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Model-Based Feedforward for Cooling of Steel Strips in a Hot Strip Rolling Mill

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I. INTRODUCTION

In a hot strip rolling mill, steel slabs are reduced to thinner strips, heated beyond the crystallization temperature, and then cooled, to achieve enhanced material properties, e.g., with regard to grain structure and porosity. The result is a higher-quality steel with improved mechanical properties. In the cooling section, the steel strips are cooled by spraying the strips with water through nozzles, where the water is pressurized by a pump. The flow of water is controlled by individual valves for each nozzle section. A schematic view of the cooling section is shown in Fig 1.

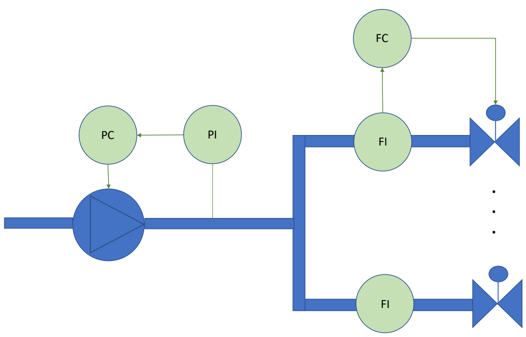

Fig. 1. Schematic overview of the cooling section with pumps, nozzles, sensors (FI, PI) and controllers (FC, PC).

For the process in the case study, a supervisory control layer delivers recipes with cooling water flow rates for optimal cooling, and the regulatory layer is responsible for controlling the flow rates and pressure to match the recipe. Fast and accurate regulatory control is essential for high production rates and material quality, where faster control means that the time between steel strips with different steel grades can be reduced. To avoid large changes in the control signals a circulation flow can be used, with the price of a lower energy efficiency.

The control problem is challenging due to the batch-like operation, with strong physical coupling and nonlinearities, where the physical coupling impacts the possibility of using high-gain feedback control. The setpoint recipes from the supervisory control span over a large range of flow rates and corresponding pressure operating points, making linearization around operating points problematic. The physical coupling is shown as a block diagram in Fig. 2.

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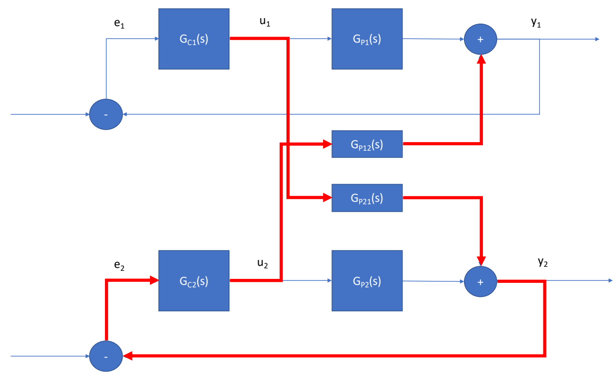

Fig. 2. Block diagram of the physical coupling between the flow of two cooling nozzle sections, where G_{Ci} denotes the flow controller, G_{Pi} denotes the nozzle section, and G_{Pij} the coupling between the nozzle sections.

Common ways to deal with the presented control problems are decoupling or combining feedforward and feedback control [1], where the latter was used for the case study.

II. METHOD

For the case study, a model-based feedforward approach was used, where the pressure setpoint was calculated from the flow setpoints, valve curves, and the affinity laws for pumps [2]. The model mismatch was handled by feedback control, and the pressure was kept as low as practically possible to achieve the best energy efficiency. A challenge with feedforward control in a highly nonlinear process is to avoid reliance on measuring every possible operating point.

The problem was reduced to finding the valve curves and the relation between pump speed and flow rate at a nominal pressure increase for the pump, given a maximum valve opening O_{max}. By algebraic transformations of the well-known affinity laws, a general expression for the pump speed was calculated. The affinity laws for volumetric flow rate Q, pressure rise H and pump speed n is

$$\left(\frac{Q_{sp}}{Q_{nom}}\right) = \left(\frac{n}{n_{nom}}\right) \tag{1}$$

$$\left(\frac{H_{sp}}{H_{nom}}\right) = \left(\frac{n}{n_{nom}}\right)^2 \tag{2}$$

where the subscript nom denotes the nominal value and sp the setpoint. Combining the equations and rearranging gives that

$$H_{sp} = H_{nom} \left(\frac{Q_{sp}}{Q_{nom}} \right)^2 \quad (3)$$

$$n = n_{nom} \sqrt{\left(\frac{H_{sp}}{H_{nom}} \right)} \quad (4)$$

and hence that the feedforward pump speed and pressure setpoint at *any* valid operating point only requires the estimation of $n_{nom} = f(Q_{nom})$ and $Q_{nom} = f(O_{max})$ at *one* pressure operating point H_{nom}, that can be approximated from relatively few measurements. Using the feedforward approach, the PI controllers could be tuned less aggressively compared to the pure feedback approach.

III. Results

Practical tests showed a reduction in consumed pumping power by 60% while reaching process values within 10% of the setpoint within 10 seconds, a significant reduction of the settling time from feedback control without feedforward. Resulting flow rates before and after feedforward was applied are seen in figures 3 and 4, where the controllers in both cases were tuned using internal model control-based tuning rules.

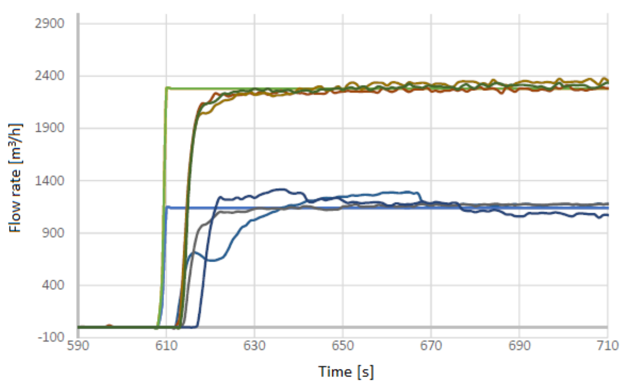

Fig. 3. Setpoints and flow rates with traditional feedback control after tuning.

The main limiter of control performance was the relatively slow valve actuation. The control strategy has been operating for several years without issues.

IV. Summary and Conclusions

In the industry abstract, an industrial implementation of a feedforward control strategy based on the affinity laws is presented, and validated in a real process. While relatively simple in its approach, the strategy is built on knowledge of the physics and the process, controller tuning methods, and control theory. The results showed improved control performance with significant energy savings. With the proposed approach, the model has to recalibrated manually on a regular basis due to, e.g., wear and tear. In the future, an adaptive calibration method could provide more convenience for operators and engineers alike.

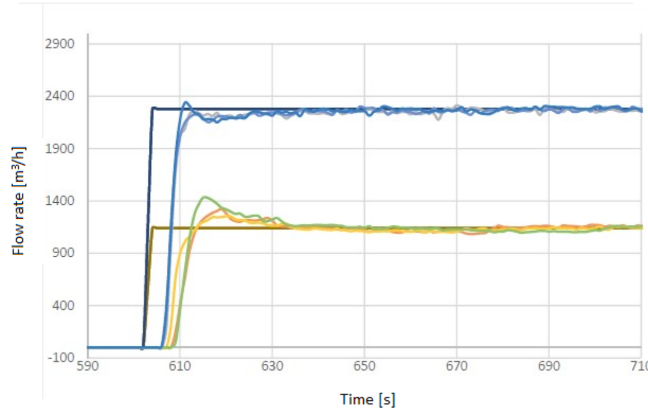

Fig. 4. Setpoints and flow rates with model-based feedforward control after tuning.

References

[1] Karl J. Åström (2006) *Advanced PID Control*, ISA - Instrumentation, Systems and Automation Society.
[2] Henrik Alvarez (2006) *Energiteknik*, Studentlitteratur.