Mill-balance Control Technique for Tandem Cold Mill

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This paper describes a mill balance control (MBC) for a tandem cold mill (TCM) with an automatic gage control system (AGC).

The stand exit gages are controlled by the AGC, but the motor currents and the rolling forces of stands cannot be controlled.

When the setup control is not proper or when the incoming strip has variations in gage and hardness, the distribution pattern of the motor currents and the rolling forces (mill balance) sometimes becomes inappropriate. When a motor current exceeds its rated value, usually all roll speeds are reduced manually, and the productivity decreases. When a rolling force varies to a great extent, strip shape defects may occur.

The MBC operates the stand exit gages except for the finish gage and the interstand tensions, and it controls the distribution pattern of the motor currents and the rolling forces while guaranteeing the finish gage accuracy.

The MBC controller is designed based on the ILQ design method and is applied to an actual process.

Experimental results show that desired mill balance is achieved and the finish gage accuracy is maintained.

KEY WORDS: rolling; process control; ILQ control; mill balance control; rolling force; motor current.

1. Introduction

In the tandem cold mill (TCM), the stand exit gages and the interstand tensions are controlled by the setup control and the automatic gage control (AGC).1–3)

Specifically, the setup control determines the aim gages and the aim tensions using the setup model prior to the rolling. And in the rolling, the AGC regulates the stand exit gages at aim gages. When the AGC system is equipped with tension control function, the interstand tensions are also regulated at aim tensions. In this study, this type of AGC system is assumed, and it is called an automatic gage and tension control (AGTC) system hereafter.

Recently, the variety of steel strips to be rolled has been increasing, for example, due to the demand in the automobile industry. For the new kinds of steel strips, the setup models sometimes have errors. And the distribution pattern of the motor currents and the rolling forces (mill balance) is unbalanced.

When a motor current exceeds its rated value, usually all roll speeds are reduced manually, and the productivity decreases.

It is difficult to decrease the excessive motor current independently of other motor currents or rolling forces because of the interaction between them.

Therefore, a mill balance control (MBC) system which controls the distribution pattern of all the motor currents and all the rolling forces as well as the finish gage is introduced.

Even if a motor current exceeds its rated value owing to the setup model error, the motor current can be decreased without reducing the rolling speed. Moreover, the rolling forces are also controlled, and the MBC can prevent strip shape defects.

In this paper, the model of the TCM with the AGTC system is explained and the design of the MBC system is described in Chap. 2. Then, experimental results are shown in Chap. 3 in order to confirm the effectiveness of the MBC.

2. Design of MBC System

2.1. Outline of MBC

Figure 1 shows a 5-stand TCM. The AGTC system controls the finish gage at an aim value. In order to achieve the

![Fig. 1. Tandem cold mill.](image-url)
desired motor currents and rolling forces (mill balance), a new control loop is added to the AGTC loop, and a cascade control system of MBC is constructed (Fig. 2).

2.2. Model of TCM with AGTC System

The controlled plant of the MBC consists of the mill and the AGTC system. First, a static model of the plant is derived from the rolling theories. Next, a dynamic model of the plant is obtained by combining the static model with the dynamic property of the plant.

2.2.1. Static model

The static Model is obtained using influence coefficients. Equations of the volumetric velocity, the exit strip speeds, the exit strip gages, the AGTC-controlled variables, the non-controlled variables, the rolling forces and the motor currents are derived based on the rolling theories, and they are linearized around a steady rolling state. As a result, the static model is described as follows:

\[ \dot{x}_{m&c} = A_{u_{tox}} \cdot u \]  \hspace{1cm} (1)

where

- \( x_{m&c} \): state vector of rolling (38 elements)
- \( A_{u_{tox}} \): influence coefficient matrix (38×8 elements)
- \( u \): input vector of MBC (8 elements)

The details of \( x_{m&c} \), \( A_{u_{tox}} \) and \( u \) are shown in the Appendix.

Though it is possible to simply use Eq. (1) at regular intervals for MBC, the negligence of the dynamics hinders stable high-gain feedback. The MBC response can be either too slow or unstable.

Therefore, the MBC system should be designed as a stable one with high-gain feedback by using a dynamic model of the plant.

2.2.2. Dynamic Model

By combining the static model with the dynamic property of the plant, the dynamic model is constructed. Considering the strip travel delay and the AGTC response, the dynamics of the plant are approximated to a first-order lag which corresponds to the slowest dominant response of the plant. \( T_{m&c} \) denotes the time constant. The dynamic model is described by the following state equations.

\[ \dot{x}_{m&c} = Ax_{m&c} + Bu \]  \hspace{1cm} (2)

\[ y_{m&c} = C \cdot x_{m&c} \]  \hspace{1cm} (3)

where

\[ A = - \frac{1}{T_{m&c}} \cdot I \]  \hspace{1cm} (38×38 elements)  \hspace{1cm} (4)

\[ B = \frac{1}{T_{m&c}} \cdot A_{u_{tox}} \]  \hspace{1cm} (38×8 elements)  \hspace{1cm} (5)

In Eqs. (3) and (4), \( x_{m&c} \) is chosen to include all rolling state variables so that the model can also be applied to other types of AGC systems without tension control.

2.3. Design of MBC System Using ILQ Method

Since the TCM with the AGTC system is a multivariable system with complex interaction, the MBC system must be designed by one of the multivariable control theories.

Therefore, the ILQ design method for optimal servo systems is applied. Along with an optimality guarantee, the ILQ method has advantages such as a decoupling property and easy tuning with a few parameters. Since the dynamics of the TCM with the AGTC system are approximated to a first-order lag, there is no unstable “zero” and the ILQ method can be applied.

Figure 3 shows the block diagram of the MBC system based on the ILQ design method. \( K_i \) and \( K_i \) are gain matrices whose sizes are 8×38 and 8×8 respectively, and \( \Sigma \) is a diagonal matrix whose elements \( \sigma_i \)'s \((i=1, 2, \cdots, 8)\) adjust the norms of \( K_i \) and \( K_i \). The \( \sigma_i \)'s are tuning parameters and are easy to tune unlike the conventional LQ design method.

In order to satisfy the decoupling condition, the size of the output vector \( y_{m&c} \) must be the same as that of the control input \( u \), namely “8”. Now, the elements of \( y_{m&c} \) are selected so that the influence of the disturbance can be dispersed to all the stands as explained below.

There are a variety of disturbances, e.g. variations of the incoming strip in gage and hardness. Without the MBC, a few motor currents or rolling forces may be changed to a large extent (Fig. 4(a)) since the influence of the disturbance tends to concentrate on specific stands. Therefore, in order to disperse the influence of the disturbance to all the stands and especially to reduce the influence at the final stand, the 8 elements of \( y_{m&c} \) are selected as follows:

\[ \begin{align*}
1 & \Delta G_1 \left( \begin{array}{c}
G_1 \\
G_3
\end{array} \right) \\
\frac{1}{5} & \Delta G_2 \left( \begin{array}{c}
G_2 \\
G_4
\end{array} \right) \\
\frac{1}{5} & \Delta G_3 \left( \begin{array}{c}
G_2 \\
G_4
\end{array} \right)
\end{align*} \]

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There are a variety of disturbances, e.g. variations of the incoming strip in gage and hardness. Without the MBC, a few motor currents or rolling forces may be changed to a large extent (Fig. 4(a)) since the influence of the disturbance tends to concentrate on specific stands. Therefore, in order to disperse the influence of the disturbance to all the stands and especially to reduce the influence at the final stand, the 8 elements of \( y_{m&c} \) are selected as follows:

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G_1 \\
G_3
\end{array} \right) \\
\frac{1}{5} & \Delta G_2 \left( \begin{array}{c}
G_2 \\
G_4
\end{array} \right) \\
\frac{1}{5} & \Delta G_3 \left( \begin{array}{c}
G_2 \\
G_4
\end{array} \right)
\end{align*} \]
This selection indicates that the influence of the disturbance are dispersed to all the stands in the ratio of 5:5:5:5:1 and the variations of the motor current and the rolling force relating to the final stand are suppressed within small values (Fig. 4(b)).

The gain matrices \( K_0 \) and \( K_i \) in Fig. 3 are calculated according to the ILQ design method7) for the case where entry gage is 3.2 mm, finish gage 0.711 mm, and \( T_{indc} \) is 2.0s.

All the tuning parameters \( \sigma_i \)'s are increased up to 0.05. They are determined so that the MBC response is about 10 times slower than the plant response.

As a result, the MBC system, which guarantees optimality and stability, is obtained.

\[
K_0 =
\begin{bmatrix}
0.000 & -0.000 & -0.437 & 0.359 & 0.068 & 0.011 & -0.004 \\
0.000 & -0.000 & -0.364 & -0.302 & 0.567 & 0.101 & -0.008 \\
0.000 & -0.000 & -0.318 & -0.219 & -0.295 & 0.587 & 0.013 \\
0.000 & -0.000 & -0.022 & -0.014 & -0.003 & -0.0004 & 0.196 \\
0.000 & -0.000 & 2.568 & -2.130 & -0.372 & -0.066 & 0.006 \\
0.000 & -0.000 & 2.485 & 1.374 & -3.254 & -0.599 & -0.025 \\
0.000 & -0.000 & 2.286 & 1.238 & 0.208 & -3.691 & -0.205 \\
0.000 & -0.000 & 0.000 & 0.0095 & 0.012 & 0.003 & -1.547 \\
\end{bmatrix}
\]

\[
K_i =
\begin{bmatrix}
-0.042 & -0.058 & 0.036 & 0.057 & 0.035 \\
0.008 & -0.151 & -0.012 & 0.136 & 0.093 \\
0.034 & -0.043 & -0.100 & 0.085 & 0.123 \\
0.003 & -0.001 & -0.005 & -0.006 & 0.047 \\
-0.421 & 0.548 & -0.007 & -0.106 & -0.071 \\
-0.474 & -0.355 & 0.813 & 0.028 & -0.058 \\
-0.452 & -0.379 & -0.056 & 0.875 & -0.055 \\
-0.048 & -0.060 & -0.035 & -0.036 & 0.894 \\
\end{bmatrix}
\]

3. Experimental Results

The MBC has been applied to an actual process. Without the MBC, as Fig. 5 shows, the rolling speed is decreased manually when a motor current exceeds its rated

\[
C =
\begin{bmatrix}
0.0 & 0.0 & 0.2 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.2 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.2 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & -0.2 & 0.0 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & -0.2 & 0.0 & 0.0 \\
0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.2 & -1.0 \\
\end{bmatrix}
\]

This selection indicates that the influence of the disturbance
value. At first, the No. 2 motor current is greater than its rated value 8000 A due to the setup model error. In order to decrease the No. 2 motor current for safety, the rolling speed is reduced by a mill operator.

In Fig. 6, with the MBC, the desired motor currents of No. 2, No. 3 and No. 4 stands are properly changed automatically into the average of the three motor currents.

At first, the No. 3 motor current is about 8300 A and exceeds its rated value due to the setup model error. Then the references of the stand exit gages except the final gage and interstand tensions are operated by the MBC. The No. 3 stand exit gage reference is increased by almost 40 μm and the No. 2–3 interstand tension reference is decreased by almost 40 kN. As a result, No. 3 motor current is controlled under the rated value.

The influence of the disturbance is dispersed to all the stands, and the rolling forces are kept almost constant. In the experiments, the steepness of the rolled strip was 0.6% and there was no strip shape defect.

Furthermore, since the response of the MBC is slower than that of the AGTC so as to avoid interference between the two control loops, the strip gage accuracy under the MBC is maintained, as is shown in Fig. 6.

In this way, the MBC compensates the setup model error during the rolling, and it is possible to obtain strips with desired gage and desired shape without decreasing the rolling speed.

4. Concluding Remarks

The MBC system for the TCM has been newly developed.

The MBC not only maintains the finish gage accuracy but also controls the distribution pattern of the motor currents and the rolling forces.

The MBC system was constructed by adding a new control loop to the AGTC system. The MBC controller was designed using the ILQ method, and it was applied to an actual TCM.

The experimental results were as follows.

(1) The motor currents were controlled under their rated values without decreasing the rolling speed. As a result, the MBC system was able to maintain high productivity even if the setup control was inappropriate due to the model error.

(2) The rolling forces were kept almost constant, and there was no strip shape defect.

(3) The finish gage accuracy was maintained compared with the cases where the MBC was not applied.

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Appendix. Static Model of TCM with AGTC System

The elements of $x_{\text{m&c}}$ and $u$ are shown as follows.

$$
x_{\text{m&c}} = \begin{bmatrix} \Delta h_0, \Delta h_1, \Delta h_2, \Delta h_3, \Delta h_4, \Delta h_5, \\
q_0, \Delta q_1, \Delta q_2, \Delta q_3, \Delta q_4, \Delta q_5, \\
\Delta v_1, \Delta v_2, \Delta v_3, \Delta v_4, \Delta v_5, \\
\Delta N_1, \Delta N_2, \Delta N_3, \Delta N_4, \Delta N_5, \\
\Delta U_1, \\
\Delta P_1, \Delta P_2, \Delta P_3, \Delta P_4, \Delta P_5, \\
\Delta G_1, \Delta G_2, \Delta G_3, \Delta G_4, \Delta G_5 \end{bmatrix}
\tag{A-1}
$$

$$
u = \begin{bmatrix} \Delta h_1, \Delta h_2, \Delta h_3, \Delta h_4, \\
q_1, \Delta q_1, \Delta q_2, \Delta q_3, \Delta q_4, \Delta q_5 \end{bmatrix}
\tag{A-2}
$$

Each "*" shows a non-zero value.