PASS SCHEDULE OPTIMIZATION FOR A TANDEM COLD MILL


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Abstract: Pass schedules for a tandem cold mill affect not only the uniformity quality and productivity of rolled strips but also the operation safety. This paper describes pass schedule optimization, which consists of two stages. One is robust pass schedule optimization (RPSO) before rolling, which optimizes pass schedules under distributions in strips' properties and rolling conditions. The other is mill balance control (MBC) during rolling, which slowly changes the pass schedules to cope with remaining distributions and unpredictable during-rolling variations. Results with an actual mill showed an 8% decrease in off-gage length and a 2.4% increase in maximum rolling speed without deterioration in gage accuracy. Copyright © 2005 IFAC

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1. INTRODUCTION

A tandem cold mill (TCM) is one of the plants in the steel works, which rolls a strip from initial gage to final gage in order to produce high surface-quality strips. Specifically, the mill is composed of several stands as shown in Fig.1, and the strip is reduced in gage by the stands' rolling forces and interstand tensions which are dependent on a pass schedule. The pass schedule, which designates the combination of reductions in gage at all stands and all interstand tensions in this paper, is crucial for proper rolling. There have been a number of attempts to improve the pass schedules (Okado, et al., 1969), but there has been no attempt to optimize the pass schedules taking account of the distributions and variations in strips' properties and rolling conditions.

In this paper, pass schedule optimization with two stages is considered. One is robust pass schedule optimization (RPSO) before rolling, and the other is mill balance control (MBC) during rolling at constant rolling speeds. The outline of pass schedule optimization is described in chapter 2. The RPSO and the MBC are illustrated in chapter 3 and chapter 4 respectively.

2. OUTLINE OF PASS SCHEDULE OPTIMIZATION

Figure 1 shows a 5-stand tandem cold mill. In cold rolling, the rolling forces of the first and last stands as well as motor currents are important to achieve safe

![Fig. 1. Tandem cold mill](image)

![Fig. 2. Pass schedule optimization which consists of robust pass schedule optimization and mill balance control](image)
operation and good strip quality. Here, a type of automatic gage control system with interstand tension control, which has recently become a trend, is assumed, and it is referred to as automatic gage and tension control (AGTC) hereafter.

Figure 2 shows the outline of pass schedule optimization. First, prior to the rolling, the RPSO calculates each pass schedule for its corresponding group of strips and sets them as initial values of stand exit gages and interstand tensions. Then, during the constant-speed rolling, the MBC operates the stand exit gages and interstand tensions to regulate rolling forces and motor currents. The MBC is constructed as a cascade control system by adding a new control loop to the AGTC loop.

3. ROBUST PASS SCHEDULE OPTIMIZATION

3.1 Outline of robust pass schedule optimization

Firstly, the RPSO is considered which is the first stage of pass schedule optimization. Usually, the strips to be rolled are classified into groups depending on the initial gages, the final gages, the widths and the hardnesses of the strips, and each group has its own pass schedule in a table. Here, the values of a pass schedule, i.e. the values of reductions and interstand tensions, can be arbitrarily determined because only the values of the initial and the final gages are fixed.

In general, the determination of pass schedules is done in consideration of the uniformity quality and productivity of the rolled strips and safety operation. The reason is that the reductions and interstand tensions affect the rolling forces and motor currents at the stands and these values affect the quality, productivity, and operation safety. For example, inappropriate rolling forces can cause poor shape quality and snaking of the rolled strip, and inappropriate motor currents can cause motor damage and mill operation stoppage in the worst case. Moreover, manual adjustments to change the inappropriate reductions and interstand tensions can increase the off-gage length of the rolled strips. These are the facts that are taken into account when designing a pass schedule.

Conventionally, some pass schedules are designed based on prior good pass schedules which were arrived at empirically by mill operators, and others are designed based on numerical optimization methods (Okado, et al., 1969). However, in recent years, the required quality of the steel strips is becoming higher, demand for productivity is becoming stronger, and safety operation is becoming more important than ever. And, the distributions in strips’ properties and rolling conditions are becoming not negligible. Therefore it is becoming more difficult for conventional methods to determine appropriate pass schedules.

Accordingly, a new pass schedule design method has been developed as a robust optimization problem which utilizes a rolling model. The utilization of the model enables not only quantitative evaluation of interactions and tradeoffs of the rolling variables but also quick redesign of pass schedules when rolling conditions such as the mill entry tension are changed. Moreover, the robustness for distributions of strip properties and rolling conditions is taken into consideration since the strips of the same group are not exactly the same in size, hardness and rolling condition. This is achieved by identifying the distribution from past rolling data and introducing reliability based constraints (Thanedar, 1991) with the sigmoid function.

In this way, the pass schedules are optimized to minimize the effect of the rolling variables’ distributions, and each strip starts to be rolled based on the pass schedule of its group.

3.2 Model

The rolling force and the motor current at No.i stand (hereafter referred to as No.i motor current ditto for other variables) are modelled as follows (Hirano, et al., 1984):

\[
P_i = P_i(H_i, H, h_i, q_i, q_k, k, \mu, w) \quad (i = 1, \ldots, 5) \tag{1}
\]

\[
G_i = G_i(H_i, h_i, q_i, q_k, k, \mu, w) \quad (i = 1, \ldots, 5) \tag{2}
\]

where \( P_i \): rolling force, \( G_i \): motor current, \( H_i \): stand entry gage, \( h_i \): stand exit gage, \( q_i \): front tension, \( q_k \): back tension, \( k \): deformation resistance, \( \mu \): friction coefficient, \( w \): strip width.

3.3 Optimization using Sequential Quadratic Programming method considering robustness

The performance index and constraints are determined as follows:

\[
\begin{align*}
\text{minimize} & \quad \sum_{j=1}^{N_{all}} f_j(x) \\
\text{such that} & \quad \text{Prob}(g_k(x) \geq 0) = \frac{N(g_k(x) \geq 0)}{N_{all}} \\
& \quad = \frac{\sum_{j=1}^{N_{all}} \text{signf}(g_k(x), a_k)}{N_{all}} \geq R_k \\
& \quad (k = 1, \ldots, M) \tag{4}
\end{align*}
\]

where \( N_{all} \): the number of previously-rolled strips of a group under concern, \( f_j(x) \): part of performance index corresponding to j-th strip, \( x \): an \((8 \times 1)\) vector of the pass schedule variables, \( \text{Prob}(.) \): probability, \( g_k(x) \): k-th constraint function, \( N(.) \): the number of strips which satisfy the k-th constraint, \( \text{signf}(.) \): the sigmoid function, \( a_k \): a parameter of the sigmoid function, \( R_k \): an approximate reliability, \( M \): the number of constraints.
Here, since the constraint functions must be differentiable so that the problem is solvable by the Sequential Quadratic Programming (SQP) method (Ibaraki, et al., 1991), the sigmoid function is used. Because of this, a reliability $R_i$ is treated as an approximate value and the optimization problem is solved in an approximate manner.

The details of the variables and functions are determined mostly from the operators’ empirical knowledge as follows:

$$\mathbf{x} = \begin{bmatrix} h_1, h_2, h_3, q_{11}, q_{12}, q_{21}, q_{22} \end{bmatrix}$$

$$r_i = \frac{H_i - h_i}{H}$$

$$J_i(x) = \sum_{j=1}^{4} \alpha_j (r_{ij} - r_{ij,0})^2 + \sum_{j=1}^{4} \beta_j (p_{ij} - p_{ij,0})^2$$

$$+ \sum_{j=1}^{4} \gamma_j (G_{ij} - G_{ij,0})^2$$

$$g_i(x) = p_{ij} - p_{ij,0} \quad (8), \quad g_i(x) = \overline{p_{ij}} - p_{ij,0} \quad (9)$$

$$g_i(x) = p_{ij} - p_{ij,0} \quad (10), \quad g_i(x) = \overline{p_{ij}} - p_{ij,0} \quad (11)$$

$$g_i(x) = p_{ij} - p_{ij,0} \quad (12), \quad g_i(x) = \overline{p_{ij}} - p_{ij,0} \quad (13)$$

$$g_i(x) = G_{ij} - G_{ij,0} \quad (i = 1, \ldots, 5) \quad (14)$$

$$g_{i2}(x) = p_{ij} - p_{ij,0} \quad (15)$$

$$g_{i12}(x) = G_{ij} - G_{ij,0} \quad (i = 1, \ldots, 5) \quad (16)$$

$$g_{i2}(x) = r_{ij} + \Delta r_{ij} - r_{ij,0}$$

$$g_{i2}(x) = r_{ij} + \Delta r_{ij} - r_{ij,0}$$

$$\text{signf}(b, a) = \frac{1}{1 + \exp(-ab)} \quad (21)$$

where

$r$: reduction in gage, $p$: rolling force per unit width ($P/w$), $r_{ij}$: No.i rolling value of j-th strip, $p_{ij,0}$: No.i desired rolling value of j-th strip, $\alpha_i, \beta_i, \gamma_i$: weights, $\Delta r_{ij}$: desired difference between No.i and No.i+1 stand reductions.

Eqs. (3), (7) mean that a new pass schedule is obtained near the desired one. Eqs. (4), (8) - (21) mean that the new pass schedule satisfies the constraints on a probabilistic basis. The approximate reliabilities $R_i$’s are determined by decreasing them until the optimal solution is obtained.

### 3.4 Application of robust pass schedule optimization

Figure 3 shows actual rolling data before and after a robust optimal pass schedule is applied to one group of strips. Firstly, subfigures (1-1) and (1-2) show that the root mean square errors (RMSE) of No.1 rolling forces and No.5 rolling forces were decreased from 1.74 to 0.73 and from 0.84 to 0.75 [kN/mm] respectively so that strips can be rolled in good shape without snaking.

Here, the thick solid lines indicate desired rolling forces, and the thin solid lines indicate desired upper limits and lower limits. As is shown, the number of strips whose No.1 currents are increased to be greater than 0 [A] to achieve safe operation. And the No.2, No.3 and No.4 motor currents are changed to be close to each other so that the maximum motor current becomes low and allows a margin to increase the rolling speed. As is shown in subfigures (3-1) and (3-2), the above-mentioned changes are achieved by increasing No.1 reductions and decreasing No.2 and No.5 reductions.

![Fig. 3. Rolling data before (*)-1 and after (*)-2 a robust optimal pass schedule is applied](image1)

![Fig. 4. Effects of robust optimal pass schedules](image2)
Figure 4 shows that gap operation and roll speed operation by operators and other automatic control compensations have been reduced. As a result, the off-gage length was decreased by 8 [%].

4. MILL BALANCE CONTROL

4.1 Outline of mill balance control

Secondly, the MBC is considered which is the second stage of pass schedule optimization. In principle, if the pass schedule is appropriate and there is no disturbance, changing it is not necessary. However, in reality, there exist the above-mentioned distributions, so rolling forces and motor currents can be inappropriate. Furthermore, there exist disturbances such as hardness variation and friction coefficient variation, so rolling forces and motor currents can change for the worse during the rolling.

Conventionally, an inappropriate pass schedule is modified by operators’ manual adjustments or by a simple static single-shot compensation (Okamura, et al., 1999). However, due to the interaction among the rolling variables, it is difficult to determine how to change the pass schedule, i.e. which variables of reductions and interstand tensions to operate and how much to operate them. Moreover, if the pass-schedule change is quick and large, the gage accuracy can be deteriorated.

Accordingly, a new on-line pass schedule changing method to regulate the rolling forces and motor currents is developed as multivariable control. Hereafter, all the rolling forces and motor currents are referred to as “mill balance”, and the control of the mill balance by changing a pass schedule is referred to as “mill balance control (MBC)”. The control law is designed based on an ILQ design method (Fujii, 1987, 1994), which is a design method of LQ regulators and was developed by reverse application of pertinent results on the inverse regulator problem. An ILQ control law requires no Riccati solutions, and it is obtained in an explicit form regulator problem. An ILQ control law requires no Riccati solutions, and it is obtained in an explicit form.

The MBC controls a plant which consists of the mill and the AGTC system. The model of the plant is derived as simply as possible with a view to applying the MBC. Specifically, firstly, a static model of the plant is derived from the rolling theories (Hirano, et al., 1984), and they are linearized around a steady rolling state. As a result, the static model is described as follows:

\[
\dot{x}_{\text{str}} = A_{x_{\text{str}}} \cdot u
\]  

where

\[
x_{\text{str}} = \begin{bmatrix} \Delta P_1 & \Delta P_2 & \Delta P_3 & \Delta P_4 & \Delta P_5 & \Delta P_6 & \Delta P_7 \\ \Delta G_1 & \Delta G_2 & \Delta G_3 & \Delta G_4 & \Delta G_5 & \Delta G_6 & \Delta G_7 \\ \end{bmatrix}^T
\]

\[
\Delta h_1 \Delta h_2 \Delta h_3 \Delta h_4 \Delta h_5 \Delta q_1 \Delta q_2 \Delta q_3 \Delta q_4
\]

\[
\begin{bmatrix} \Delta h_1 & \Delta h_2 & \Delta h_3 & \Delta h_4 & \Delta h_5 & \Delta q_1 & \Delta q_2 & \Delta q_3 & \Delta q_4 \\ \end{bmatrix}^T
\]

and \(A_{x_{\text{str}}}\): influence coefficient matrix, \(\Delta P\): rolling force deviation, \(\Delta G\): motor current deviation.

Next, 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. \(T_{\text{str}}\) denotes the time constant of the dominant response. The dynamic model is described by the following state equations:

\[
\dot{x}_{\text{str}} = A \cdot x_{\text{str}} + B \cdot u
\]

\[
y_{\text{str}} = C \cdot x_{\text{str}}
\]

where

\[
A = \frac{-I}{T_{\text{str}}}
\]

\[
B = \frac{I}{T_{\text{str}}} \cdot A_{x_{\text{str}}}
\]

and \(I\): a unit matrix, \(y_{\text{str}}\): an \((8 \times 1)\) output vector, \(C\): an arbitrary \((8 \times 10)\) matrix.

The matrix \(C\) is determined so that the variations of the important rolling variables at the final stand are dispersed to the upstream stands.

\[
C = \begin{bmatrix} 0.2 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & -0.2 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & -1.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \\ 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 & 0.0 \end{bmatrix}
\]
4.3 Design of MBC

Feedback control based on the ILQ design method

Figure 5 shows the block diagram of the MBC system based on the ILQ design method. $K_r^o$ and $K_t^o$ are gain matrices, and $\Sigma$ is a diagonal matrix whose elements $\sigma$’s adjust the norms of $K_r^o$ and $K_t^o$. The $\sigma$’s are tuning parameters.

For the case where the initial gage is $4.2$ mm, the final gage is $1.01$ [mm], and the time constant $T_{dcl}$ is $1.0$[s], the coefficient matrix is

$$A_{x_{s_{1-4}}x_{s_{1-4}}} =
\begin{bmatrix}
-1.73 & 0.00 & 0.00 & 0.01 & -0.10 & 0.00 & 0.00 & 0.01 \\
0.50 & -0.99 & 0.00 & 0.01 & -0.21 & -0.11 & 0.00 & 0.00 \\
0.00 & 0.74 & -1.04 & 0.00 & 0.00 & -0.20 & -0.11 & 0.00 \\
0.00 & 0.00 & 0.00 & 1.02 & 0.00 & 0.00 & -0.19 & -0.30 \\
0.00 & 0.00 & 0.00 & 0.48 & 0.00 & 0.00 & 0.00 & 0.00 \\
-9.59 & 0.00 & 0.00 & 0.18 & -1.58 & 0.00 & 0.00 & 0.00 \\
2.67 & -3.30 & 0.00 & 0.16 & 0.59 & -0.57 & 0.00 & 0.00 \\
0.00 & 3.19 & -3.67 & 0.16 & 0.00 & 0.00 & -0.59 & 0.04 \\
0.00 & 0.00 & 1.29 & -1.64 & 0.00 & 0.00 & 0.54 & -0.55 \\
0.00 & 0.00 & 0.00 & 7.12 & 0.00 & 0.00 & 0.00 & 0.39
\end{bmatrix}$$

And the gain matrices are obtained in explicit form as follows:

$$K_r^o = T_{dcl} \cdot \left[C \cdot A_{x_{s_{1-4}}x_{s_{1-4}}} \right]^T \cdot C$$

$$K_t^o = T_{dcl} \cdot \left[C \cdot A_{x_{s_{1-4}}x_{s_{1-4}}} \right]^T \cdot \text{Diag} \left( \frac{1}{T_{dcl}} \right)$$

where $\sigma_i$ ($i=1,\ldots,8$) and another tuning parameter $T_{dcl}$ ($i=1,\ldots,8$) were tuned to be 0.05 and 10.0[s] respectively. These values are determined so that the MBC response is slow and do not deteriorate final gage accuracy.

Addition of feedforward compensation

The above-mentioned feedback control of the MBC is suitable for suppression of slowly changing rolling forces and motor currents. However, when the variations of rolling variables such as motor currents exist from the beginning, they should be changed more quickly as long as final gage accuracy is maintained. For this reason, feedforward compensation in ramp form is added, as shown in Fig.5.

$$G_{rr} = \left[C \cdot A_{x_{s_{1-4}}x_{s_{1-4}}} \right]^T$$

4.4 Application of MBC

Motor current regulation

The MBC has been applied to an actual process. Without the MBC, as Fig.6 shows, the rolling speed is decreased manually when a motor current exceeds its rated value $8000$ [A]. At first, the No.2 motor current is greater than its rated value due to the remaining distributions and during-rolling variations. In order to decrease the No.2 motor current for safety, the rolling speed is reduced by a mill operator.

In Fig.7, with the MBC mentioned in 4.3, 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 by the MBC as an example. At first, the No.3 motor current is about $8000$ [A] and exceeds its rated value. Then the references of the stand exit gages except the final gage and interstand tensions are controlled under the rated value.

Furthermore, the rolling forces are kept almost constant. Besides, 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.7.

In this way, the MBC compensates the remaining distributions and during-rolling variations, and it is possible to avoid decreasing the rolling speed while maintaining gage uniformity.
Rolling force regulation

Without the MBC, as Fig.8 shows, there were cases where the No.5 rolling force increased by during-rolling disturbances such as hardness variations. In contrast, with the MBC, Fig.9 shows that the No.5 rolling force stops increasing. The influence of the disturbance is dispersed to all stands, and the rolling forces are maintained almost constant. In the experiments, the steepness of the rolled strip was 0.6[%] and there was no strip shape defect.

In this way, with the MBC, it is possible to obtain strips with desired shape through the rolling without manual adjustments.

Feedforward compensation

The feedforward compensation is added in ramp form for 5[s] after the MBC begins to work. Figure 10 shows the result where the MBC was turned on in the middle of a constant speed rolling. The No.3 motor current decreased by almost 100 [A], and the No.4 motor current increased almost 100[A] while maintaining the final gage accuracy. When putting the MBC to practical use, the changes of motor currents are limited to 300 [A]. Figure 11 shows that the mean maximum rolling speed increased by 2.4 [%] while maintaining strip quality.

5. CONCLUSIONS

A new pass schedule optimization method, which consists of robust pass schedule optimization and mill balance control, was developed. The pass schedules are robustly optimized prior to the rolling in consideration of distributions, and they are refined during the rolling by the ILQ-design-method based mill balance control. The rolling forces and the motor currents were maintained in optimal condition through the rolling. The results with an actual mill showed an 8% decrease in off gage length and a 2.4% increase in maximum rolling speed without deterioration in gage accuracy.

REFERENCES


