Abstract

In steel rolling industry, control of hot metal rolling process plays an important role in assuring high product quality and safe process operation. Although many advanced looper control technologies for finishing rolling processes have emerged, looperless interstand tension control of roughing rolling mills remains a challenging problem. This paper proposes a multistand fuzzy tension control system for a roughing rolling mill. Combined with a novel decoupling strategy, the proposed scheme makes it possible to realize intelligent tension-free control of multiple roughing rolling stands. The results from a virtual rolling test demonstrated the applicability and effectiveness of the proposed technique.

Keywords: Fuzzy Control, Hot Metal Rolling, Complex Systems, Process Control, Virtual Reality

1. Introduction

Hot metal rolling mill is a key steel processing facility in steel plants. A typical hot rolling mill usually consists of a roughing rolling sub-mill, an intermediate rolling sub-mill and a finishing sub-mill, each of which contains various number of rolling stands. Different long products with various cross-sectional profiles, such as strips or bars, are produced on the principle of multistage shaping. That is, the cross-section of a billet or slab is reduced step by step under high pressure while it is passing through each mill stand such that the final product would meet dimensional and mechanical specifications.

If the strip entry speed at a roll stand differs from its exit speed from the previous stand, a longitudinal force will result inside the rolled billet between these two stands. This force, generally called interstand tension, will cause a push or pull action of the rolled steel, introducing variations in gauge (thickness and/or width) of the product and thus deteriorating the product quality. In an extreme case, the excessive tension may break the product or/and damage the machinery. Therefore, it is very necessary to control the interstand tension to achieve a safe, stable and high quality rolling process [1].

In most finishing mills, a looper [4] is usually formed intentionally between each two adjacent roll stands to buffer the speed mismatch between stands. The tension control is converted into maintaining a suitable looper height. With successful looper control, the interstand tension is then often negligible due to the formation of the looper and the lightweight of the bent thin strip.

Many advanced control techniques have recently been developed for looper control, such as non-interference control (NIC) [5], Optimal looper control [6], H-inf control [5, 7], and intelligent looper control [8, 9]. However, looper scheme cannot be employed in roughing and intermediate rolling mills. Looperless interstand tension control remains a challenging problem [2]. The top two obstacles are the unavailability of suitable process modeling and the strong interstand interactions between adjacent rolling stands. Current practice is usually to rely on a human operator who manually controls the tension occurring at each interstand zone by a watch-and-correct procedure. Due to high skills required and possible inconsistencies, high product quality cannot be achieved in this way.

This paper reports a multistand fuzzy tension control system for a roughing rolling mill. Combined with a novel decoupling strategy [3], the proposed scheme makes it possible to separate interstand interactions and realize intelligent tension-free control of multiple roughing rolling stands. To verify the developed control strategy, a virtual reality based system test was conducted. Test results are given to show the effectiveness and applicability of the proposed scheme.
2. Rolling mill and virtual reality

A typical hot rolling mill usually consists of a number of roll stands. All roll stands are arranged in alignment and they are often categorized into roughing, intermediate and finishing stands. Fig. 1 shows a general composition of a rolling mill containing 8 roll stands.

A roll stand is typically composed of a housing structure, a pair of work rolls, a pair of back rolls, a gearbox, a motor, a motor drive and a closed loop automatic speed regulator (ASR) for the drive.

The roll drive system of a stand is able to fully control the roll speed of the stand but unable to fully govern the speed of the strip through that stand. The dynamical relationship between the motor speed and the mass entry and exit speeds is highly nonlinear and dependent on the complicated deformation process. It is for this reason that obtaining a suitable model for tension control system design is usually very difficult.

A rolling mill is usually continuously operated on 24-hours basis. Any unscheduled or prolonged process-down could result in a significant loss of plant revenue. Furthermore, any inappropriate operation of the mill may cause serious personal injury and/or property damages. These features of rolling mills prevent the development and utilization of new control technologies. Therefore, virtual reality is then a good solution to control system development. A virtual mill [10] can be employed as a testbed for both control system design and evaluation. It can also serve as a tool to train operators without requirement of exposure to the real plant, which avoids possible harm to involved human beings and damage to mill equipment resulting from any inappropriate operation.

Shown in Fig. 2 is a schematic of the virtual rolling mill employed in this study. It is primarily composed of a virtual mill simulator (VMS), a mill master control system (MCS) and a human machine interface (HMI) facility.

VMS is to simulate the complex dynamics of a real mill consisting of 5 roughing rolling stands, 3 intermediate rolling stands and 8 finishing rolling stands. Although highly ordered, nonlinear, coupled and imprecise process models are not suitable for control system design, they are very useful in process simulation and numerical analysis.

The information exchange in the virtual rolling mill is completed through a MB Plus network. The MCS and HMI can be switched to serve the real rolling mill through a soft switching between aforementioned two signal interfaces of MCS to the real mill or the VMS. It is for this reason that the virtual reality technology becomes increasingly useful.
3. Multiple interstand fuzzy tension control

For 5 roughing rolling stands, there are 5 interstand zones appealing for tension control. Since the tension results equivalently from the speed mismatch of the upstream and downstream stand driving motors, it is possible to control (reduce or eliminate) the interstand tension by correcting the motor speed of either upstream or downstream stand.

Interstand tension affects the dynamics of both upstream and downstream stands. This makes the multiple interstand tension control a strongly coupled and highly ordered problem. The more the rolling stands, the more complex the control problem. Apparently, each interstand zone cannot be individually controlled well without a suitable decoupling strategy.

The rolling dynamics of each stand is highly nonlinear and difficult to model due to the complex metal deformation process. Intelligent fuzzy control is then a good candidate to deal with such a nonlinear and imprecise problem.

Shown in Fig. 3 is a schematic of the proposed fuzzy multiple interstand tension control system. To ensure a constant product speed, the upstream speed correction scheme is used. For each stand, there are 3 controllers of different type. They are cascade controller (CC), interval controller (IC) and fuzzy tension controller (FTC). All these controllers are implemented in the PLC based MCS. Instead, the automatic speed regulator (ASR) is built in the speed drive system of each stand. The process control is through the correction of the reference speed applied to each ASR.

3.1. Cascade controller (CC) and interval controller (IC)

The combination of cascade controller and interval controller is the means to physically decouple the multiple-stand interactions caused by the interstand tension.

The cascade controller is to apply proportionally a correction to the speed drive of its upstream stand while the speed of this stand is being corrected. The purpose is to eliminate the interaction between the regulated stand and its adjacent upstream stand by means of avoiding the introduction of an extra...
change to the backward tension of the regulated stand.

The interval controller is to periodically control the switch-in and switch-out of the fuzzy tension controller so as to remove the interaction caused by the forward tension between the stand being regulated and its adjacent downstream stand.

### 3.2. Fuzzy tension controller

Interstand tension can be either sensed through installation of load cells or derived from other detected physical variables [11]. Therefore, tension control can be classified into direct and indirect schemes.

Due to physical limitations in most rolling mills, the interstand tension in the proposed system is indirectly inferred through detecting the motor armature current. That is, the indirect current comparison method [11] is employed for achieving tension control. The difference of the armature current between before and after the billet hits on the next downstream stand indicates the occurrence of a forward interstand tension. If the armature current is controlled to trace its value before the billet hits on the downstream stand, the forward tension will be brought to zero.

Fuzzy tension controller takes both the difference and the change in difference of the armature current between before and after the billet hits on the downstream stand as inputs. It emulates human operator and bases on a Mamdani and Sugeno-type fuzzy reasoning to generate a correction signal for the motor speed of the upstream stand.

Let $e_i$ stand for the current difference between the forward-tension-free current and the actual armature current of the $i$-th stand, $\Delta e_i$ the change in the current difference and $\Delta v_i$ the correction to the reference speed of the ASR of the $i$-th stand. The controller output for each stand can be expressed as

$$
\Delta v_i = \frac{k_{e,i} \sum_j w_j \cdot \mu_{i,j}^e (k_{e,i} \cdot e_i) \cdot \mu_{i,j}^{\Delta e} (k_{\Delta e,i} \cdot \Delta e_i)}{\sum_j \mu_{i,j}^e (k_{e,i} \cdot e_i) \cdot \mu_{i,j}^{\Delta e} (k_{\Delta e,i} \cdot \Delta e_i)}
$$

$i = 1, \ldots, 5$

where

- $k_{e,i}$, $k_{\Delta e,i}$, $k_{v,i}$ ----- Current error, change of error and speed correction scaling factors
- $\mu_{i,j}^e$, $\mu_{i,j}^{\Delta e}$ ----- Input membership mappings
- $w_j$ ----- Output fuzzy singletons

Five triangular membership functions are selected for the current difference (Error), three membership functions for the change of difference (Change of Error) and seven symmetrical fuzzy singletons are chosen for the output speed correction (Output). These membership functions are defined as follows. Error: NB [-1, -1, -0.6, -0.3], NS [-0.6, -0.3, 0], Z [-0.3, 0, 0.3], PS [0, 0.3, 0.6], PB [0.3, 0.6, 1, 1]; Change of Error: N [-1, -1, -0.5, 0], Z [-0.5, 0, 0.5], P [0, 0.5, 1, 1]; Output: NB [-0.75], NM [-0.5], NS [-0.25], Z [0], PS [0.25], PM [0.5], PB [0.75]. The rule base contains fifteen rules as shown in Table 1. The scaling factors are selected as $k_{e,i} = 0.4$, $k_{\Delta e,i} = 1.5$, and $k_{v,i} = 0.1$.

The control algorithms of Eq. (1) are digitally implemented in Modicon PLC programs.

<table>
<thead>
<tr>
<th>Output</th>
<th>Error</th>
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<tbody>
<tr>
<td>NB</td>
<td>NS</td>
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<tr>
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<td>NB</td>
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<td>P</td>
<td>NB</td>
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### 4. Virtual rolling test

An initial mill setup prescribing the reference speed of each roll stand is usually designed to establish a theoretically “perfect” speed-matching condition based on the Conservation of Mass principle and stand parameters for each production schedule. Such a mill setup is a necessity for the process startup although it cannot realize perfect speed matching in reality due to complicated deformation dynamics and other external disturbances.

Interstand tension results from speed mismatch. To evaluate on the virtual rolling mill the multiple-stand fuzzy tension control system, a speed mismatch is therefore generated for each interstand zone before rolling. This was done by bringing the motor speed of the upstream stand away from the selected initial mill setup.

The selected production schedule has a finishing speed of 800FPM (feet per minute). The initial billet size is 5.5 in$^2$ and the product size is 0.75 in$^2$. Table 2 shows the intentionally disturbed startup speed of each roughing stand and the tension at each interstand zone after the first billet has been rolled.
The tension control system coordinates 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 a tension-free status. Table 2 also shows the final speeds of roughing stands and the final values of interstand tensions (data in the parentheses).

To evaluate the transient performance of the control system, Figs. 4 and 5 show the overall armature current and motor speed responses of the selected stands 4 and 5. The response curves are for 20 rolled billets. Fig. 6 is an enlarged view of partial responses of Stand 5 for the last 5 billets. It can be seen that the armature current of each stand traces well its reference value after a few billets. Note that the current impacts while the billet is hitting on or leaving the controlled stand or hitting on its downstream stand are inevitable in the rolling process and not handled by the control system.

The current reference of a stand represents the armature current of that stand in the forward-tension-free status. It is sampled for every billet and may include a backward tension. Hence, the current reference is not fixed until all interstand zones become tension-free as seen in Figs. 4 and 5.

From the speed responses, one can see that the stand reference speed is automatically adjusted to make its own match the speed of the downstream stand. The instantaneous drop and rise of actual speed occurring while the strip is hitting on or leaving the controlled stand are unavoidable and not controlled by the tension control system. There is a leading speed compensation designed to reduce the speed drop from stand impact to an acceptable extent. One can clearly see the speed auto-adjustment process from the first half of the enlarged partial speed response of Fig. 6.

5. Conclusion

Looperless interstand tension control of roughing rolling mills remains a hard-to-resolve problem. This paper proposes a successful multis tand fuzzy tension control system for a roughing rolling mill. Test results on a virtual rolling mill show that the proposed technique has made it possible to realize a satisfactory multiple stand tension control of roughing rolling process.

<table>
<thead>
<tr>
<th>Stand/Zone</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
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<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>-177.6 (0)</td>
<td>-250 (0)</td>
<td>239.6 (0)</td>
<td>-205.4 (0)</td>
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Table 2: Initial and final motor speed and interstand tension

Acknowledgement

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References

Fig. 4  Overall current and speed responses of Stand 4

Fig. 5  Overall current and speed responses of Stand 5

Fig. 6  Enlarged partial current and speed responses of Stand 5