Feedforward control of lateral asymmetries in heavy-plate hot rolling using vision-based position estimation

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Abstract: This paper presents a feedforward control concept for lateral asymmetries in heavy-plate hot rolling. A lateral off-center plate position generally entails asymmetric rolling forces, asymmetric mill stretch, and thus a wedge-shaped exit thickness that may cause a cambered plate contour and a rotatory motion of the plate. In this paper, a model of the mill stand and of the plate movement is presented. The model demonstrates that the plate movement in the reversing mill can be unstable and may cause the plate to collide with the mill housing in the worst case. The developed control concept makes use of the measurement of the shape and the position of the plate by an infrared camera. The controller compensates asymmetric deflections of the two sides of the mill stand associated with laterally asymmetric rolling forces caused by an off-centered plate position. Both simulations and long-term operation results at an industrial rolling mill confirm the robustness of the proposed control concept and show an improvement of the accuracy of the plate contour.

Keywords: Steel industry, Model-based control, Feedforward control, Image processing

1. INTRODUCTION

In heavy-plate hot rolling, the thickness of a plate is reduced at a reversing mill stand in consecutive rolling passes. The primary goals are to achieve the required accuracy of the plate thickness and a rectangular shape of the finished plate. Asymmetric rolling conditions in lateral direction are generally unfavorable for the resulting plate contour. Such asymmetric rolling conditions may be caused by temperature gradients, non-homogeneous input profiles, or if the plate moves through the roll gap with some lateral offset with respect to the center of the mill stand. Such asymmetries can entail an unstable lateral movement of the plate, cf. (Tarnopolskaya and Gates, 2008). In the worst case, the lateral movement causes the plate to collide with the mill housing, which results in product losses and damaged plant components. Kampmeijer et al. (2014) presented an example plate that had been pinched in the finishing mill.

In this paper, the plate movement due to lateral asymmetries in the roll gap is analyzed. The considered mill stand is outlined in Fig. 1. The plate is deformed in the mill stand and its contour is measured by infrared cameras upstream and downstream the mill stand. The measurement is used to adjust the roll gap by the hydraulic cylinders, i. e., to move the upper backup roll at the drive side (DS) and at the operator side (OS). A disturbance feedforward control approach to minimize the lateral asymmetries and thereby

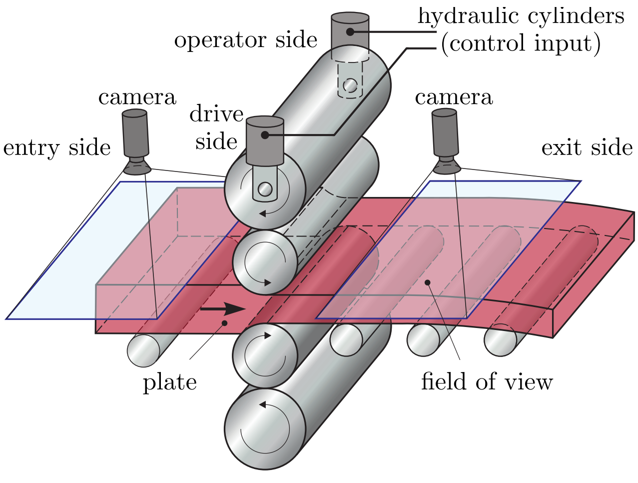

Fig. 1. Rolling mill with infrared cameras.

the plate movement in lateral direction is developed in this paper.

Feedforward control strategies for the reduction of the plate movement and the improvement of the plate contour are rarely described in literature. Tanaka et al. (1987) cover the feedback control of the plate camber by an asymmetric adjustment of the roll gap. Hol et al. (2013) tilt the rolls if asymmetric roll forces are detected at strip tail-out in a hot strip finishing mill. In (Schausberger

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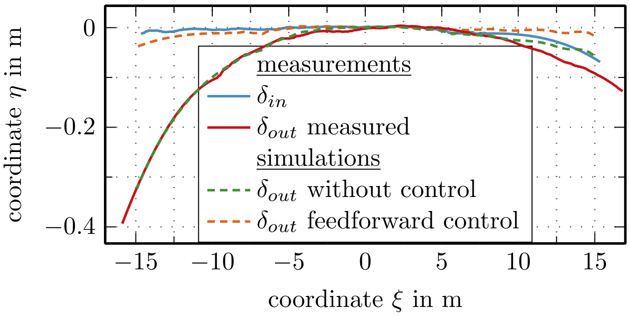

Fig. 2. Measurements of the plate movement without feedforward control of the lateral plate position and simulations from Section 3.3 with the entry curvature with and without feedforward control.

et al., 2017), a feedback controller for the considered mill stand is shown. This controller can be combined with the feedforward concept presented in this paper.

The impact of a misaligned strip or plate are analyzed in (Ishikawa et al., 1988). Kwon et al. (2015) and Hol et al. (2013) present models of the strip movement and asymmetric rolling conditions. The model of the plate movement reported in (Schausberger et al., 2015b) serves as a basis for the results presented in this paper.

There are some mechanisms in the considered system that can reduce the off-centering movement of the plate: (i) The friction forces between the plate and the roller table counteract the plate movement. (ii) The roll gap crown may keep the plate in the roll gap center. (iii) Side guides are installed up- and downstream the mill stand and can be used to center the plate in lateral direction. Despite these mechanisms, the plate can have an off-center position and in the worst case collide with the mill housing. Fig. 2 shows measurements for an exemplary plate finished at the considered mill stand without any countermeasures against laterally asymmetric rolling conditions. Although the incoming curvature of the plate is very small (blue line), the plate exhibits an undesirable shape after the rolling pass (red line).

In this paper, the mechanisms listed above are not further considered because they do not target the root cause of the lateral plate movement. It is assumed that forces are applied to the plate only in the roll gap. The upstream and the downstream part of the plate are considered as a rigid body each. The structure of the system with the feedforward controller is outlined in Fig. 3. Based on the measured lateral position of the plate δ, the control input Δx_h for the mill stand is calculated so that the expected asymmetries of the roll gap are minimized. The outputs of the mill stand model determine the velocities of the plate and thus its angular rotation φ and its lateral position δ, relative to the mill stand center.

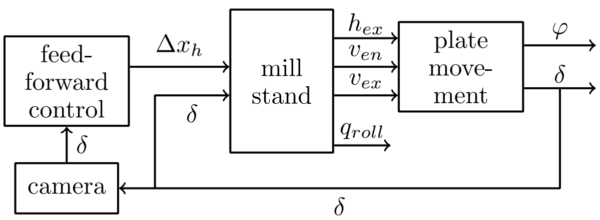

Fig. 3. Structure of the system with feedforward controller for the measured plate position δ.

The paper is organized as follows: In Section 2, mathematical models of the plate deformation in the mill stand and of the plate movement are developed. The behavior of an off-centered plate is discussed by means of simulation results. A feedforward control strategy is proposed in Section 3 and verified by simulations. Measurements from an industrial plant are shown and discussed in Section 4.

2. MATHEMATICAL MODEL OF HEAVY-PLATE HOT ROLLING

2.1 Model of the mill stand

A mathematical model of heavy-plate hot rolling is used to analyze the effects of lateral asymmetries, in particular the asymmetries caused by an off-centered plate. The model is also used to develop and validate a disturbance feedforward control concept. The outputs of the model are the exit thickness of the plate, the roll force, and the material velocities at the entry and the exit of the roll gap. The model yields the asymmetries of these values as well, e. g., the wedge-shape of the exit thickness. The entry velocities at the DS and at the OS are used in the model of the plate movement in Section 2.2. The model outputs depend on the properties of the plate (e. g., temperature, geometry, and position), and on the position of the hydraulic cylinders.

The considered mill stand is shown in Fig. 1. It consists of two work rolls that deform the plate. The upper and the lower backup roll reduce the bending deflection of the work rolls. To adjust the roll gap height, the upper roll stack is moved by hydraulic cylinders mounted at both the operator and the drive side. The applied roll force causes an elastic deflection of the mill housing.

For the considerations in this paper, a linear model of the mill stand together with Sims roll gap model is employed, see, e. g., (Prinz et al., 2017) for more details. This means, the exit thickness profile is approximated by the average thickness h_{ex}^0 and the difference between DS and OS Δh_{ex}. This is sufficient to study the effects of lateral asymmetries in terms of the evolution of the plate curvature.

For the model, the operating point is defined by the cylinder positions $\bar{x}_h^{DS}$ and $\bar{x}_h^{OS}$ that yield the roll force $\bar{F}_R^{DS}$ and $\bar{F}_R^{OS}$ and the exit thickness $\bar{h}_{ex}$. In the mill stand model, the exit thickness at the mill stand center $\eta = 0$ is calculated in the form

$$h_{ex}^0 = \frac{1}{2}\left(-\left(\Delta x_h^{DS} + \Delta x_h^{OS}\right) + \frac{\Delta F_R^{DS} + \Delta F_R^{OS}}{m}\right) + \bar{h}_{ex} \, , \tag{1}$$

with the mill modulus m and the differences of the cylinder positions $\Delta x_h^i = x_h^i - \bar{x}_h^i$ and the roll forces $\Delta F_R^i = F_R^i - \bar{F}_R^i$, $i \in \{DS, OS\}$. Using the stiffness modulus m_Δ for the asymmetric roll stack deflection, cf. (Hol et al., 2013), the wedge of the plate is given by

$$\Delta h_{ex} = \left(-\left(\Delta x_h^{OS} - \Delta x_h^{DS}\right) + \frac{\Delta F_R^{OS} - \Delta F_R^{DS}}{m_\Delta}\right)\frac{w}{b_{cyl}} \, . \tag{2}$$

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Here, w is the width of the plate, and b_{cyl} is the distance between the hydraulic cylinders. In case of a rigid roll stack m_Δ equals the mill modulus m identified in the calibration process (König et al., 2013).

Another part of the mill stand model is the roll gap model. In this paper, the model of Sims (1954) which is the standard model in hot rolling, is used. This roll gap model relates the local roll force q_{roll} with the plate entry h_{en} and exit thickness h_{ex}, the circumferential speed of the work rolls u_R, and the mean yield stress of the material k_{fm}

$$f_R\left(q_{roll}, h_{en}, h_{ex}, u_R, k_{fm}\right) = 0 \;. \tag{3}$$

This nonlinear equation can be solved for q_{roll} at each lateral position η with $-\frac{w}{2} + \delta \leq \eta \leq \frac{w}{2} + \delta$. That is, (3) is evaluated with

$$h_{ex}(\eta) = h_{ex}^0 + \frac{\eta}{w}\Delta h_{ex} \;. \tag{4}$$

Consider that the plate center is laterally misaligned with respect to the vertical center of the rolling mill by the distance δ. The rolling forces F_R^{DS} and F_R^{OS} are obtained by integrating q_{roll}

$$F_R^{DS} = \frac{1}{b_{cyl}} \int_{-\frac{w}{2}+\delta}^{\frac{w}{2}+\delta} \left(\frac{b_{cyl}}{2} - \eta\right) q_{roll}(\eta)\,\mathrm{d}\eta \tag{5a}$$

$$F_R^{OS} = \int_{-\frac{w}{2}+\delta}^{\frac{w}{2}+\delta} q_{roll}(\eta)\,\mathrm{d}\eta - F_R^{DS} \;. \tag{5b}$$

Using these forces in (1) and (2), and inserting in (3), and discretizing for η yield an equation system that is numerically solved for the unknowns h_{ex}^0, Δh_{ex}, F_R^{DS}, and F_R^{OS}.

With this solution for $h_{ex}(\eta)$, the entry and exit velocity profiles $v_{en}(\eta)$ and $v_{ex}(\eta)$ are obtained using the forward slip model of Montmitonnet (2006). The angular position of the neutral plane is given by

$$\alpha_n(\eta) = \sqrt{\frac{h_{ex}(\eta)}{R_{eff}(\eta)}} \tan\left(\frac{1}{2}\left(\operatorname{atan}\left(\alpha_0(\eta)\sqrt{\frac{h_{ex}(\eta)}{R_{eff}(\eta)}}\right) - \frac{1}{2\mu}\log\left(\frac{h_{en}(\eta)}{h_{ex}(\eta)}\right)\sqrt{\frac{h_{ex}(\eta)}{R_{eff}(\eta)}}\right)\right) \;. \tag{6}$$

Here, $R_{eff}(\eta)$ is the effective work roll radius by Hitchcock, μ is the friction coefficient between the plate and the roll, and α_0 is the angle of contact,

$$\alpha_0(\eta) = \operatorname{asin}\left(\frac{l_d(\eta)}{R_{eff}(\eta)}\right) \;, \tag{7}$$

with the length of the roll gap l_d. At the neutral plane, the roll gap height is

$$h_n(\eta) = h_{ex}(\eta) + 2R_{eff}(\eta)\left(1 - \cos\alpha_n(\eta)\right) \tag{8}$$

and the plate speed is equal to the circumferential speed of the rolls u_R. Based on the continuity equation, the plate velocity at the entry and at the exit side are

$$v_{ex}(\eta) = \frac{h_n(\eta)}{h_{ex}(\eta)} u_R \tag{9a}$$

$$v_{en}(\eta) = \frac{h_n(\eta)}{h_{en}(\eta)} u_R \;. \tag{9b}$$

With the mill stand model explained so far, the exit thickness, the plate speeds, and the roll forces can be computed. The lateral position of the plate center is obtained from the model of the plate movement presented in the following section, see Fig. 3 for the structure of the models.

2.2 Model of the plate movement

The model of the plate movement and the lateral position of the plate in the roll gap is based on (Schausberger et al., 2015b). The model calculates the movement of the entry side of the plate based on the entry velocity profile from (9). The plate movement and the centerline before the rolling pass are then used to determine the lateral position of the centerline of the plate in the roll gap.

A top view of the plate and the mill stand is shown in Fig. 4. The global coordinate frame (ξ, η, ζ) is fixed at the center of the mill stand. Another coordinate frame $(\xi_{pl}, \eta_{pl}, \zeta_{pl})$ is fixed to the head of the incoming plate. The origin of this coordinate frame is shifted by $(\Delta\xi, \Delta\eta, 0)$ and rotated by the angle φ with respect to the intersection point between the plate centerline and the roll axis to parameterize the movement of the incoming plate. Assuming that the slip in lateral direction is zero, this movement is governed by

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\Delta\xi \\ \Delta\eta \\ \varphi\end{bmatrix} = \begin{bmatrix}\bar{v}_{en} - \omega_{en}\left(\Delta\eta - \delta\right) \\ \omega_{en}\Delta\xi \\ \omega_{en}\end{bmatrix} \;, \tag{10}$$

with the angular velocity

$$\omega_{en} = \frac{v_{en}(-\frac{w}{2}+\delta) - v_{en}(\frac{w}{2}+\delta)}{w} \tag{11}$$

and the mean entry velocity

$$\bar{v}_{en} = \frac{v_{en}(-\frac{w}{2}+\delta) + v_{en}(\frac{w}{2}+\delta)}{2} \;. \tag{12}$$

The centerline $\delta_{pl}(\xi_{pl})$ of the incoming plate is uniquely parameterized in the plate-fixed coordinate frame, e. g., by a polynomial. The lateral position of the centerline in the roll gap measured in the global coordinate frame follows then from solving the equation

$$\begin{bmatrix}\xi_{pl} \\ \delta_{pl}(\xi_{pl})\end{bmatrix} = \begin{bmatrix}\cos\varphi & \sin\varphi \\ -\sin\varphi & \cos\varphi\end{bmatrix}\begin{bmatrix}-\Delta\xi \\ \delta - \Delta\eta\end{bmatrix} \tag{13}$$

for ξ_{pl} and δ. Eq. (13) maps the intersection point of the centerline and the roll axis from the global coordinate frame to its representation $(\xi_{pl}, \delta_{pl}(\xi_{pl}))$ in the plate-fixed coordinate frame.

The evolution of the centerline at the exit side of the mill stand can also be approximated by the presented model. For this, the differential equations (10) are adapted for

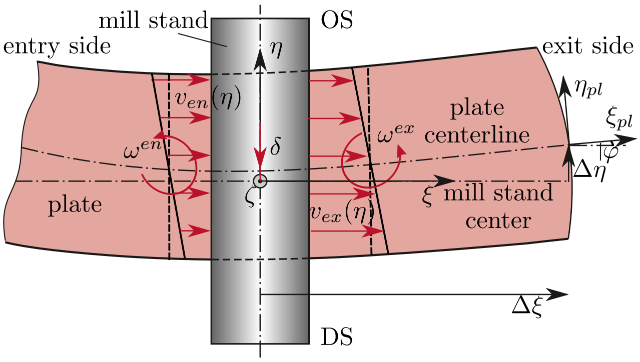

Fig. 4. Model of the plate movement.

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the exit velocity profile $v_{ex}(\eta)$. In the model, the plate movement is uniquely characterized by the upstream and downstream velocities at the roll gap. It is assumed that there are no external loads outside the roll gap.

2.3 Simulated case study of a laterally off-centered plate

In the following, the effect of an off-centered plate on the thickness and velocity profiles is analyzed by simulations. The plate has a uniform temperature, a uniform entry thickness of $h_{en} = 8.98\,\mathrm{mm}$, a width of $w = 2.7\,\mathrm{m}$, an exit length of 40 m, and a desired exit thickness of $\bar{h}_{ex} = 8.43\,\mathrm{mm}$. A rectangular shape of the incoming plate is presumed. At the beginning of the rolling pass, the plate centerline is perpendicular to the roll axis ($\varphi = 0$) and there is a small off-center position $\delta = [0, 1, 10, 50, 100]\,\mathrm{mm}$ (five scenarios). For these five initial off-center positions, Fig. 5 shows the asymmetric profiles of the exit thickness h_{ex}, the distribution of the roll force q_{roll}, the plate entry velocity v_{en}, and the plate exit velocity v_{ex}.

Fig. 6 shows simulation results for the scenario with $\delta(t = 0) = 1\,\mathrm{mm}$. This initial off-center position entails a higher roll force at the OS compared to the DS as a result of (5). Therefore, the deflection of the mill stand is asymmetric and in the case without control this results in a wedge-shaped exit thickness profile, i. e., the plate is thicker at the OS and thinner at the DS. The plate velocity profiles $v_{en}(\eta)$ and $v_{ex}(\eta)$ follow from (9). This yields an angular velocity $\omega_{en} > 0$ for the entry side and $\omega_{ex} < 0$ for the exit side.

Fig. 6 shows the states of the plate movement $\Delta\eta$ and φ depending on the plate coordinate $\Delta\xi$ for both the entry

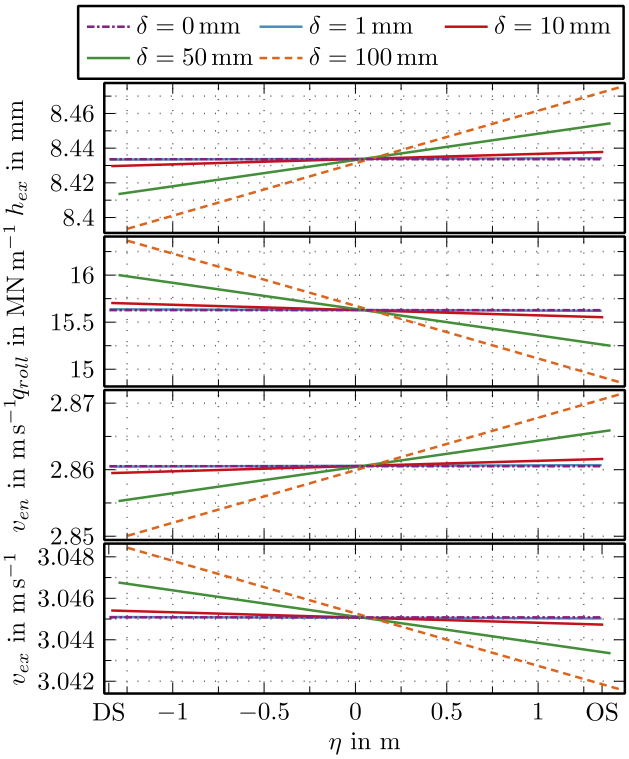

Fig. 5. Simulation results of the asymmetric profiles without feedforward control of the lateral plate position.

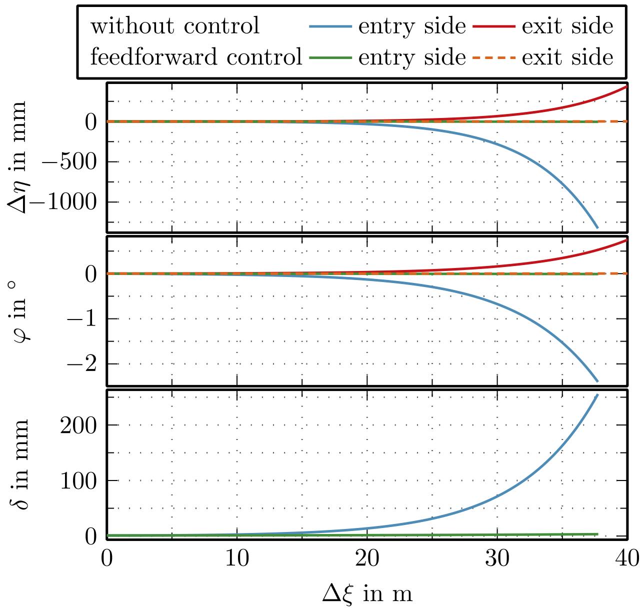

Fig. 6. Simulation results for the plate movement with initial plate position $\delta(0) = 1\,\mathrm{mm}$.

and the exit side. As shown in the bottom of the figure, the evolution of the plate center position δ is exponentially increasing. The instability can also be proven after a short study by means of the proposed mathematical model. The instable behavior agrees with the results of Nilsson (1998) obtained from FE simulations.

3. FEEDFORWARD CONTROL STRATEGY USING VISION-BASED CONTOUR ESTIMATION

In this section, a feedforward control approach that compensates for the lateral asymmetries due to an off-centered plate position is developed. First, the lateral position δ of the plate centerline is estimated from measurements of an infrared camera. Then, this lateral position is used for feedforward control of the cylinder position, i. e., the rolls are tilted to compensate for the asymmetric deflection.

3.1 Estimation of the lateral plate position

The approach for the estimation of the lateral plate position is based on an idea of Schausberger et al. (2015b). The approach utilizes two infrared cameras mounted at the ceiling of the rolling mill downstream and upstream the mill stand to measure the entry and exit contour of the plate. Compared to (Cuzzola and Dieta, 2003; Tanaka et al., 1987), where laser distance sensors are used for measuring the plate camber, infrared cameras can be assembled above the roller table farther away from the plate. That is why infrared cameras are less susceptible to steam, dust, cooling water, and heat.

The cameras usually cannot capture the whole plate in a single image because of the plate length. This is why the contour has to be stitched together from several consecutively captured images. To this end, the edge sections of the plate that are currently in the field of view (FOV) of the camera are extracted by a tailored edge detection algorithm. The detected edge sections from

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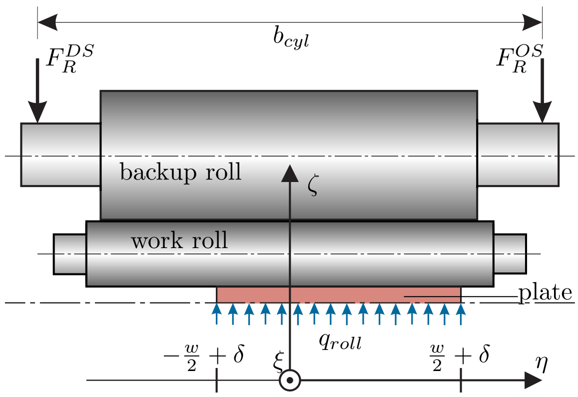

Fig. 7. Roll force distribution for an off-centered plate.

several images are then fed into an optimization-based algorithm which estimates both the movement and the contour of the plate. Furthermore, the mean longitudinal velocity of the plate is estimated based on the motion of the head end of the plate as long as this is in the FOV of the camera. After the head end has left the FOV, the mean longitudinal velocity of the plate is estimated by means of the longitudinal plate temperature profile as presented in (Schausberger et al., 2015a).

The lateral coordinate δ of the centerline of the plate directly follows as arithmetical mean of the estimated longitudinal boundaries of the plate. Generally, the centerline could be calculated based on the measurements of the camera at the entry and at the exit side. The FOVs of the cameras are located a few meters away from the roll axis because next to the mill stand itself, the plate surface is hidden by other parts or steam. The distance between the downstream camera and the roll gap brings along a time delay of the contour measurement. Contrary, the upstream camera measures the contour and movement of those sections of the plate which will enter the roll gap in future. Hence, it is favorable to use the upstream camera for the estimation of the lateral plate position to avoid the unwanted time delay. To this end, the incoming plate contour known from previously captured images is shifted and rotated based on the estimated plate movement.

3.2 Feedforward control strategy

The plate position δ is used for feedforward control using the hydraulic cylinder positions x_h^{DS} and x_h^{OS} as control inputs. As suggested in (Prinz et al., 2017), a prediction of the asymmetry of the roll forces is computed. As indicated in Fig. 7, it is assumed that the roll force q_{roll} is uniformly distributed over the plate width, i. e., $q_{roll} = \frac{\bar{F}_R}{w}$ with the total nominal roll force $\bar{F}_R = \bar{F}_R^{DS} + \bar{F}_R^{OS}$. The roll forces $\bar{F}_R^{DS}$ and $\bar{F}_R^{OS}$ at the operating point are determined during the mill stand setup. From (5), the predicted deviations from the nominal roll forces follow in the form

$$\Delta F_R^{DS} = F_R^{DS,ff} - \bar{F}_R^{DS} = -\frac{\delta}{b_{cyl}}\bar{F}_R \tag{14a}$$

$$\Delta F_R^{OS} = F_R^{OS,ff} - \bar{F}_R^{OS} = \frac{\delta}{b_{cyl}}\bar{F}_R \,. \tag{14b}$$

This means, for a uniform q_{roll}, the distribution of the roll force between DS and OS is simply shifted. The sum of the expected roll force is the roll force at the operating point $\bar{F}_R$. The assumption of a uniform q_{roll} is reasonable for homogeneous entry properties and a uniform desired exit thickness, i. e., the parameters of (3) are constant with respect to η.

The asymmetric deflection that is caused by asymmetric roll forces can be compensated by tilting the backup roll. The difference of the cylinder positions follows from (2) with $\Delta h_{ex} = 0$

$$\Delta x_h^{OS} - \Delta x_h^{DS} = \frac{\Delta F_R^{OS} - \Delta F_R^{DS}}{m_\Delta} = 2\frac{\delta}{b_{cyl}}\frac{\bar{F}_R}{m_\Delta} \tag{15}$$

and is equally distributed on DS and OS, i. e.,

$$x_h^{DS} = \bar{x}_h^{DS} - \frac{\delta}{b_{cyl}}\frac{\bar{F}_R}{m_\Delta} \tag{16a}$$

$$x_h^{OS} = \bar{x}_h^{OS} + \frac{\delta}{b_{cyl}}\frac{\bar{F}_R}{m_\Delta} \,. \tag{16b}$$

With this feedforward control strategy, a non-uniform thickness profile due to an off-centered plate is avoided. As suggested in (Prinz et al., 2017), a known entry wedge can be compensated as well using the roll gap model (3) to obtain the distribution of the roll force $q_{roll}(\eta)$. Unknown causes of laterally asymmetric rolling conditions, e. g., unknown temperature inhomogeneities, cannot be compensated by a feedforward approach. Therefore, a feedback part can be added to (16). This feedback controller may consist of a standard AGC and a feedback controller for the contour as described in (Schausberger et al., 2017).

3.3 Simulation results

Simulation results comparing the model with and without the proposed feedforward control approach are shown in Fig. 6. The resulting off-center position with feedforward control (green line at the bottom of Fig. 6) is practically zero, i. e., the plate remains nicely in the center of the mill stand.

Simulation results for a measured incoming plate curvature are shown in Fig. 2 without (green line) and with feedforward control (orange line). The exit curvature is kept very small with the feedforward approach. These simulation results demonstrate a major benefit of the feedforward control strategy and encouraged the authors to implement the controller on an industrial rolling mill.

4. MEASUREMENT RESULTS

The feedforward control concept was implemented and tested on a reversing mill stand of AG der Dillinger Hüttenwerke. Fig. 8 shows the measured results for an exemplary plate. The measurement of the shape of the plate centerline δ^{out} is shown for the last five passes. The ξ-axis is shifted by the half plate length $\frac{L}{2}$. Thus, the longitudinal plate center is aligned for the rolling passes. The feedforward controller together with the feedback controller proposed in (Schausberger et al., 2016) is active during the last 3 rolling passes. The tilting position $\Delta x_h^{OS} - \Delta x_h^{DS}$ according to (15) is shown at the bottom of the figure. The curvature of the plate shape after the last rolling pass (cf. top of Fig. 8) is acceptably small. Compared to the measured shape in the introductory scenario without

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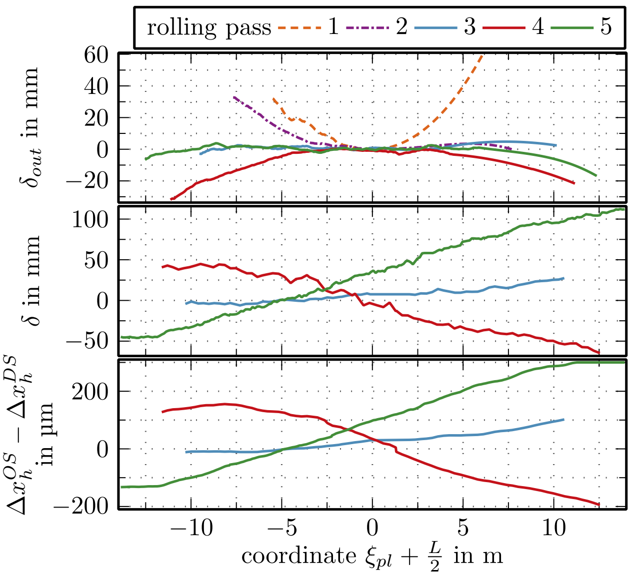

Fig. 8. Measurement results from an industrial application of the proposed feedforward controller.

feedforward control (see Fig. 2), where δ was in the range of a few 100 mm, there is a significant reduction of the curvature.

The proposed control strategy is now in permanent long-term operation at the considered mill stand. No collisions of the plate with the mill housing occurred since commissioning of the feedforward controller.

5. CONCLUSIONS

Based on models of the plate movement and of the lateral asymmetries in the roll gap, the essentially unstable mechanism of a plate moving off the machine center was investigated and reproduced in simulations. To avoid off-center positions of the plate, a feedforward control approach was developed and implemented on an industrial plant. The actual position of the plate center relative to the mill stand is measured by infrared cameras and used for feedforward control utilizing the tilting position of the hydraulic cylinders as control input. The improvements of the feedforward control strategy were demonstrated by simulation and measurement results. Long-term operation of the proposed control strategy at AG der Dillinger Hüttenwerke proved its effectiveness and high accuracy.

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