_i, V_i, B) \qquad (3)$$

$$vb_i = f_{(3)}(P_i, H_i, h_i, T_i, V_i, B) \qquad (4)$$

Second, for inter-stands relations, we consider

(1) Propagation of strip thickness:

$$H_{i+1}(t) = h_i\left(t - \frac{L}{vf_i}\right) \qquad (5)$$

(2) Treatment of temperature:

$$T_{i+1}(t) = T_i\left(t - \frac{L}{vf_i};\ vf_i\right) - \frac{T_1 - T_6}{5} i$$

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$$(6)$$

(3) Looper model:

$$vb_{i+1}(t)=vf_i(t)(1-e^{-\beta_i t}) \qquad (7)$$

These are the fundamental equations of our model.

3. Construction of mathematical model

As presented in fundamental equations, (1) to (7), rolling parameters we treat are H_i, Sr_i, V_i, T_i, h_i, vf_i, vb_i.

In our model, these parameters take the deviated values from the fundamental rolling state.

That is, we choose variables for our model as follows: these are $\bar{H}_i$, $\overline{Sr}_i$, $\bar{V}_i$. $\bar{T}_i$, $\bar{h}_i$, $\overline{vf}_i$ and $\overline{vb}_i$.

Here, we define

$$\bar{H}_i=\Delta H_i/H_i,\ \overline{Sr}_i=\Delta Sr_i/h_i,\ \bar{V}_i=\Delta V_i/V_i,$$
$$\bar{T}_i=\Delta T_i/T_6,\ \bar{h}_i=\Delta h_i/h_i,\ \overline{vf}_i=\Delta vf_i/vfi,$$
$$\overline{vb}_i=\Delta vb_i/vb_i. \qquad (8)$$

Expanding eq's (1) to (7) in Taylor's series expansion, the eq's are approximately reduced to linear equations as follows:

$$\bar{h}_i^{(2)}=\bar{h}_i^{(1)}+g_{11i}\bar{H}_i^{(1)}+g_{12i}Sr_i^{(1)}+g_{13i}\bar{V}_i^{(1)}+g_{14i}\bar{T}_i^{(1)}, \qquad (9)$$

$$\overline{vf}_i^{(2)}=\overline{vf}_i^{(1)}+g_{21i}\bar{H}_i^{(1)}+g_{22i}\overline{Sr}_i^{(1)}+g_{23i}\bar{V}_i^{(1)}+g_{24i}\bar{T}_i^{(1)}, \qquad (10)$$

$$\overline{vb}_i^{(2)}=\overline{vb}_i^{(1)}+g_{31i}\bar{H}_i^{(1)}+g_{32i}\overline{Sr}_i^{(1)}+g_{33i}\bar{V}_i^{(1)}+g_{34i}\bar{T}_i^{(1)}, \qquad (11)$$

$$\bar{T}_{i+1}^{(1)}(s)=\bar{h}_i^{(2)}(s)\cdot\exp(-LS/vf_i), \qquad (12)$$

$$\bar{H}_{i+1}^{(1)}(s)=\bar{h}_i^{(2)}(s)\cdot\exp(-LS/vf_i), \qquad (13)$$

$$vb_{i+1}^{(1)}(s)=vf_i^{(2)}(s)\Big/\left(1+\frac{S}{\beta_i}\right). \qquad (14)$$

where upper suffices (1) define the state of pre-entry to roll gap and that of (2) define the state of post-exit from roll gap. Here, we define the state vector at the state of pre-entry, X_i, and that of post-exit, Y_i, as follows:

$$X_i^t=(\bar{H}_i^{(1)}, \overline{Sr}_i^{(1)}, \bar{V}_i^{(1)}, \bar{T}_i^{(1)}, \bar{h}_i^{(1)}, \overline{vf}_i^{(1)}, \overline{vb}_i^{(1)}), \qquad (15)$$

$$Y_i^t=(\bar{H}_i^{(2)}, \overline{Sr}_i^{(2)}, \bar{V}_i^{(2)}, \bar{T}_i^{(2)}, \bar{h}_i^{(2)}, \overline{vf}_i^{(2)}, \overline{vb}_i^{(2)}). \qquad (16)$$

where $(\ .\ )^t$ means the transpose-of vector $(\ .\ )$.

Then eq's of single stand, (1) to (4) and eq's of inter-stands relation, (5) to (7) are rewritten in vector form as follows:

$$Y_i=G_i\cdot X_i\ ;\ (i=1\sim6), \qquad (17)$$

$$X_{i+1}=H_i\cdot Y_i\ ;\ (i=1\sim5). \qquad (18)$$

Here, we define the input and output vectors of total system, $\hat{X}$ and $\hat{Y}$ as follows:

$$\hat{X}^t=(X_1^t, X_2^t, X_3^t, X_4^t, X_5^t, X_6^t), \qquad (19)$$

$$\hat{Y}^t=(Y_1^t, Y_2^t, Y_3^t, Y_4^t, Y_5^t, Y_6^t). \qquad (20)$$

Then, the relations (17) and (18) are reduced to

$$\hat{Y}=B\hat{X} \quad \text{and} \quad \hat{X}=A\hat{Y}, \qquad (21)$$

where, matrices B and A are given by

$$B=\mathrm{dia}\ g(G_i), \qquad (22)$$

and

$$A=\begin{bmatrix} 0 & & & & & \\ H_i & 0 & & & & 0 \\ & H_2 & 0 & & & \\ & & H_3 & 0 & & \\ & 0 & & H_4 & 0 & \\ & & & & H_5 & 0 \end{bmatrix} \qquad (23)$$

Presentation of eq. (21) in the form of block diagram is illustrated in Fig. 2. In Fig. 2, U

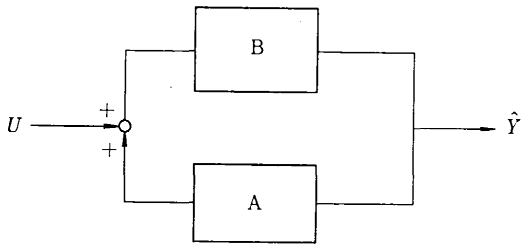

Fig. 2 Block diagram of hot tandem mill.

represents the disturbance to the system. From the figure, the relation between $\hat{Y}$ and U is given by

$$\hat{Y}=(B^{-1}-A)^{-1}\cdot U=D(s)\cdot U, \qquad (24)$$

where $D(s)$ is called influence matrix of the system.

4. Addition of A. G. C. System

In practical system, A. G. C. system is introduced for the purpose of compensating deviation of the strip thickness.

The characteristics of A. G. C. system are presented in vector from as follows:

$$\Delta U=M(s)\cdot\hat{Y}. \qquad (24)$$

Therefore, for the total system of hot tandem mill with A. G. C. system, the mathematical model

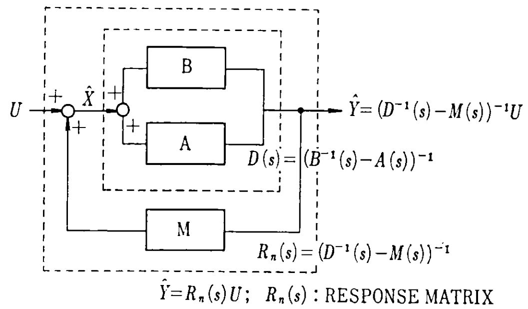

Fig. 3 Mathematical model for hot tandem mill with A. C. system.

is constructed with eq's (24) and (25). These relations are shown in Fig. 3.

From the discussions above, we can relative $\hat{Y}$ to U as follows:

$$\hat{Y}=(D^{-1}(s)-M(s))^{-1}\cdot U=Rn(s)\cdot U, \quad (26)$$

where $Rn(s)$ is called response matrix. Depending on eq. (26), we can simulate responses of hot tandem mill with automatic control system.

5. Simulation of response

Mathematical model given above can be applied for simulation. Here, we consider the system whose fundamental pass schedules are presented on Table 2.

Table 2 Fundamental pass schedule in example

		♯4	5	6
H	mm	7.89	4.99	3.49
h	mm	4.99	3.49	3.26
r	%	36.7	30.0	6.6
T	℃	890	860	830
V	m/s	6.0	8.72	9.92
Sr	mm	2.77	2.01	2.91
P	t.	1119	897	175
G	t.m.	34980	20039	1615
K	t./m.	500	500	500

Disturbance, in this case, is the deviation of incoming strip thickness at ♯4 stand and this the step one.

Responses of the system are shown in Figs 4 and 5.

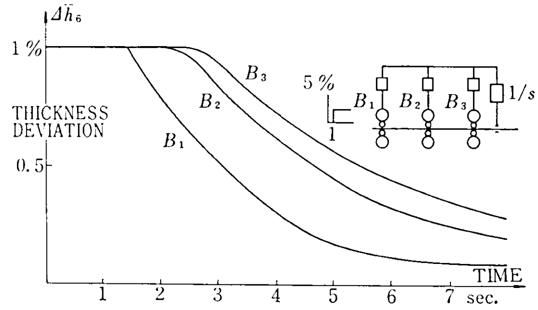

Fig. 4 Simulted responses of the system.

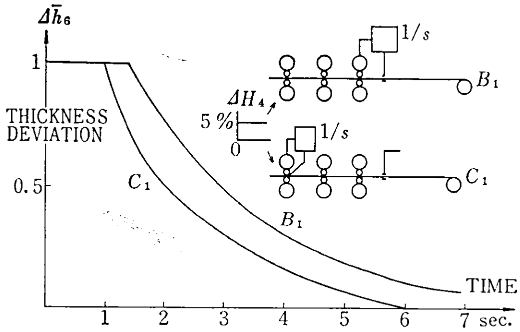

Fig. 5 Simuluted responses of the system.

6. Conclusion

As discussed above, in this paper, we proposed mathematical model that is convenient not only for simulation but also for the analysis of optimum control system and its simulated examples are presented. (Manuscript received Sept. 18, 1971)

Reference

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