Automatic gauge control under laterally asymmetric rolling conditions combined with feedforward

Automatic gauge control under laterally asymmetric rolling conditions combined with feedforward

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***Abstract*—The most common and well proven control strategy for thickness control in industrial rolling mills is the automatic gauge controller (AGC). However, it is still unclear how to use AGC for the control of asymmetries in lateral direction. How should the controller react to different thickness estimations at both sides of the mill. Such laterally asymmetric rolling conditions may originate from strip track-off, asymmetric friction in the mill stand, or a wedge-shaped entry profile of the strip thickness. In this paper, three control approaches are discussed. Two different setups of AGC are compared and a feedforward approach is developed for lateral asymmetries of the entry thickness profile. Simulation studies based on a validated mill stand model demonstrate the benefit of combining AGC with a feedforward controller to compensate for asymmetries.**

***Index Terms*—Metals industry, Steel, Industrial plants, Mathematical model, Numerical simulation, Control system analysis, Feedforward systems.**

Nomenclature

Variables

b_{br}	distance between HGC cylinders
b_R	material width
F_R	roll force
F_{wrb}	work roll bending force
h_{en}	material entry thickness
h_{ex}	material exit thickness
m	mill modulus
x_h	HGC cylinder position
x_m	lateral position of material
δ_{hen}	wedge shape of entry thickness
δ_{hex}	wedge shape of exit thickness

Subscript and superscript labels

AGC	output of AGC
br	backup roll
DS	drive side
FF	output of feedforward
OS	operator side
d	desired values
$\bar{}$	operating point
Δ	difference to operating point
$\hat{}$	estimated values

I. Introduction

Automatic gauge control (AGC) is the most commonly used method for thickness control in rolling. For the conventional AGC, the mean exit thickness is estimated using measurements of the roll force F_R and the hydraulic cylinder position x_h. The deviation of the estimated exit thickness from the desired exit thickness is used in a feedback control law to compute an additional setpoint Δx_h for the cylinder position, see Fig. 1. The subordinate control loop for the hydraulic cylinder is considered as a part of the plant in this paper. Therefore, the control input is the desired cylinder position x_h^d. The position and the roll force are measured at both sides of the mill stand, i.e., the drive side (DS) and the operator side (OS). Fig. 2 shows a mill stand with the work rolls and backup rolls and the HGC cylinder from a side view. A front view of the upper roll stack is shown in Fig. 5. As outlined in Fig. 2, the control input x_h changes the vertical position of the upper roll stack at one side. The cylinder positions at the DS and at the OS are labeled x_h^{DS} and x_h^{OS}. The details of the system are given in Section IV.

For many years, this standard AGC has been successfully used in industrial applications, see, e.g., [1], [2]. Some additional features have been developed, e.g., compensation of roll eccentricity [3], wear and thermal expansion, [4], [5], hardness estimation and feedforward, [6], [7], multivariable control for mill stand and looper, [8], [9], etc. However, there is no systematic consideration of the thickness deviation in lateral direction.

For some operating situations in strip or plate rolling, the exit thickness profile can exhibit a wedge shape. This can be a major problem because the asymmetry may lead to a lateral movement. A lateral strip movement is potentially unstable, see also [10], and thus can cause the strip to crash with the side guides in the worst case. An interesting research question is whether AGC can identify the wedge shape of the strip and compensate it, in order to keep the strip in the center of the mill.

A change in the lateral strip position can be detected based

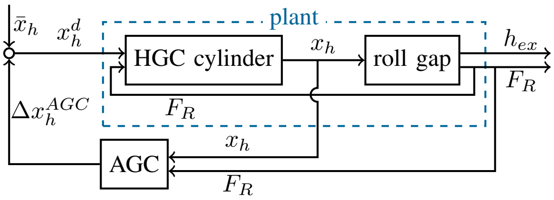

Fig. 1. Structure of the AGC.

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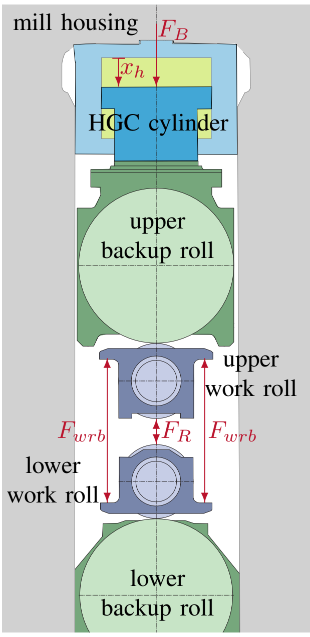

Fig. 2. Side view of the mill stand with the HGC cylinder adjusting the height of the roll gap by moving the upper roll stack.

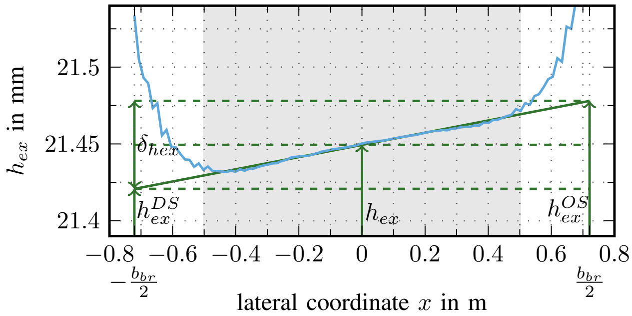

Fig. 3. Parameters of lateral profile.

on the difference of the measured forces at the DS and OS, see, e. g., [11]. Recent developments track the lateral strip position using a camera system installed above the strip, see [12]. The lateral movement of the strip is controlled by tilting the rolls according to a strip steering controller, see, e. g., [13].

In [14], the effect of laterally asymmetric rolling conditions on the lateral position of the strip are analyzed. Asymmetries can lead to a lateral movement of the strip and further increase the off-center position. For correction, asymmetric roll forces are applied and it is suggested to increase the strip tension at the entry and exit side to reduce the lateral movement. Based on [14], in [10], a model for the dynamics of the lateral strip motion is developed.

The effect of tilted backup rolls and asymmetric roll bending forces is described in [15] and [16] by influence coefficients. In a controller, these asymmetric input variables are used to reduce single-sided flatness errors or waves. In [17], an asymmetric stress distribution is analyzed and corrected by tilting the rolls. However, all of these flatness controllers are realized independently of the thickness controller.

In this paper, two different AGC approaches are discussed. As described in Section III, one controller uses the same thickness correction for both sides of the mill and the other controller uses individual AGC laws on each side. Therefore, the thickness estimation is enhanced to correctly estimate a wedge shape of the strip. Additionally, a feedforward controller is presented. In Section IV, the considered system of the mill stand and its model are briefly described. Finally, the proposed control concepts are tested in simulation studies with different sources of asymmetries.

II. Parameters of Lateral Thickness Profile

Fig. 3 shows an example of the simulated exit thickness profile $h_{ex}(x)$ over the strip width (blue line). To characterize this profile, the strip shape near the edges is not considered. As the rolling conditions near the edges are unknown, due to three dimensional edge effects of the deformation and significantly lower strip temperature near the strip edges compared to the rest of the strip, there may occur errors due to simplifications and assumptions of the model, see Section IV. That is, the considered profile is restricted to the more important center zone of the strip marked in gray in Fig. 3 (approx. 15 % are omitted at both strip edges). The average strip thickness in this center zone is denoted by h_{ex}. To characterize the wedge shape, a linear curve is fitted and extended to the strip edges at $x = \mp\frac{b_R}{2}$ (green line). The value of this curve at $x = -\frac{b_R}{2}$ (DS) is referred to as h_{ex}^{DS} and at $x = \frac{b_R}{2}$ (OS) as h_{ex}^{OS}. The difference between these two values is $\delta_{hex} = h_{ex}^{OS} - h_{ex}^{DS}$.

III. Automatic Gauge Control (AGC)

The standard AGC concept shown in Fig. 1 uses the measurements of the roll force F_R and the position of the hydraulic cylinder x_h to estimate the exit thickness $\hat{h}_{ex}$. Typically, the gaugemeter equation is written in the form

$$\Delta\hat{h}_{ex} = -\Delta x_h + \frac{\Delta F_R}{m} \tag{1}$$

(cf. [1]), where m is the mill modulus, i. e., $\frac{\Delta F_R}{m}$ is the increase of h_{ex} caused by the deformation of the mill housing due to an increase of the rolling force by ΔF_R. This estimation is based on linearizing the mill stand model, described in Section IV, at an operating point characterized by $\bar{x}_h, \bar{F}_R, \bar{h}_{ex}$. The corresponding quantities are thus written as

$$\begin{aligned} x_h = \bar{x}_h + \Delta x_h \ , \quad F_R = \bar{F}_R + \Delta F_R \ , \\ h_{ex} = \bar{h}_{ex} + \Delta h_{ex} \ . \end{aligned} \tag{2}$$

The estimated deviation $\Delta\hat{h}_{ex}$ of the strip exit thickness and its desired value Δh_{ex}^d are used in the AGC feedback law

$$\begin{aligned} \Delta x_h^{AGC} = k_B\left(\Delta\hat{h}_{ex} - \Delta h_{ex}^d\right) \ , \quad k_B > 0 \\ x_h^d = \bar{x}_h + \Delta x_h^{AGC} \end{aligned} \tag{3}$$

to obtain the reference value x_h^d for the position of the hydraulic cylinder, which is controlled by a subordinate

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controller, the so-called hydraulic gap control (HGC). The bandwidth of the AGC is limited due to the response time of subordinate control loops and possible eccentricities of the rolls. This limits the value of k_B, cf. [11], [18], and generally causes a non-zero steady state control error.

At most rolling mills, there are separate measurements of the roll force and the cylinder position at each side of the mill stand. This means, the gaugemeter equation (1) can be independently computed for the drive and operator side or the average of the two measurements can be used. The pros and cons of these two approaches are analyzed in the following. Additionally, the idea of a feedforward controller is discussed. In Section V, the three control concepts are compared in simulation studies.

A. AGC formulation for DS and OS

With the deviations for roll force and cylinder position at both sides

$$\begin{aligned} \Delta F_R^{DS} &= F_R^{DS} - \bar{F}_R^{DS} \quad & \Delta F_R^{OS} &= F_R^{OS} - \bar{F}_R^{OS} \\ \Delta x_h^{DS} &= x_h^{DS} - \bar{x}_h^{DS} \quad & \Delta x_h^{OS} &= x_h^{OS} - \bar{x}_h^{OS} \ , \end{aligned} \tag{4}$$

the estimations

$$\Delta \hat{h}_{br}^{DS} = -\Delta x_h^{DS} + \frac{\Delta F_R^{DS}}{m} \tag{5a}$$

$$\Delta \hat{h}_{br}^{OS} = -\Delta x_h^{OS} + \frac{\Delta F_R^{OS}}{m} \tag{5b}$$

are obtained. These estimations hold for the fictitious roll gap height at the position of the bearings of the backup rolls $x = \mp \frac{b_{br}}{2}$ since the measurements of the roll force and the cylinder position are at these lateral positions. The average of these estimations is

$$\Delta \hat{h}_{ex} = \frac{\Delta \hat{h}_{br}^{OS} + \Delta \hat{h}_{br}^{DS}}{2} \ . \tag{6}$$

Assuming the roll gap to be of straight wedge shape, an estimation of the thicknesses at the two strip edges according to Fig. 3 could be calculated as linear combination of (5a) and (5b)

$$\begin{aligned} \Delta \hat{h}_{ex}^{DS} &= \left(\frac{1}{2} + \frac{1}{2}\frac{b_R}{b_{br}}\right) \Delta \hat{h}_{br}^{DS} + \left(\frac{1}{2} - \frac{1}{2}\frac{b_R}{b_{br}}\right) \Delta \hat{h}_{br}^{OS} \\ &= \Delta \hat{h}_{ex} - \frac{1}{2}\frac{b_R}{b_{br}} \left(\Delta \hat{h}_{br}^{OS} - \Delta \hat{h}_{br}^{DS}\right) \\ \Delta \hat{h}_{ex}^{OS} &= \left(\frac{1}{2} + \frac{1}{2}\frac{b_R}{b_{br}}\right) \Delta \hat{h}_{br}^{OS} + \left(\frac{1}{2} - \frac{1}{2}\frac{b_R}{b_{br}}\right) \Delta \hat{h}_{br}^{DS} \\ &= \Delta \hat{h}_{ex} + \frac{1}{2}\frac{b_R}{b_{br}} \left(\Delta \hat{h}_{br}^{OS} - \Delta \hat{h}_{br}^{DS}\right) \ . \end{aligned}$$

However, it was seen in simulations that this estimation is quite inaccurate due to the bending and flattening of the rolls. Hence, the wedge shape is estimated using a distinct modulus m_δ for the difference of the measured forces at the OS and at the DS

$$\hat{\delta}_{hex} = \left(-\left(\Delta x_h^{OS} - \Delta x_h^{DS}\right) + \frac{\Delta F_R^{OS} - \Delta F_R^{DS}}{m_\delta}\right) \frac{b_R}{b_{br}} \tag{7a}$$

$$\Delta \hat{h}_{ex}^{DS} = \Delta \hat{h}_{ex} - \frac{\hat{\delta}_{hex}}{2} \tag{7b}$$

$$\Delta \hat{h}_{ex}^{OS} = \Delta \hat{h}_{ex} + \frac{\hat{\delta}_{hex}}{2} \ . \tag{7c}$$

For a roll stack with high stiffness, i. e., the effect of mill housing deflection is leading compared to the roll stack deformation, the moduli m in (5) and m_δ are equal.

The estimated values, $\Delta \hat{h}_{ex}$ and $\hat{\delta}_{hex}$, and their desired values, Δh_{ex}^d and δ_{hex}^d, are used in the proportional feedback controller to obtain

$$\Delta x_{h,DS}^{AGC} = k_B \left(\Delta \hat{h}_{ex} - \Delta h_{ex}^d\right) - \frac{k_{B\Delta}}{2} \left(\hat{\delta}_{hex} - \delta_{hex}^d\right) \tag{8a}$$

$$\Delta x_{h,OS}^{AGC} = k_B \left(\Delta \hat{h}_{ex} - \Delta h_{ex}^d\right) + \frac{k_{B\Delta}}{2} \left(\hat{\delta}_{hex} - \delta_{hex}^d\right) \tag{8b}$$

and hence the desired values of the cylinder positions read as

$$x_{h,DS}^d = \bar{x}_h^{DS} + \Delta x_{h,DS}^{AGC} \tag{9a}$$

$$x_{h,OS}^d = \bar{x}_h^{OS} + \Delta x_{h,OS}^{AGC} \ . \tag{9b}$$

In the next subsections, the appropriate assignment of the feedback gains, k_B for the average thickness and $k_{B\Delta}$ for the lateral asymmetry, is discussed.

B. AGC1: Same control for the DS and the OS

This AGC concept uses the average of the measured rolling forces and the average of the measured cylinder positions, i. e., $k_{B\Delta} = 0$. Therefore, only the average value of the thickness estimation $\hat{h}_{ex}$ is used for the DS and the OS and the control action Δx_h^{AGC} is equal on both sides of the mill. As the control output of the AGC Δx_h^{AGC} is equal for both sides of the mill stand, tilting of the rolls is avoided by this control strategy. Furthermore, the reliability is increased since both measurements are used and measurement errors, which may occur at only one side (e. g., due to different friction conditions between the mill frame and the chocks of the rolls), are fed back by the factor 0.5, see Section V-B for this simulation result.

C. AGC2: Separate control for the DS and the OS

For the separate AGC, the distinct estimation of the exit thickness for the OS and the DS is used for each side, i. e., $k_{B\Delta} = k_B$. Hence, the corrections of the position $\Delta x_{h,DS}^{AGC} \neq \Delta x_{h,OS}^{AGC}$ are different. The advantage of this separate thickness controller is that asymmetric roll force variations, e. g., due to lateral inhomogeneities of the strip hardness, are reduced. On the other hand, it may occur that the rolls are unreasonably tilted when the estimation of the wedge $\hat{\delta}_{hex}$ is too high. The accuracy of $\hat{\delta}_{hex}$ strongly relies on the correctness of all the measurements of the roll forces and the cylinder positions.

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D. AGC3: Feedforward controller in combination with AGC1

To overcome the disadvantages of AGC2 (tilting, which may lead to unsafe operation) but also react to laterally asymmetric rolling conditions, a feedforward control strategy is proposed. It is assumed that the root cause of asymmetric roll forces can be measured or otherwise identified. Possible causes are, e. g., a non-uniform strip temperature profile, which can be measured by pyrometers or an infrared camera, or the strip off-center position, which may be measured by a machine vision system. In case of a wedge-shaped entry thickness profile, the strip thickness profile can be measured before the mill stand or the entry thickness can be estimated by an observer using the measurements of the upstream mill stands.

In the feedforward contoller, the expected differences of the roll forces $\Delta F^{FF}_{R,DS}$ and $\Delta F^{FF}_{R,OS}$ from the reference forces is used to obtain additional values for the hydraulic cylinder positions. As these forces also cause a generally unequal deflection of both sides of the mill housing and the roll stack, the positions of the hydraulic cylinders are corrected in the same way, i. e.,

$$\Delta x^{FF}_{h,DS} = \frac{\Delta F^{FF}_{R,OS} + \Delta F^{FF}_{R,DS}}{2m} - \frac{\Delta F^{FF}_{R,OS} - \Delta F^{FF}_{R,DS}}{2m_\delta} \tag{10a}$$

$$\Delta x^{FF}_{h,OS} = \frac{\Delta F^{FF}_{R,OS} + \Delta F^{FF}_{R,DS}}{2m} + \frac{\Delta F^{FF}_{R,OS} - \Delta F^{FF}_{R,DS}}{2m_\delta} . \tag{10b}$$

Finally, in an enhanced version of (9), the desired positions used by the HGC are

$$x^d_{h,DS} = \bar{x}^{DS}_h + \Delta x^{AGC}_{h,DS} + \Delta x^{FF}_{h,DS} \tag{11a}$$

$$x^d_{h,OS} = \bar{x}^{OS}_h + \Delta x^{AGC}_{h,OS} + \Delta x^{FF}_{h,OS} , \tag{11b}$$

where both approaches, AGC1 and AGC2, can in principle be employed for $\Delta x^{AGC}_{h,DS}$ and $\Delta x^{AGC}_{h,OS}$, respectively. Since the feedforward strategy already accounts for the correction of asymmetries, AGC1 is used in combination with the feedforward controller. Fig. 4 shows the 2-degrees-of-freedom control structure of this feedforward concept for one side. The control input of the feedback controller (the AGC) is smaller when it is combined with the feedforward controller since the AGC only takes care of the remaining thickness errors after the compensation with the feedforward controller. E. g., there can be remaining errors due to model-plant mismatch, disturbances in the measurements, or non-measurable sources of strip inhomogeneities.

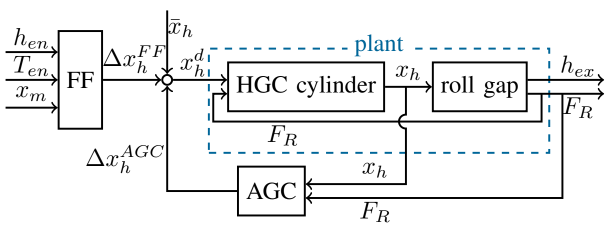

Fig. 4. Structure of the AGC combined with feedforward (FF).

The next steps show the feedforward control approach for a lateral off-center position of the strip. The measured position of the lateral strip center is denoted by x_m and defined positive in x-direction, i. e., in the direction of the OS. This means, the strip edges are at the lateral coordinates $\left[-\frac{b_R}{2} + x_m , \frac{b_R}{2} + x_m\right]$. Therefore, assuming that the distribution of the roll force q_{roll} along the direction x is uniform, the additional roll forces for both sides can be approximated in the form

$$\Delta F^{DS}_R = -\frac{x_m}{b_{br}} \left(\bar{F}^{DS}_R + \bar{F}^{OS}_R\right) \tag{12a}$$

$$\Delta F^{OS}_R = \frac{x_m}{b_{br}} \left(\bar{F}^{DS}_R + \bar{F}^{OS}_R\right) . \tag{12b}$$

In a similar way, control laws for asymmetric entry temperature or an entry thickness wedge can be designed using a roll gap model to obtain $\Delta F^{FF}_{R,DS}$ and $\Delta F^{FF}_{R,OS}$.

E. Feedforward of a desired wedge shape

The target exit thickness profile is not necessarily flat, e. g., for strip steering a certain wedge shape may be desired. This desired wedge shape is defined by δ^d_{hex} (cf. Section II). The average value of the desired exit thickness Δh^d_{ex} is kept constant. To establish this target profile, the preset values of the reference positions $x^d_{h,DS}$ and $x^d_{h,OS}$ have to be adjusted in the form

$$x^d_{h,DS} = \bar{x}^{DS}_h + \Delta x^{AGC}_{h,DS} + \Delta x^{FF}_{h,DS} + \frac{\delta^d_{hex}}{2}\frac{b_{br}}{b_R} \tag{13a}$$

$$x^d_{h,OS} = \bar{x}^{OS}_h + \Delta x^{AGC}_{h,OS} + \Delta x^{FF}_{h,OS} - \frac{\delta^d_{hex}}{2}\frac{b_{br}}{b_R} . \tag{13b}$$

It is also possible to combine this feedforward contoller for a wedge shape with the compensation of entry asymmetries shown in the previous Section III-D. Therefore, in (13) $\Delta x^{FF}_{h,DS}$ and $\Delta x^{FF}_{h,OS}$ are obtained from (10). Also concurrent asymmetries can be handled with the feedforward control concept. For example for an off-centered strip with a temperature gradient, the feedforward roll forces $\Delta F^{FF}_{R,DS}$ and $\Delta F^{FF}_{R,OS}$ in (10) are the sum of the corresponding roll forces according to (12) and the roll forces acquired from the roll gap model outlined in Section IV-A. This superposition is valid for the local linearization around the operating point defined at the beginning of Section III.

For validation, the presented controllers are tested in simulation scenarios in Section V. The simulation model of the mill stand including a roll gap model is briefly described in the next section.

IV. Mill Stand Model

A mathematical model for a single mill stand in a tandem hot rolling mill shown in Fig. 2 is used for an analysis of the proposed control concepts. However, the conclusions of the simulations of these control concepts are valid for cold rolling as well.

As outlined in Fig. 5, the mill stand consists of an upper and a lower work roll (WR) to deform the strip and two backup rolls (BR) to reduce the bending deflection of the work rolls. To control the uniformity of the thickness profile,

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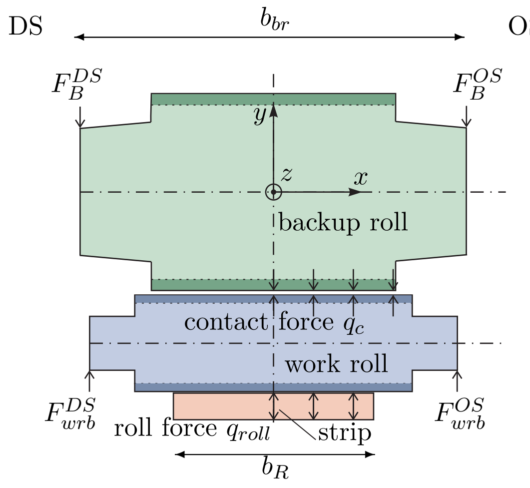

Fig. 5. Section of upper roll stack (front view).

the considered mill stand is equipped with a WR bending system (WRB) and the roll stack features continuous variable crown shape (CVC), [19]. The mean height of the roll gap is controlled by hydraulic cylinders, which define the position of the bearings of the upper BR at the DS and the OS.

Existing mathematical models describing the strip deformation in the roll gap, [20], [21], and the elastic deformation of the rolls, their bearings, and the mill stand, cf. [22], [23], are combined and augmented to a simulation model. The main parts of this model are A. the roll gap model, B. the static model of the deformation of the rolls and the mill housing, and C. the dynamic model of the roll gap adjustment system, which captures hydraulic circuits, existing subordinate controllers, and friction.

A. Roll gap model

Roll gap models based on Sims' model [20] are widely used in the steel industry and allow a simple calculation of the local roll force q_{roll} depending on the strip entry and exit thickness, the strip tension and the yield stress of the strip material. As this yield stress varies with strip temperature, deformation rate, etc., its behavior is modeled using [24]. For instance, an exponential function models the dependence of the yield stress on the strip temperature.

B. Static mill stand model

To calculate the deflection of the four rolls, Timoshenko beam theory is used [25]. The Hertzian contact model (between WR and BR) and the roll gap model (WR-strip-WR contact including the model from Section IV-A) couple these beams. The beam and the contact models are locally evaluated, i. e., for slices of infinitesimal width. The derivation yields a 16-dimensional (4 Timoshenko beams with 4 states each) nonlinear boundary value problem, which is solved by a tailor-made numerical solver. This solver applies the single shooting method based on the matrix exponential of the linearized differential equation.

The deflection of the frame of the mill stand depends on the force applied by the backup roll bearings and accounts for a deflection y_{br} of the upper BR along the direction y at the bearings $x = \pm\frac{b_{br}}{2}$. The corresponding force-deflection curve is regularly recorded using special calibration routines at the real plant. This force-deflection curve $F_B(y_{br})$ is used for the boundary conditions of the Timoshenko beam model together with the forces applied by the WRB cylinders at the bearings of the work rolls F_{wrb}, cf. Fig. 5. The bending and shear stiffness of the rolls are calculated considering the geometry and the material properties of the soft core and the hard boundary layer of the rolls [26]. The thermal crown and wear profile of the work rolls are computed according to [27]. The local flattening of the WR due to q_{roll} is captured as described in [28].

The outputs of this static mill stand model are the roll force $F_R = \frac{1}{2}\int_{-\frac{b_R}{2}}^{\frac{b_R}{2}} q_{roll}\,\mathrm{d}x$ and the exit thickness profile $h_{ex}(x)$ of the strip. The estimations of the exit thickness in (1) and (7) are based on a linearization of this static model. This mill stand model was validated by comparing the calculated exit thickness profile and the profile measured by a downstream thickness measurement device.

C. Dynamic model of the roll gap control system

In a dynamic model (state-space model) of the roll gap control system, the hydraulic valves and cylinders, rolling and friction forces, as well as the underlying control loops, i. e., the HGC, according to [29], have been considered. For simulation of the dynamic model, in every time step, the static mill stand model from Section IV-B including the roll gap model from Section IV-A is evaluated to compute the current deflection of the roll stack.

The structure of this dynamic simulation model can be seen in Fig. 6. This comprehensive simulation model is used as a verification environment for the developed control concepts.

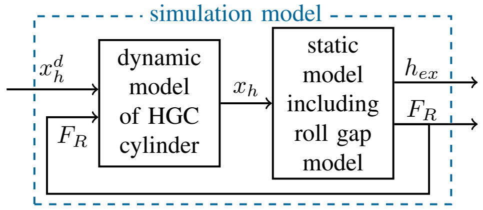

Fig. 6. Structure of the dynamic simulation model of the plant.

V. SIMULATION RESULTS

In this section, simulation scenarios with asymmetric rolling conditions in lateral direction are considered. The two AGC approaches are compared and analyzed. If applicable, the results of the feedforward control concept are also shown. The main result of the simulation model is the exit thickness profile, especially the wedge shape characterized by the value δ_{hex}. Further consequences of these asymmetries regarding lateral strip movement are not considered.

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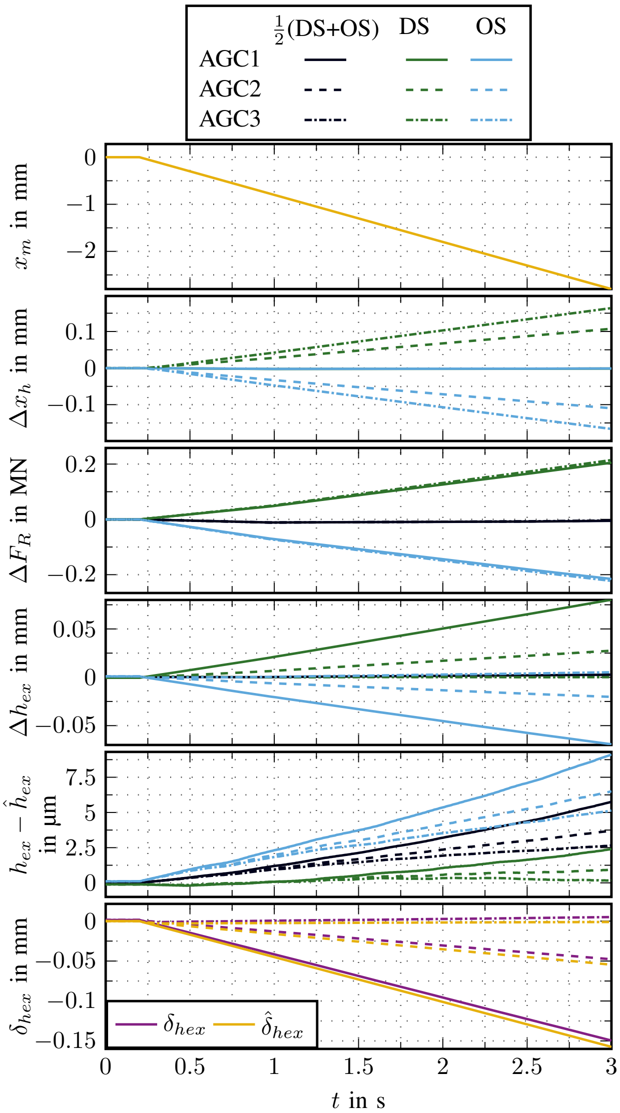

Fig. 7. Simulation results of the three proposed AGC versions for strip off-center.

A. Strip off-center

Fig. 7 presents simulation results for the three control approaches for a strip moving at an off-center position through the mill stand. The simulation results from the strategy AGC1 are plotted as solid lines, from the strategy AGC2 as dashed lines, and from the feedforward strategy AGC3 as dash-dotted lines. In the top part of Fig. 7, the lateral strip position x_m is shown. For this simulation, the strip position x_m is linearly decreased, starting at $t = 0.2\,\mathrm{s}$. Next, the additional cylinder positions Δx_h are shown in green for the DS and in blue for the OS. Next, the deviation from the reference roll force is shown in black for the average ΔF_R, in green for the DS ΔF_R^{DS}, and in blue for the OS ΔF_R^{OS}. Then the exit thickness is plotted. Here, the black, green, and blue lines are according to the definitions of h_{ex}, h_{ex}^{DS} and h_{ex}^{OS} in Section II minus the reference exit thickness $\bar{h}_{ex}$. For all simulation results, the desired exit thickness is equal to the reference thickness, $h_{ex}^d = \bar{h}_{ex}$, $\Delta h_{ex}^d = 0$. Next, the errors of the estimated thicknesses $h_{ex} - \hat{h}_{ex}$, for the average thickness and for the thicknesses at the DS and the OS, of the three controllers are shown. Generally, the thickness estimations are quite accurate, the remaining errors in all cases are very small. At the bottom of the figure, the simulated thickness asymmetries δ_{hex} are compared (difference of the green and the blue lines for Δh_{ex}). The yellow lines show the estimation of this asymmetry $\hat{\delta}_{hex}$.

As the strip is moving towards the DS, the roll force F_R^{DS} is increased and F_R^{OS} is decreased. Because the sum of these changes is $\Delta F_R = 0$, i. e. the total rolling force is almost constant, there is no control action due to AGC1. The exit thicknesses at the OS and the DS (green and blue line in the fourth plot of Fig. 7) diverge due to the different deflections on both sides. This results in a strip wedge δ_{hex} that is shown in the lower part of Fig. 7. This undesirable behavior is improved using AGC2, because there the rolls are tilted to reduce the wedge. However, the improvement achieved by AGC2 compared to AGC1 is smaller than the improvement associated with the feedforward controller.

B. Erroneous measurement of the roll force

In the next simulation scenario, an erroneous measurement of the roll force at the DS is considered, which could for instance be caused by asymmetric friction in the mill stand. Fig. 8 shows the results of this scenario. Because of $x_m = 0$, the results of AGC3 are equal to those of AGC1. Hence, they are omitted in the figure. There is an increasing error in the measurement of the roll force at the DS F_R^{DS} whereas the roll force at the OS F_R^{OS} is correctly measured. Consequently, the sum of the measured roll force deviation also changes, which entails an erroneous estimation of $\hat{h}_{ex}$ even in case of AGC1. All considered controllers generate an error in the mean exit thickness. However, AGC2 additionally tilts the roll stack due to the asymmetric measurement error of the roll force, which entails an additional control error in terms of δ_{hex}.

Compared to the results of Fig. 7, where the benefit of AGC2 over AGC1 is rather small, here the results of AGC2 are highly undesirable. As a consequence, using AGC1 or AGC3, where the tilt of the roll stack is not based on the measured roll forces, can be recommended.

C. Desired wedge shape

For a desired wedge shape $\delta_{hex}^d \neq 0$, outlined in green in the bottom of Fig. 9, the cylinder positions are adjusted according to (13). As shown in Fig. 9, both AGC1 and AGC2 yield satisfactory results. AGC2 is only slightly better than AGC1, since the small estimated error $\hat{\delta}_{hex} - \delta_{hex}^d$ is corrected.

D. Asymmetric entry temperature and entry thickness

In this simulation scenario, an asymmetric temperature profile is considered, the average temperature of the strip is kept constant. ΔT is the difference between the strip temperature at the OS and at the DS. The considered values of ΔT are

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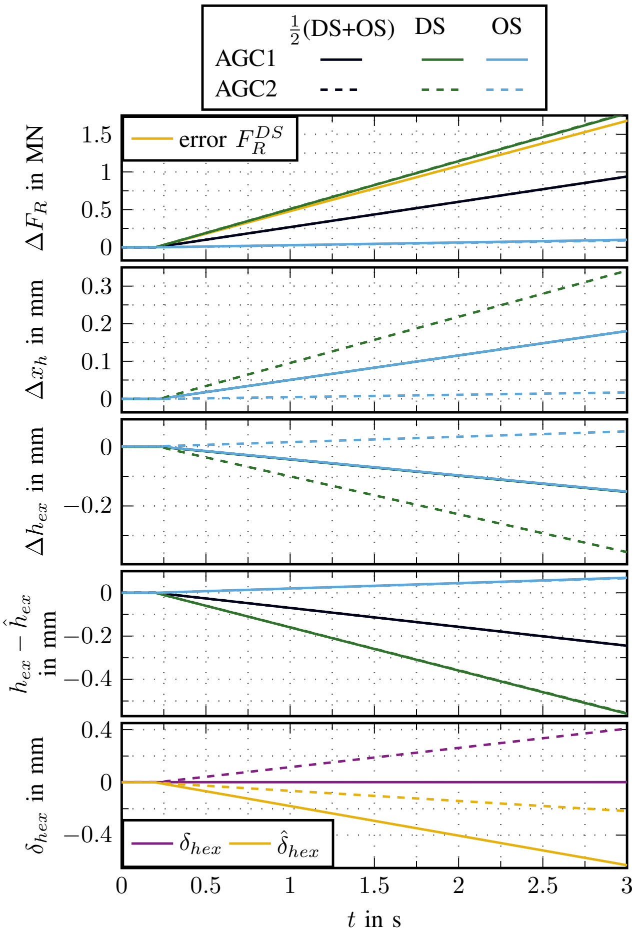

Fig. 8. Simulation results for an asymmetric error of the roll force measurement.

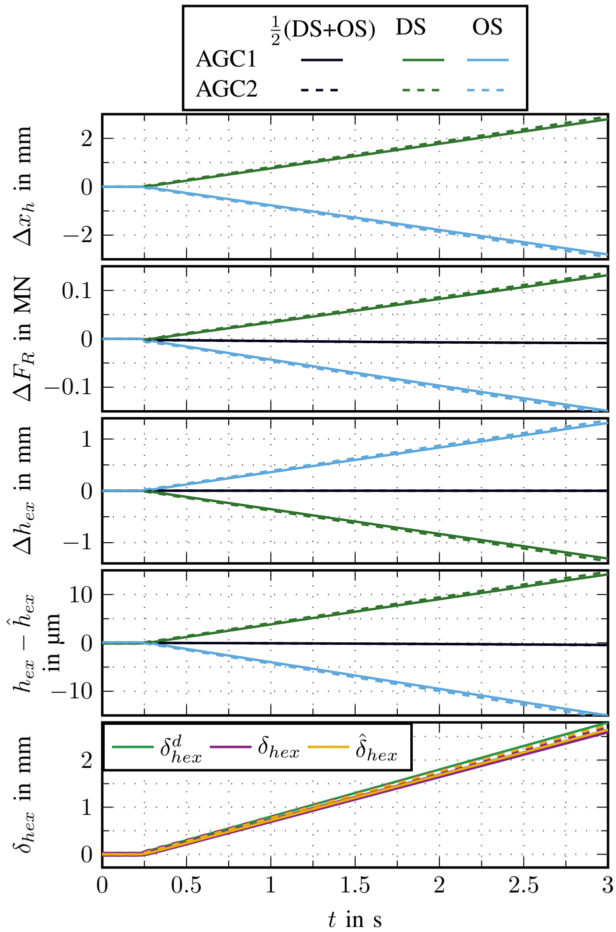

Fig. 9. Simulation results for a desired wedge shape.

shown at the top of Fig. 10. A higher value ΔT results in a smaller yield stress. If the positions of the HGC cylinders are not changed and if $\Delta T > 0$ (cf. Fig. 10), the exit strip thickness at the OS is lower than at the DS. The lower roll force F_R^{OS} causes a lower mill stretch. Only a small amount of the exit thickness wedge can be corrected by AGC2 because the estimation of the error $\hat{\delta}_{hex}$ is slightly too small. Similar to the results discussed in Section V-A, the feedforward strategy AGC3 is superior to both other AGC approaches.

An entry thickness profile in the form of a known wedge shape gives similar results which are shown in Fig. 11. Here, the thicker strip at the OS yields a higher roll force at this side. Again, the adjustment of the feedforward controller corrects the cylinder position so that there is no remaining wedge shape δ_{hex} in the exit thickness profile.

Based on the foregoing simulation results, it is recommendable that the AGC strategy described in Section III-B, using the same control action for both DS and OS, is preferably implemented. Whenever possible, asymmetrical input values should be considered with an additional feedforward controller.

The simulations are carried out for the model of Section IV of a single mill stand of a tandem hot rolling mill. However, the control concepts and the conclusions of the simulations are transferable to all mill stands of a tandem rolling mill and single reversing mill stands alike. The interactions between mill stands of a tandem rolling mill are minor and not considered at the moment. With the proposed feedforward controller, asymmetric strip tension due to a wedge shaped strip is avoided or reduced, so the standard looper controllers work well. An asymmetric feedforward control concept also for the looper would need a sophisticated plant model and would not yield a big benefit.

VI. Conclusions

Using separate AGC for the two mill stand sides can cause an unacceptable wedge shape of the exit thickness profile if asymmetric rolling conditions, e. g., friction, deteriorate the measurements of the roll force. A separate AGC approach features only a small benefit for asymmetric strip properties (e. g., temperature wedge) and strip off-center. Treating such asymmetric effects with a suitable feedforward strategy proved to be a much better approach.

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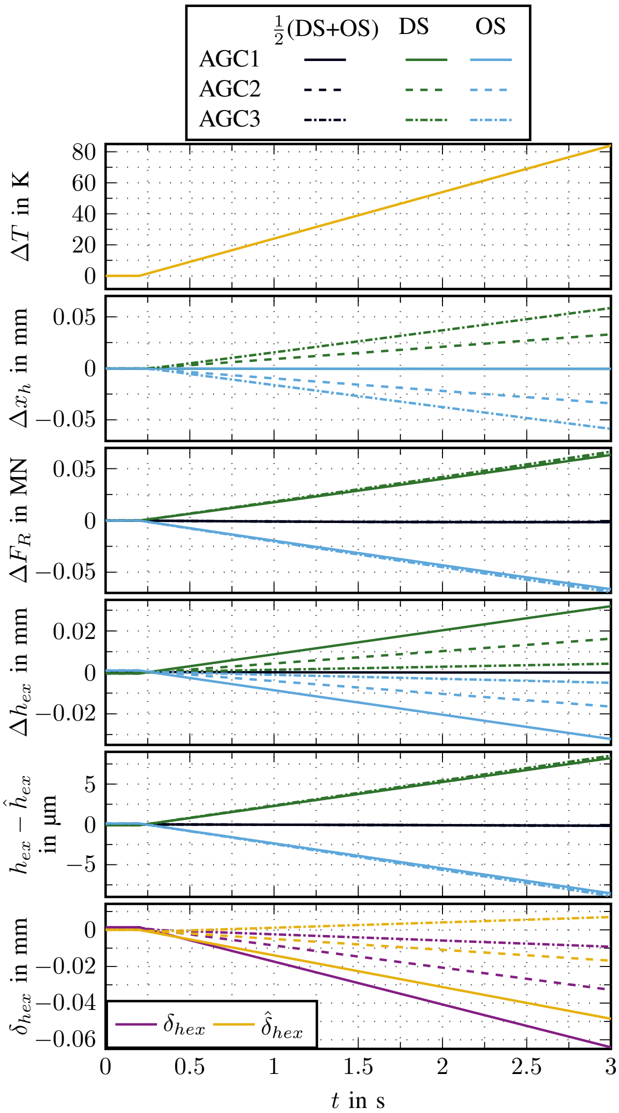

Fig. 10. Simulation results for asymmetric entry temperature.

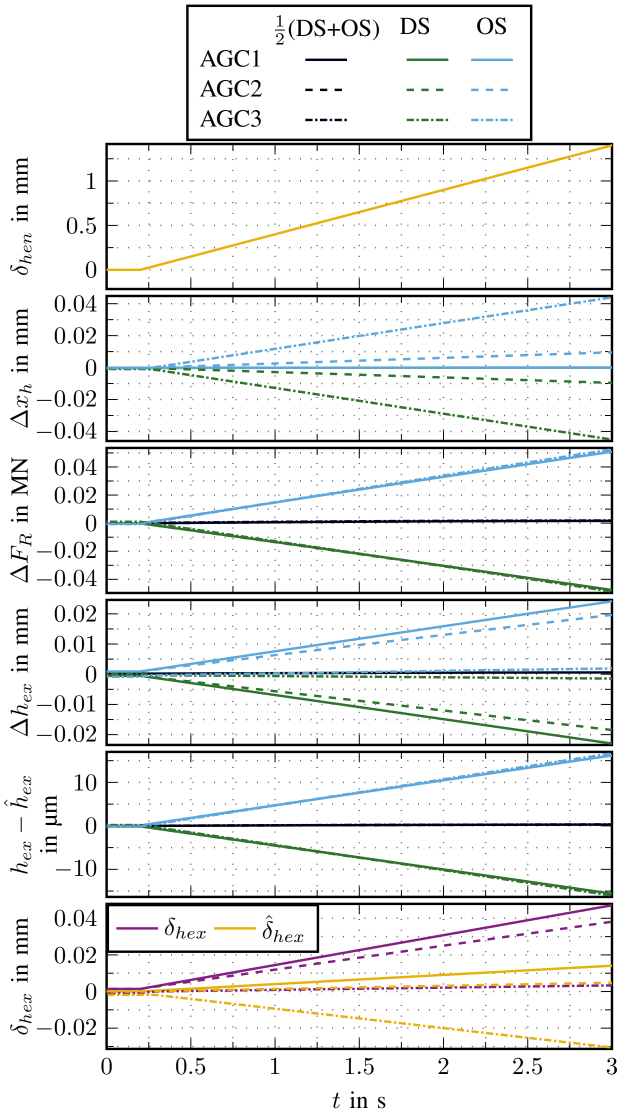

Fig. 11. Simulation results for asymmetric entry thickness (wedge shape).

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