Mass Flow Control for Intercritical Rolling in Hot Mills

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1. Introduction

This paper describes the technological advances being made in hot strip mill controls to improve the mass flow stability by exploiting accurate mathematical models of the rolling process to estimate the strip hardness, gauge and using the primary mill actuators of gap and speed in a coordinated fashion.

Intercritical hot rolling is a problem for gauge control quality but it is a more serious problem for controlling the mass flow between stands and enabling the mill to continue rolling. The challenges to mill stability are illustrated from results showing the effects of a material phase change before the last stand in a mill.

The essential interactions in a hot mill are described to motivate the control architectures now being used. A typical conventional scheme is initially described followed by the advancements made in strip hardness estimation and multivariable control leading to an industrial solution for mills where phase changes are expected to occur between stands.

Fig. 1 shows two stands of a mill, the roll force is used to control the exit gauge via the gap while the looper angle is controlled using the upstream stand work roll speed. The job of the looper is to store strip between stands during periods when the exit mass flow from one stand does not match the entry mass flow to the next. It must also maintain the interstand strip tension using the torque applied to the looper arm via a motor or cylinder.

![Figure 1: Two stands of hot strip mill with main control loops.](image-url)
2. Phase Changes & Mass Flow Instability

Fig. 2 shows results from a 6 stand finishing mill, rolling an interstitial-free product. A phase change occurs between stands 5 and 6 and we can see that this corresponds to the mill exit temperature dropping below 900 deg. A decrease in temperature due to the incoming skid chills has triggered the transformation from austenite to ferrite with a corresponding larger drop in temperature and decrease in hardness [1]. An increase in mill entry temperature takes the mill back to austenitic rolling.

The gauge control on the last stand sees the roll force drop and hence the roll gap opens to compensate for the mill stretch. Despite the gauge control the gauge at the X-ray still shows a large deviation which corresponds with the estimated material hardness getting softer during the phase change. More worrying is the large movement on the last looper which reacts to the strip entry speed to the last stand decreasing by rising up. This coil managed to be rolled successfully but there was still a risk of a cobbles.

These results illustrate the challenges facing mills today. Controlling the mass flow is essential to preventing cobbles and maintaining efficient production. While gauge control is relatively mature, designing and implementing controllers that understand the complex interactions in a mill is still progressing.

![Figure 2: Phase change occurring in last interstand of 6 stand hot strip mill.](image-url)
3. Hot Strip Mill Interactions

It is worth while looking at the interactions between gauge, hardness and mass flow using mathematical models which are also required to be used internally inside the dynamic control. The linear equation obtained from a nonlinear roll force model for the strip force $P$ is a function of the entry gauge $H$, exit gauge $h$ and entry hardness $k$:

$$\Delta P = \frac{\partial P}{\partial H} \Delta H + \frac{\partial P}{\partial h} \Delta h + \frac{\partial P}{\partial k} \Delta k = R\Delta H - Q\Delta h + N\Delta k$$

The $R$, $Q$, $N$ sensitivities are calculated by a Level 2 model and are essential in a modern automation systems. The exit gauge $h$ depends on the mill modulus, $M$ obtained from a mill stretch experiment, roll force $P$ and roll gap $S$:

$$\Delta h = \Delta S + \frac{\Delta P}{M}$$

Combining the two equations we obtain:

$$\Delta h = \frac{R}{M + Q} \Delta H + \frac{M}{M + Q} \Delta S + \frac{N}{M + Q} \Delta k$$

$$\Delta h = \alpha \Delta H + \beta \Delta S + \gamma \Delta k$$

The equations describe small changes around the operating point which is usually the mill setup. The mass flow is conserved through the stand with entry speed $V$, exit speed $v$ and assuming the strip width is constant:

$$vhVH = \Delta$$

With the sensitivities around the setup point $[v, v, H, \alpha, \beta, \gamma]$ of entry speed to exit and entry gauge being:

$$\frac{\partial V}{\partial h} = \frac{v}{h} = \frac{V}{h} \quad \text{and} \quad \frac{\partial V}{\partial H} = \frac{v}{H} \frac{\partial h}{\partial H} = \frac{v}{H} \frac{h}{H} = \frac{V}{h} \frac{\alpha}{H}$$

Therefore the strip entry speed is function of entry gauge, entry hardness and gap:

$$\frac{\Delta V}{V} = \left(\frac{\alpha}{h} - \frac{1}{H}\right) \Delta H + \left(\frac{\beta}{h}\right) \Delta S + \left(\frac{\gamma}{h}\right) \Delta k$$

The change in entry speed is a disturbance to the upstream looper which is regulating the length of strip between the stands and the strip tension. From a gauge point of view the roll gap is the primary actuator. Increasing the gap will increase the exit gauge from the stand and increase the entry speed which in turn will pull the tension in the upstream interstand tighter and pull the looper down. The length of strip (which is a function of looper angle) between the stands depends on the integrated speed difference between the exit speed of the upstream stand and the entry speed to the downstream stand:

$$L = L_0 + \int (v_{i-1} - V_i) dt = func(\theta)$$
Apart from exit slip $f$ we have good control of the upstream exit speed, $v$ via the main drive, $\omega$ with work roll radius $R$:

$$v = (1 + f)R\omega$$  \hspace{1cm} (8)

For the entry speed we have partial control via the gap and some control of the upstream exit gauge which is now the entry gauge and little control of the entry hardness. Disturbances to the mass flow affect the ability of the looper to maintain strip storage between stands and also affect strip tension which can change the strip dimensional quality and also propagate to other mill stands via changes to roll force and torque.

4. **Gauge & Mass Flow Control**

**Conventional Scheme with Mass Flow Compensation**

Automatic Gauge Control [2] has two main functions – to bring the strip onto target gauge as quickly as possible if the head-end setup is not perfect, and to hold it there by compensating for disturbances as the coil is rolled. This must be accomplished without undue looper movement and with minimum disruption to the stand loading pattern.

The primary weapon in the AGC armoury is the gaugemeter, which estimates the gauge out of each stand from the measured gap and force (Equ. 2), and adjusts the gap to hold it at reference. Sensitivities from the Level 2 setup are used to guarantee consistently fast gaugemeter response for every product rolled. The standard General Electric hotmill automation has the Level 2 closely integrated with the AGC to provide the model data required to make the AGC optimal for all products rolled. This also reduces commissioning time.

Fig.3 illustrates the local stand functions of gaugemeter (GM), looper height control (LHC) and mass flow compensation (MFC). Also shown are some of the global functions such as feed-forward control, X-ray feedback control. The LHC takes the measured looper angle, calculates the interstand strip length and trims the upstream work roll speed. The strip tension is controlled by the looper arm motor torque. On a mill with hydraulic capsules the fast acting GM will disturb the upstream looper which is controlled by the slower main drive. To enhance the stability of the looper, MFC is required which is a feed-forward trim to the upstream main drive. The conventional MFC method is to use an estimate of how the entry speed changes due to the estimated exit gauge change due to the gap movement, which is only one of the three terms in Equ. 6:

$$\frac{\Delta v_{ref}}{v_{ref}} \approx \left( \frac{\beta_i}{h_i} \right) \Delta S_i$$  \hspace{1cm} (9)

The upstream MFC speed reference is proportional to the downstream gap. While this is relatively straightforward to implement is does have performance drawbacks in that we are only compensating for the gap movement and not the entry gauge and hardness variations which also disturb the looper.
Hardness Estimation and Enhanced Mass Flow Compensation

GE advocates an enhanced method of MFC which aims to compensate for all terms in Equ. 6 in particular the strip hardness. The exit gauge error from a stand can be estimated using the mill stretch, Equ 2. which can be tracked to the entry of the next stand to provide an estimate of the entry gauge. We still require an estimate of the entry hardness which can be obtained by rearranging Equ. 3 and using the exit gauge estimated from our current stand, the fed forward exit gauge estimate from the upstream stand and the gap feedback on the current stand.

\[ \gamma \Delta h_i = \Delta h_i - \alpha \Delta H_i - \beta \Delta S_i \]  \hspace{1cm} (10)

The hardness estimate from one stand can be fed forward to the next stand where it is updated with the new information obtained from the current stand. This update of hardness estimate is performed using a Kalman Filter [3] to ensure the optimal mixing of information as we proceed along the mill. During the delay from one stand to the next we need to consider the temperature loss and how that affects the entry hardness. While it looks straightforward to rearrange this equation, the successful application of it requires accurate tracking of the strip, optimal filtering of the signals and accurate model parameters from an adaptive Level 2 system [4]. The filtering is critical since the speed reference should be a smooth signal but we cannot afford any phase lag which will be detrimental to the performance of feed-forward control. The upstream speed reference from the MFC is now:

\[ \frac{\Delta v_{i+1}^{ref}}{v_{i+1}} = \left( \frac{\alpha}{h} - \frac{1}{H} \right) \Delta H_{i+1}^{ref} + \left( \frac{\beta}{h} \right) \Delta S_i + \left( \frac{1}{h} \right) \gamma \Delta k_{i+1}^{ref} \]  \hspace{1cm} (11)

The MFC can now compensate for all disturbances that affect the looper by calculating an accurate MFC speed trim using Equ. 6. GE have around 15 years of implementing this function using High Performance Controllers (HPC) and as you would expect the improvements to mill stability have been achieved of mills which large hardness variations. Results in Fig. 5 show the improved looper angle control with the enhanced MFC.
Figure 4: HSM finishing mill control with enhanced mass flow compensation.

Figure 5: Result from conventional and enhanced MFC.

Multivariable Control

So far we have discussed using the mill actuators of gap and speed to control gauge and mass flow separately. To compensate for the strong interaction, MFC has been used as a feed-forward control to attempt to decouple gauge and mass flow in particular for hardness disturbances. With the processing power available in modern controllers and accurate models of the mill we can progress to using the
mill actuators in a co-ordinated fashion i.e. multivariable control [5]. As well as using the upstream speed to control the looper we can also use the downstream gap to directly control the entry speed.

The scheme with MFC can be written as:

\[
\begin{bmatrix}
\text{Speed Trim} \\
\text{Gap Trim}
\end{bmatrix} = 
\begin{bmatrix}
\text{LHC} & \text{MFC} \\
0 & \text{GM}
\end{bmatrix} 
\begin{bmatrix}
\text{Looper Angle} \\
\text{Estimated Exit Gauge}
\end{bmatrix}
\]

And with multivariable control combined with the hardness estimator as:

\[
\begin{bmatrix}
\text{Speed Trim} \\
\text{Gap Trim}
\end{bmatrix} = 
\begin{bmatrix}
\text{MVS} & \text{MFC} \\
\text{MVG} & \text{GM}
\end{bmatrix} 
\begin{bmatrix}
\text{Looper Angle} \\
\text{Estimated Exit Gauge}
\end{bmatrix} + 
\begin{bmatrix}
\text{MFC} \\
0
\end{bmatrix} \text{[Entry Hardness & Gauge]}
\]

The gains of the MVS and MVG controllers are again calculated using the model sensitivities to be optimal for all products. Using the gap to improve the mass flow control comes with the trade off that the gauge control may deteriorate. The objective is to preserve mill stability and keep the coil rolling during dramatic events such as phase changes occurring in the finishing mill. Fig. 6 shows that the hardness estimator is still essential to providing the MFC feed-forward trim to speed. The individual controllers do not operate in isolation since they share information. The diagram does not show the many connections between the dynamic control and the Level 2 computer.

GE have obtained trial rolling results (Fig. 7) showing how the combined use of speed and gap can reduce the looper angle variation since the gap controlled with a hydraulic capsule will be higher bandwidth than the speed controlled with the main drive. As a demonstration a reference change is made to the looper angle which is controlled only using the downstream gap.

Figure 6: HSM Finishing Control with Multivariable Control to Gap and Speed.
5. **Industrialized Solution**

Consideration has to be given to when we may wish to use the control loop from loop length to gap. It can be seamlessly enabled when large looper movements are detected or it can be pre-enabled if we think there is a risk of a phase occurring in a particular interstand zone. Being able to predict a phase change is linked to having a good estimate of the absolute strip temperature throughout the mill and knowledge of the strip chemistry. GE use an online dynamic model to predict the temperature at multiple zones throughout the finishing mill as part of the temperature control using interstand sprays and mill speed [6]. Fig. 8 shows a comparison between the conventional controls and the multivariable control reacting to a simulated phase change. The multivariable control is quicker to move the gap to minimise movement in the looper with the trade-off that the gauge deviation lasts longer. With the conventional control there is a large drop in the looper angle when the strip hardness decreases.

The combination of mass flow compensation using a strip hardness estimator, the use of gap and speed for multivariable control of gauge and mass flow along with integrated Level 2 dynamic models provides the technology for mill control that can cope with phase changes in the finishing mill. This technology has now been industrialized and is ready for deployment.

![Figure 7: Looper with conventional and multivariable control, only controlled using gap.](image)

![Figure 8: Looper with conventional and multivariable control, only controlled using gap.](image)
6. Conclusions

It is essential for mill stability and throughput that the dynamic controls can cope with mass flow disturbances from gauge and hardness changes that are incoming as well as hardness changes within the mill due to material phase changes.

GE have been continually developing the HSM dynamic control to exploit today's high performance controllers and the model information available from an integrated Level 2.

Being able to accurately estimate the strip hardness at each stand in the mill during rolling, predict the likelihood of a phase change and exploiting the interactions between roll gap and speed to improve the mass flow control are essential to HSM controls that are robust to such events as phase changes.

7. References
