Decoupling of Multiple Stand Interactions in Looperless Rolling Control Process

G. Li1  F. Janabi-Sharifi   L. Witnisky*
Department of Mechanical, Aerospace & Industrial Engineering
Ryerson University, Toronto, On M5B 2K3, CANADA
guominli@hotmail.com   fsharifi@ryerson.ca
* Quad Engineering Inc., Toronto, On M3B 2R2, CANADA

1 Previous address: Department of Automation, Tianjin University, China

Abstract
Control of hot metal rolling process plays an important role in assuring high product quality and safe process operation. However, looperless interstand tension control remains a hard-to-solve problem due to strong interactions of adjacent rolling stands. This paper proposes a novel decoupling strategy to address this problem. Incorporating the proposed method with fuzzy control theory, an intelligent multiple stand tension control system is realized. Results from a virtual rolling test demonstrate the effectiveness and applicability of the proposed decoupling strategy.

Keywords: Interaction, Decoupling, Hot metal rolling, Looperless rolling, Complex systems, Intelligent control.

1. Introduction
Hot metal rolling mill is a key steel processing facility in many steel plants. A typical hot rolling mill usually consists of a number of rolling stands. These stands are aligned in line and often separated into three different groups. They are called roughing, intermediate and finishing sub-mills respectively. Different long products with various cross-sectional profiles, such as strips or bars, are produced based on the principle of multistage shaping.

To maintain a stable, safe and high quality process operation, the speed of a rolled strip leaving a previous stand is required to be identical to its entry speed into the adjacent downstream stand. If these two speeds differ, a longitudinal force will result inside the rolled billet between the spanned stands. This force, generally called interstand tension, can introduce variations to the thickness and/or width of the billet, thus deteriorating the product quality. In extreme cases, the excessive tension may break the product or the rolled strip may fly away and damage surrounding facilities or even injure involved human beings.

In most finishing mills, therefore, a looper [1] is usually formed intentionally between each two adjacent roll stands to buffer speed mismatches. The control task then turns to maintaining a suitable looper height. The interstand tension becomes negligible due to the formation of the looper and the lightweight of the bent thin strip.

Loopers, however, can hardly be applied to intermediate rolling mills and cannot be applied to roughing rolling processes because of the size and hardness of the billets passing through there.

Many advanced control techniques have recently been developed for looper control, such as H-inf control [4], optimal looper control [5], and intelligent looper control [6]. However, looperless interstand tension control remains a very tough problem and appeals for increasing research efforts [2]. The reason is that there exists a strong interaction between each two adjacent rolling stands and it is also difficult to appropriately model a rolling process for the purpose of control system design. Current practice is usually to employ a human operator who manually controls the tension by a repetitive watch-and-correct procedure.

This paper proposes a decoupling strategy to deal with the aforementioned multiple stand interactions. The proposed method employs a cascade control and a sequential interval control to make the tension controller for each interstand zone equivalently independent. Incorporating the proposed strategy with a fuzzy tension control scheme [3, 8], a multiple stand intelligent tension control system was implemented. A virtual rolling test was conducted to evaluate the developed strategy. Some test results are given to show the effectiveness and applicability of the proposed decoupling technique.

2. Looperless Rolling and Interstand Interaction
Fig. 1 shows a mill segment containing three stands and two looperless interstand zones. An interstand zone is a physical area of the mill between two adjacent roll stands and it conveys the billet from the previous stand to the next stand in rolling direction. If the strip between Stands N-1 and N leaves Stand N-1 at a speed different from that it enters Stand N, there will occur an interstand tension in Zone N-1. Similarly, there will exist an interstand tension in Zone N if the strip between Stands N and N+1 leaves Stand N and enters Stand N+1 at two different speeds.
There is no explicit or easy way to control the strip speeds. A mill control system usually realizes its control over strip speeds through applying an adequate control to the motor speed of each stand. Apparently, the roll peripheral speed of a stand is in general not equal to either the entry speed of the upstream strip or the exit speed of the downstream strip due to the deformation existent at each stand.

If there is no speed mismatch between the exit and entry speeds of a strip segment, the roll speed of its downstream stand is said to be matched perfectly with that of the upstream stand. The ratio of the downstream stand speed to the upstream stand speed is therefore called an ideal R-Factor. Clearly, the ideal R-Factor between two specified stands is not usually known and may vary with the change in rolling conditions, such as the changes of size and temperature of a rolled billet.

Since ideal R-Factors in a rolling mill are usually unknown and may be changing from time to time, the stand speeds often do not match perfectly. The goal of tension control system is then to continuously adjust the motor speeds of all stands in a way such that the actual R-Factors are as close to as possible, ideally, identical to, the ideal R-Factors. Apparently, the interstand tension is an indicator of a non-ideal R-Factor.

There are two interstand zones around a specified stand except for the first and finishing stands. They are called backward (upstream) zone and forward (downstream) zone respectively. For a specified interstand zone, its tension can be removed by adjusting the motor speed of either its upstream or downstream stand. Usually, the upstream adjustment scheme is employed. For example, with reference to Fig. 1 the tension in interstand zone N is controlled through applying a correction to the motor speed of Stand N.

Unfortunately, the correction applied to the speed of Stand N will induce a speed mismatch between Stands N and N-1 and thereby cause a further speed dynamics to Stand N. This type of interstand interactions makes the tension control dynamics of backward and forward zones of Stand N highly coupled with each other. It is this type of coupling that has made the tension control of roughing and intermediate rolling mills a very difficult problem and has greatly prevented the development of looperless interstand tension control technology.

For any given Stand i, one can easily derive a dynamic equation of the motor speed as

\[
J_i \frac{d\omega_i}{dt} = -k_{f,i} \omega_i + T_{q,i} - T_{r,i} - R_i (F_{f,i} + F_{b,i})
\]

Where
\[
\omega_i \quad \text{-- Roll speed of Stand } i
\]
\[
T_{q,i} \quad \text{-- Electrical torque of Stand } i \text{ referred to work roll}
\]
\[
T_{r,i} \quad \text{-- Rolling force produced torque}
\]
\[
F_{b,i} \quad \text{-- Backward tension}
\]
\[
F_{f,i} \quad \text{-- Forward tension}
\]
\[
k_{f,i} \quad \text{--Viscous friction coefficient of Stand } i
\]
\[
J_i \quad \text{-- Moment of inertia of Stand } i
\]
\[
R_i \quad \text{-- Effective roll radius of Stand } i
\]

In general, the dynamic behavior of any interstand segment of strip can be modeled as a serious of lumped masses, springs and dampers [7]. Assume that the end speeds of each segment are slow varying variables and the viscous damping is negligible. The backward and forward tensions of Stand i can be expressed as [3, 7]

\[
\frac{dF_{f,i}}{dt} = k_{s,i} (v_{i,\text{out}} - v_{i+1,\text{in}})
\]

\[
\frac{dF_{b,i}}{dt} = k_{s,i-1} (v_{i,\text{in}} - v_{i-1,\text{out}})
\]

Where
Both entry and exit speeds of the billet at Stand i are dependent on the roll speed of the stand and the deformation process under that stand. They can be conceptually expressed as

\[ v_{i,in} = (1 + s_{f,i})R_i \omega_i \]  \hspace{1cm} (4)

\[ v_{i,out} = (1 - s_{b,i})R_i \omega_i \]  \hspace{1cm} (5)

Where \( s_{f,i} \) and \( s_{b,i} \) are uncertain forward and backward slips defined by

\[ s_{f,i} = \frac{v_{i,out} - R_i \omega_i}{R_i \omega_i} \]

\[ s_{b,i} = \frac{R_i \omega_i - v_{i,in}}{R_i \omega_i} \]

Substituting Eqs. (4) and (5) into Eqs.(2) and (3) and combining with Eq. (1) yield

\[
\begin{align*}
J_i \frac{d\omega_i}{dt} &= -k_{x,i} \omega_i + T_{g,i} + T_{r,i} - R_i (F_{f,i} + F_{b,i}) \\
\frac{dF_{f,i}}{dt} &= k_{x,i}[(1 + s_{f,i})R_i \omega_i - (1 - s_{b,i})R_{i+1} \omega_{i+1}] \\
\frac{dF_{b,i}}{dt} &= k_{x,i-1}[(1 - s_{b,i})R_i \omega_i - (1 + s_{f,i-1})R_{i-1} \omega_{i-1}]
\end{align*}
\]

Equation (6) reveals clearly that the interstand tensions make the speed and tension dynamics of a stand highly coupled with those of both its upstream and downstream stands. Therefore, interstand tension control is a highly coupled multivariable control problem in essence.

3. Decoupling Strategy

Due to multivariable behavior of Eq. (6), multivariable control theory seems a quite straightforward method to cope with looperless tension control of roughing and intermediate rolling mills. However, there are two major hurdles against the success in such an attempt.

Firstly, the dimension of the state equation governing the dynamics of a complete mill is almost three times the number of stands. A typical mill often contains 5-10 roughing and intermediate rolling stands. Therefore, the looperless tension control system might be of over 15 dimensions. That will be certainly a highly complex control problem.

Secondly, both forward and backward slips in Eq. (6) are dependent on the metal deformation at their associated stand. Metal deformation is a very complicated process and it is often very difficult to model. As a result, looperless tension control is also an ill-defined control problem. Due to the high dependency of multivariable control methods on the obtainment of a well-defined mathematical model, multivariable tension control is therefore hardly possible in practice without further advancement in rolling process modeling.

Single variable control is widely used in industrial systems nowadays due to its simplicity and relative ease in design, tuning and commissioning. In addition, single variable control is less dependent on the precision of the obtained plant model. In order to simplify the above control problem and to design an individual SISO tension controller for each interstand zone, an adequate decoupling strategy must be first developed to remove the stand interactions.

Metal rolling is a sequential and periodical process. That is, the rolled billet passes through roll stands sequentially and one billet follows another. The proposed decoupling strategy is based on this important feature of the process. Its basic idea is to control the interstand tension sequentially (one by one zone) and at interval, instead of simultaneously and continuously.

3.1 Sequential interval control

Usually, a controller takes effect all the time once it is put into use. Interval control means that the controller works periodically in such a way that it is put into effect for a certain period of time and then paused for another span of time while maintaining its previous internal states.

It is noted that the maintaining of internal controller states and their transferring from one work interval to another play an important role in the success of interval control. The time interval when the controller is in effect is not necessarily to be kept equal from one cycle to another.

Sequential control implies that the tension controllers for all interstand zones are sequentially activated one by one. That is, first put into use is the tension controller for interstand zone 1, then tension controller for interstand zone 2, and so on. The controller for the last interstand zone is activated at last.

With combined sequential interval control as illustrated in Fig. 2, it can be observed from Eq. (2) that the controlled variable of the tension controller for interstand zone i, i.e., the forward tension \( F_{f,i} \), is solely governed by the roll speed of Stand i during the in-effect interval of the controller. In other words, the interaction between Stands \( i+1 \) and i becomes null.
3.2 Cascade control

With cascade control, the roll speeds of all upstream stands are changed accordingly when the roll speed of a downstream stand is being corrected by its tension controller so that the induced speed change of each upstream stand is proportional to that of its adjacent downstream stand.

Let 
\[ r_i = \frac{\bar{\omega}_{i+1}}{\bar{\omega}_i} \]
be the ideal R-factor between Stand i+1 and Stand i where \( \bar{\omega}_i \) and \( \bar{\omega}_{i+1} \) are perfectly matched roll speeds of Stand i and Stand i+1. The speed correction generated by the tension controller of Stand i is cascaded upstream in the way such that

\[ \Delta \omega_{i-1} = \frac{\Delta \omega_i}{r_{i-1}}, \quad \Delta \omega_i = \frac{\Delta \omega_j}{r_j} \]  \hspace{1cm} (7)

If the roll speed of Stand i is already in perfect match with the roll speed of Stand i-1 before the tension controller for Stand i starts to correct its forward tension, the cascade control will ensure that this correction would not introduce any backward tension. That is, Eq. (3) becomes null and \( F_{b,i} \) can be removed from Eq. (1).

Because the ideal R-factors are usually unknown, cascade gains of Eq. (7) are calculated based on the scheduled R-factors in practice. The scheduled R-factors are product specific and are initially computed from Mass Conservation Principle. Also, it is hardly possible to bring the tension of an interstand zone to zero at one control interval. Hence, the above assumption cannot be strictly met. However, it is reasonable in practice to assume that the backward tension \( F_{b,j} \) is a constant during the correction interval of the tension controller for Stand i.

Cascade control can approximately remove the interaction between a stand and its adjacent upstream stand whereas sequential interval control is able to fully remove the interaction between a stand and its downstream stand. Therefore, with the proposed decoupling strategy, the tension controller for each interstand zone can be designed independently.

4. Multiple Stand Looperless Tension Control System

Shown in Fig. 3 is a schematic of a fuzzy multiple stand looperless tension control system employing the proposed decoupling strategy. In practice, it is part of a rolling mill control system responsible for the control of five roughing rolling stands. The complete mill contains sixteen rolling stands with five for roughing, three for intermediate and eight for finishing sub-mills.

For five roughing rolling stands, there are five individual tension controllers required, each allocated for one interstand zone. In a dominant majority of rolling mills, there is an automatic speed regulator (ASR) built in each stand drive for speed control of that stand. Hence, the electrical torque in Eq. (6) is not assessable to any tension controller. Instead, each tension controller will generate a correction to the reference speed of a roll stand. In the upstream correction scheme, that will be the correction to the reference speed of the upstream stand.

Based on the proposed decoupling strategy, a supervisory decoupling control layer is designed to carry out following two main tasks: to control the timing of all tension controllers in accordance with the position of the moving billet and to generate necessary cascaded speed corrections for all stands. The supervisory decoupling control layer needs billet tracking signals and speed corrections for its operation.

The ASR built in each stand drive receives the reference speed from process control system. The reference speed is the summation of the scheduled RPM (base speed), tension control correction and cascaded correction. The scheduled base speed comes from a specified production schedule. A production schedule prescribes the start-up speeds of all stands for a specific product to be rolled. In ideal case, these speeds are close to the perfectly matched speeds for that specified product.
Fig. 3  Schematic of fuzzy multiple stand tension control system

Table 1: Initial and (final) motor speeds and interstand tensions

<table>
<thead>
<tr>
<th>Stand/Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand Speed (RPM)</td>
<td>130 (125)</td>
<td>109 (115)</td>
<td>220 (226)</td>
<td>300 (292)</td>
<td>295 (302)</td>
</tr>
<tr>
<td>Interstand Tension (PSI %)</td>
<td>40.2 (0)</td>
<td>-17.6 (0)</td>
<td>-23.0 (0)</td>
<td>-239.6 (0)</td>
<td>-205.4 (0)</td>
</tr>
</tbody>
</table>
Due to ill-defined tension dynamics, fuzzy theory is employed in designing each tension controller. The interstand tension is inferred from the change of the motor armature current of the upstream stand. It is not difficult to understand that the difference of motor armature current between before and after the billet hits on the next downstream stand indicates an occurrence of a forward interstand tension. Hence, if the armature current is maintained at its value of before the billet hits on the downstream stand, the forward tension is controlled to zero. Refer to authors’ previous works [8] for details on the design of each FTC.

All controllers including the supervisory decoupling control layer are implemented in a PLC based mill control system.

A virtual rolling test was conducted to evaluate the implemented multiple stand fuzzy tension control system. A speed mismatch was intentionally generated for the test. The selected production schedule has a finishing speed of 800FPM (feet per minute). The initial billet size is 5.5 in² and the product size is 0.75 in². Table 1 shows the intentionally disturbed startup speeds of five roughing stands and the tension at each interstand zone after the first billet has been rolled.

The multiple stand tension control system coordinately controls the interstand tension of each interstand zone in a repetitive and interval mode. After 5 billets, all interstand tensions are brought to very insignificant values. After 18 billets, all interstand zones are brought to near tension-free status. Table 1 also gives the final motor speeds and interstand tensions (data enclosed in the brackets).

Fig. 4 shows the armature current and motor speed responses of the selected Stand 5. It is not easy to discriminate the actual response from its reference in the either left or right figure. Note that the current impacts (sharp rising impulses in the left figure) while the billet is hitting on the controlled stand or its downstream stand are inevitable in the rolling process and not handled by the mill control system.

The current reference of a stand represents the armature current of that stand in the forward-tension-free status. It is not fixed until the backward zone of the stand also becomes tension-free, as shown in the left figure.

From the speed responses, one can see that the stand speed is automatically adjusted to make its own match the speed of its downstream stand. The instantaneous speed drop and rise (sharp lighter impulses in the right figure) occurring while the strip is hitting on or leaving the stand are unavoidable and not controlled by the tension control system. There is a leading speed compensation (short darker impulses) that is designed to reduce the speed drop to an acceptable extent.

5. Conclusion

Looperless interstand tension control of roughing and intermediate rolling mills remains a hard-to-solve problem due to strong multiple stand interactions. This paper proposes a sequential interval-cascade decoupling strategy to decouple tension interactions. With a supervisory control layer based on the proposed novel decoupling strategy, the tension controller for each interstand zone can be designed independently. This is a significant breakthrough to the control of looperless rolling process. Test results on a virtual rolling mill demonstrate the effectiveness and applicability of the proposed technique. The designed intelligent multiple stand tension control system is being applied to a real bar mill.

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References


