Online Parameter Estimation for Adaptive Feedforward Control of the Strip Thickness in a Hot Strip Rolling Mill

authored by **Katharina Prinz, Andreas Steinboeck, Martin Müller, Andreas Ettl, Florian Schausberger, and Andreas Kugi**

and published in *Journal of Manufacturing Science and Engineering*.

Cite this article as:

K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575

BibTex entry:

```
@Article{acinpaper,
	author = {Prinz, Katharina and Steinboeck, Andreas and M\"uller, Martin and Ettl, Andreas and
	    Schausberger, Florian and Kugi, Andreas},
	title = {Online Parameter Estimation for Adaptive Feedforward Control of the Strip Thickness in a Hot
	     Strip Rolling Mill},
	journal = {Journal of Manufacturing Science and Engineering},
	year = {2019},
	volume = {141},
	number = {7},
	pages = {071005-1--071005-12},
	doi = {10.1115/1.4043575},
	url = {https://asmedigitalcollection.asme.org/manufacturingscience/article/doi/10.1115/1.4043575}
}
```

Link to original paper:

http://dx.doi.org/10.1115/1.4043575
https://asmedigitalcollection.asme.org/manufacturingscience/article/doi/10.1115/1.4043575

Contact:

Automation and Control Institute (ACIN)
Vienna University of Technology
Gusshausstrasse 27-29/E376
1040 Vienna, Austria

Internet: www.acin.tuwien.ac.at
E-mail: office@acin.tuwien.ac.at
Phone: +43 1 58801 37601
Fax: +43 1 58801 37699

Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill

Katharina Prinz*
Christian Doppler Laboratory
for Model-Based Process Control
in the Steel Industry
Automation and Control Institute (ACIN)
TU Wien, Vienna, Austria
prinz@acin.tuwien.ac.at

Andreas Steinboeck
Automation and Control Institute (ACIN)
TU Wien, Vienna, Austria
steinboeck@acin.tuwien.ac.at

Martin Müller
Christian Doppler Laboratory
for Model-Based Process Control
in the Steel Industry
Automation and Control Institute (ACIN)
TU Wien, Vienna, Austria
mueller@acin.tuwien.ac.at

Andreas Ettl
Christian Doppler Laboratory
for Model-Based Process Control
in the Steel Industry
Automation and Control Institute (ACIN)
TU Wien, Vienna, Austria
ettl@acin.tuwien.ac.at

Florian Schausberger
voestalpine Stahl GmbH
Linz, Austria
florian.schausberger@voestalpine.com

Andreas Kugi
Christian Doppler Laboratory
for Model-Based Process Control
in the Steel Industry
Automation and Control Institute (ACIN)
TU Wien, Vienna, Austria
kugi@acin.tuwien.ac.at

ABSTRACT

A new adaptive disturbance feedforward control strategy of the strip thickness in a hot strip rolling mill with online parameter estimation is proposed. The feedforward control strategy makes use of the measured strip temperature and strip entry thickness. To avoid that these disturbances cause a non-uniform strip exit thickness, Sims' roll gap model and a linear mill stand deflection model are used to compute control inputs which compensate for these disturbances. By minimizing the difference between the expected roll force from the model and the measured roll force uncertain parameters of the model and also errors of the strip tracking are estimated in real-time. The estimated parameters are immediately used in the adaptive feedforward controller. Experimental results of the proposed control approach obtained from an industrial hot strip rolling mill show a significant improvement of the strip thickness accuracy compared to the existing standard controllers. The proposed adaptive feedforward control strategy is now in permanent operation at the considered rolling mill.

Nomenclature
Abbreviations
AGC Automatic gauge control
BR Backup roll

*Address all corresponds to this author.

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

CVC	Continuous variable crown
FF	Feedforward control
HGC	Hydraulic gap control
MIMO	Multiple input, multiple output
SISO	Single input, single output
TCW	Thermal and wear crown
WR	Work roll
WRB	Work roll bending
WRS	Work roll shifting

Variables

b_R	Strip width
c_m	Material modulus
E_{wr}	Young's modulus of WR
F_R	Roll force
F_h	Force of the hydraulic main cylinder
f_R	Roll gap model
F_{wrb}	Work roll bending force
G	Geometric factor of roll gap model
h_{en}	Strip entry thickness
h_{ex}	Strip exit thickness
$\mathbf{K}$	Matrix penalizing changes of estimated parameters
k_0, m_1, m_2, m_3	Coefficients for yield stress
k_{agc}	Feedback gain of AGC
k_{fm}	Yield stress
L	Length of the finished strip
l_d	Length of the contact arc in the roll gap (bite length)
m	Mill modulus
p_{en}	Strip tension at entry side
p_{ex}	Strip tension at exit side
$p_h(z)$	Polynomial approximation of the exit thickness
p_{roll}	Pressure distribution in roll gap
q_{roll}	Local roll force
R'_{wr}	Effective WR radius
R_{wr}	Nominal WR radius
T	Strip temperature
u_R	Rolling velocity
v_0	Strip velocity at pyrometer
v_{en}	Entry velocity
v_{ex}	Exit velocity
X,Y,Z	Lagrangian coordinates
x,y,z	Eulerian coordinates
x_h	Position of the hydraulic main cylinder
Z_{hor}	Estimation horizon
k_k, k_T, k_Z, k_0, k_1	Parameters for estimation of model uncertainties
α_d	Angle of the contact arc in the roll gap
α_n	Angular position of neutral point
ν_{wr}	Poisson's ratio of WR
σ_{hex}	Standard deviation of the thickness error
φ	Degree of deformation
κ	Constraints of estimated variables

Subscript and superscript labels

$_{agc}$	Output of AGC
$_{en}$	Entry side of roll gap
$_{ex}$	Exit side of roll gap
$_{ff}$	Output of feedforward
$_{nom}$	Nominal value
^{ss}	Steady state value
$_{d}$	Desired values

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

Δ	Difference to operating point
$\dot{}$	Time derivative
$\hat{}$	Estimated values
$\vert_a$	Operating point

1 Introduction

Improvements of production processes in the steel industry are the topic of ongoing research. Quality demands and the variety of the products are steadily increasing while environmental regulations are getting more and more restrictive. These developments are important drivers for the application of advanced automation and control methodologies in the steel industry. With better controllers, the energy consumption can be reduced, the throughput can be increased, the number of defects and thus the recycling material can be minimized, the product quality can be increased and even new products can be produced. For flat steel production, this means that advanced control concepts have the potential to improve the accuracy and uniformity of the exit thickness of produced steel strips.

A tandem finishing mill, consisting of seven (almost identical) mill stands with six loopers in between, is considered. Fig. 1 shows a side view of a mill stand. The thickness of the steel strip is reduced at each mill stand. The strip material is deformed in the roll gap between the rotating upper and lower work rolls (WR). The backup rolls (BR) reduce the bending deflection of the work rolls. The height of the roll gap equals the outgoing strip thickness and can be controlled by hydraulic cylinders (HGC cylinders), which move the upper roll stack. When the thickness of the strip is reduced, the length of the strip and its velocity are increased due to the continuity equation. Hence, the mill stands have to operate at different but synchronized speeds. This ensures that the strip length between two mill stands is kept constant. In the mill stands, the steel strip is deformed to a target thickness profile. The strip thickness profile is influenced by a number of actuators and effects. The HGC cylinders are located at both ends of the upper BR. The average thickness of the strip is changed by moving the BR in vertical direction. Furthermore, the roll stack can be tilted by the HGC cylinders to get a wedge-shaped roll gap. In addition to the backup rolls, the considered mill stand is equipped with a work roll bending system (WRB) to counteract work roll bending and to minimize the non-uniformities of the strip thickness profile in the lateral direction. For additional shape control, the roll stack features continuous variable crown shape (CVC), i. e., the WRs can be shifted (WRS) in the lateral direction. The thermal expansion of the rolls and their wear and tear (TCW) also influence the thickness profile. The applied forces themselves also change the strip thickness profile because they entail deflection of the mill stand housing, deformation of the roll stack, flattening of the rolls, and a displacement of the BRs in the hydrodynamic journal bearings. A detailed mathematical model of the components of the mill stand can be found in [1] and [2]. For the machine model presented in Section 2, a linearized approximation is used and only the average exit thickness in the lateral direction is considered. Feedforward controllers considering the wedge shape of the exit thickness or the complete lateral profile of the exit thickness are presented in [3] and [2]. In [2], possible model-plant mismatch and material tracking errors are not considered and thus cannot be corrected. In the current paper, an advanced feedforward approach with adaptive parameters and more sophisticated synchronization of measurement signals is proposed.

In industry, typically, the automatic gauge controller (AGC) is used to control the exit thickness of the strip, see [4, 5]. The AGC estimates the mean strip exit thickness at the considered mill stand based on the measured roll force using a (typically linear) mill-stretch model, which also captures the roll stack deflection. The AGC control error is the difference between the estimated mean strip exit thickness and its reference value. This error is fed back through a proportional control law to the position of the hydraulic cylinders, i. e., the main control inputs. The corresponding equations will be given in Section 3.1. The AGC is a standard control solution for the thickness in rolling mills. However, it has some inherent limitations, cf. [6]. One significant limitation is its finite feedback gain, which entails a generally non-zero steady-state control error. The feedback gain is limited for stability reasons (see also [7] or Appendix A for an explanation). As a result, the exit thickness of the strip can exhibit undesired deviations from its desired value even under steady-state conditions. These deviations may root in inhomogeneous entry properties (temperature, thickness) of the strip, cf. [8] in combination with the finite feedback gain of the AGC. To minimize these deviations, which is a control objective, a two-degrees-of-freedom control structure is proposed. In the new disturbance feedforward part, the influences of the measured variations of the entry thickness and the temperature of the strip on the exit thickness are systematically compensated based on the mathematical model. Similar feedforward control concepts have been developed in [9] for tandem hot strip rolling and in [10] for a heavy-plate hot rolling mill. The estimates of the temperature and the yield stress of the strip material are utilized by a feedforward controller. A feedforward controller based on a linearized roll gap model is presented in [11], where variations of the yield stress over the strip length are compensated. Recent research activities on a 2-high cold rolling mill [12] propose to use the measured strip thickness in a model predictive controller (MPC) to calculate a trajectory for the position adjustment. These control concepts do not consider deviations between the design model used in the feedforward controller and the actual plant. Furthermore, the feedforward control strategy of [10] and the MPC of [12] require an exact strip tracking.

In the adaptive feedforward control strategy developed in this work, uncertain model parameters can be estimated online

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

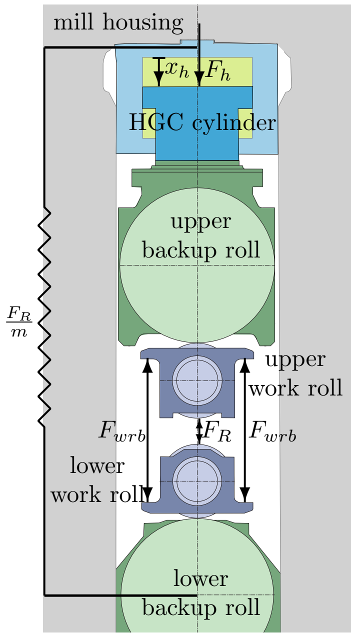

Fig. 1. Side view of the mill stand and applied forces with the deflection of the mill stand $\frac{F_R}{m}$ and the position x_h of the hydraulic cylinder.

based on measurements. With this adaptive strategy, the robustness of the achieved control accuracy is higher than with control laws that are based on nominal models. The developed adaptive controller can also be used for rolling new steel grades. In the literature, parameter estimation is typically done in one rolling pass and the estimated parameters are used in the subsequent rolling passes. In [13], for instance, errors in the thickness and the yield stress of the strip are identified at upstream mill stands and the set-points of the (yet unthreaded) downstream mill stands are adjusted. The publication [14] shows this adaptive control strategy in use at real rolling mills. In [15], the rolling force formula is inverted for calculation of the steel yield stress at a tandem cold mill controller. The publications [16, 17] use adaptive learning coefficients with exponential smoothing for the estimation of the yield stress and the friction by minimizing the quadratic error between the calculated and the measured roll force. These identified coefficients are then used for the next coil having the same specification. The authors of [18] present an adaption algorithm for parameters of the roll force model based on the weighted relative roll force error at each mill stand. Also in [19], the adaption parameters of the yield stress are passed from slab to slab and from pass to pass. With the strategy presented in this work, the parameters are estimated at a certain mill stand and immediately used by the feedforward controller at the same mill stand. Thus, the accuracy of the strip thickness is improved at the same mill stand and the same rolling pass. A single mill stand of the tandem hot rolling mill is considered in this paper. Interactions between the mill stands and the loopers will be a topic of future research. Control strategies considering these interactions are shown in, e. g., [20, 21]. Connected projects focus on increasing the accuracy of the predicted roll force for different rolling conditions and varying material parameters. With the hydrodynamic roll gap model, the influence of the rolling speed (cf. [22]) and lubrication in the roll gap (cf. [23]) are captured.

A mathematical model for the mill stand is shown in Section 2. In Section 3, limitations of the state-of-the-art thickness control concept, the AGC, are discussed. Afterwards, a new adaptive disturbance feedforward control approach for the strip thickness is proposed. The measurement of the incoming disturbances is discussed in Section 3.2, a feedforward control strategy based on the model from Section 2 is shown in Section 3.3. This nominal feedforward control strategy is extended with an estimator for uncertain model parameters in Sections 3.4 and 3.5. The control strategies (no feedforward control, nominal feedforward control, and adaptive feedforward control) are tested in a simulation scenario in Section 4. Section 5 shows simplifications for the implementation of the control concept on an industrial hot strip rolling mill. In Section 6, the control concepts are compared based on measurement results from the industrial plant. Conclusions from the work and further plans for the implementation of the control method at the industrial plant are discussed in Section 7.

2 Mathematical model of the deformation of the strip in the mill stand

This section deals with the mathematical model to compute the exit thickness, the roll force, and the exit velocity of a strip rolled in a mill stand. This mathematical model includes the influence of the material properties, e. g., the temperature of

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

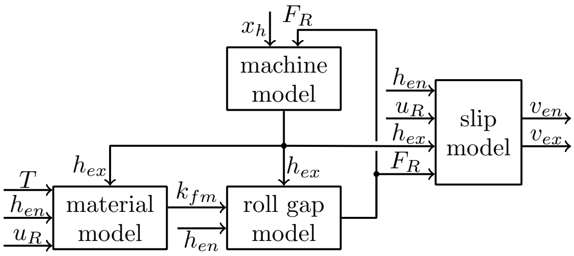

Fig. 2. Structure of the simulation model.

the steel strip on the plastic deformation, see Section 2.1. The roll force is calculated using the roll gap model of Section 2.2. The mechanic behavior of the mill stand is considered in Section 2.3. The forward slip model presented in Section 2.4 gives the velocity of the strip. These models are coupled as shown in the structure of Fig. 2. The inputs of the model are the entry thickness h_{en}, the temperature T of the strip, the rotational speed of the rolls u_R, and the cylinder position x_h. The latter is considered as the control input. The outputs of the model are the exit thickness h_{ex} of the strip and the total roll force F_R. The slip model yields the strip velocity at the entry and the exit side of the mill stand, v_{en} and v_{ex}, respectively. The slip model is not necessary for the calculation of F_R and h_{ex}, it will be used in Section 3.2 for strip tracking. The other parts of the model will be used for simulation of the plant and for the development of the feedforward control concept. The sub-models indicated in Fig. 2 are explained in detail in the following.

2.1 Material model

The mean yield stress k_{fm} is a material parameter and depends on the composition and structure of the material, its temperature T, the deformation degree φ, and the deformation rate $\dot{\varphi}$. According to [24], this dependency can be approximated in the form

$$k_{fm} = k_0 \mathrm{e}^{m_1 T} \varphi^{m_2} \dot{\varphi}^{m_3} \ . \tag{1}$$

The deformation degree is defined in the form $\varphi = \ln\left(\frac{h_{ex}}{h_{en}}\right)$. Its time derivative $\dot{\varphi}$ (the deformation rate) is proportional to the rolling velocity u_R. Its mean value is $\dot{\varphi} = \varphi \frac{u_R}{l_d}$, with l_d as the roll bite length. Dynamic effects, like work hardening or recrystallization, as discussed in [25], are not considered in this model. The constants k_0, m_1, m_2, and m_3 are material parameters, which have to be identified for each strip material, e. g., by minimizing the deviation between the measured and the calculated roll force. In the nominal feedforward control approach, it is assumed that these material parameters are exactly known in advance for each strip. Because this is not always the case, e. g., for a new steel grade with yet unknown parameters k_0, m_1, m_2, and m_3, they will be identified online and used in the adaptive feedforward control approach, see Section 3.4 and Section 3.5.

2.2 Roll gap model

The roll force F_R, which is necessary to deform the strip with the entry thickness h_{en} to the exit thickness h_{ex} is calculated by a roll gap model. In general, the mathematical relation between the roll force F_R, the strip entry thickness h_{en} and exit thickness h_{ex}, the width b_R of the strip, the strip tensions at the entry side p_{en} and at the exit side p_{ex}, the rolling velocity u_R, and the yield stress k_{fm} of the strip material can be written in the implicit form

$$f_R\left(F_R, h_{en}, h_{ex}, b_R, p_{en}, p_{ex}, u_R, k_{fm}\right) = 0 \ . \tag{2}$$

This general form is suitable for various roll gap models and thus allows an easy exchange of the roll gap model. In this work, Sims' model [26] is considered, which is also widely used in the steel industry. Actually, an extended form [27] of Sims' model is used, which also captures the influence of the up- and downstream strip tension.

According to Fig. 3, the projected bite length is

$$l_d = R'_{wr} \sin(\alpha_d) = \sqrt{R'_{wr} \Delta h - \frac{\Delta h^2}{4}} \ , \tag{3}$$

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

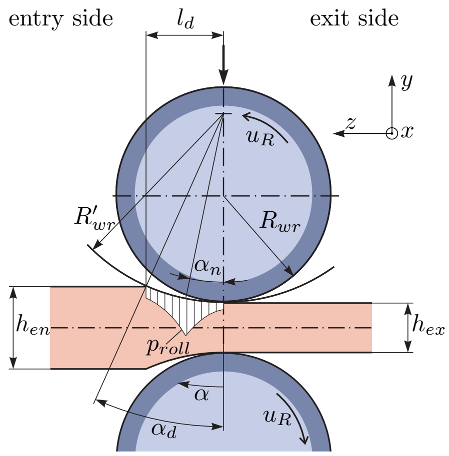

Fig. 3. Plastic deformation of the strip in the roll gap.

where R'_{wr} is the effective radius of the WR, α_d is the angular length of the roll bite, and $\Delta h = h_{en} - h_{ex}$ is the reduction of the strip thickness. Due to elastic flattening, the effective radius R'_{wr} of the WR is larger than its nominal radius R_{wr}, see [28]. To compute R'_{wr}, Hitchcock's formula

$$R'_{wr} = R_{wr}\left(1 + \frac{16\left(1-\nu_{wr}^2\right)}{\pi E_{wr}}\frac{q_{roll}}{\Delta h}\right) \tag{4}$$

is used with the local roll force q_{roll}, Young's modulus E_{wr}, and Poisson's ratio ν_{wr} of the WR material. The pressure distribution $p_{roll}(\alpha)$ as outlined in Fig. 3 is found using the differential equations of [29]. From integrating this pressure distribution along the contact arc $\alpha \in [0, \alpha_d]$, the local roll force follows in the form

$$q_{roll} = k_{fm} l_d G(h_{en}, h_{ex}, R'_{wr}, p_{en}, p_{ex}) \; . \tag{5}$$

The so-called geometric factor G captures the influence of the strip tensions p_{en} and p_{ex} and the geometry of the roll gap defined by h_{en}, h_{ex}, and R'_{wr}, see [27]. The mean yield stress k_{fm} is calculated according to (1).

Equation (5) is numerically evaluated based on the exit thickness profile h_{ex} obtained from the machine model given in Section 2.3. The entry thickness profile h_{en}, the strip width b_R, and the strip tensions p_{en} and p_{ex} are considered as input parameters. Because the rolling conditions can vary over the strip width, all parameters in (5) depend on the lateral coordinate x. That is, the roll gap model is evaluated for $x \in \left[-\frac{b_R}{2}, \frac{b_R}{2}\right]$ to obtain the distributed roll force $q_{roll}(x)$. The total roll force F_R can be readily found by integrating q_{roll},

$$F_R = \int_{-\frac{b_R}{2}}^{\frac{b_R}{2}} q_{roll}(x)\,\mathrm{d}x \approx b_R q_{roll,mean} \; . \tag{6}$$

For further simplification, the mean value of $q_{roll,mean}$ is used in (6). The mean value $q_{roll,mean}$ is obtained using the mean values over x of the respective input parameters in the equations (3 – 5).

2.3 Deflection model of the mill stand (machine model)

The applied forces cause an elastic deflection of the mill stand housing and the roll stack, which also influences the height h_{ex} of the roll gap. Thus, this deflection has to be considered for the calculation of the strip exit thickness h_{ex}. A detailed mathematical model of the mechanics of a rolling mill is given, e. g., in [2, 30, 31]. Henceforth, a simpler linearized deflection model is used, i. e., the deflection is linearized with respect to the model inputs x_h (HGC cylinder position) and F_R at a certain operating point a. This yields

$$h_{ex} = h_{ex}|_a + \Delta h_{ex} \tag{7a}$$

$$\Delta h_{ex} = -\,\Delta x_h + \frac{\Delta F_R}{m} \; , \tag{7b}$$

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

where the deviations from the operating point a are denoted by $\Delta x_h = x_h - x_h|_a$ for the position of the hydraulic cylinder and by $\Delta F_R = F_R - F_R|_a$ for the roll force. The linear mill modulus m is usually identified in a calibration routine based on the measured cylinder positions x_h and hydraulic forces F_h. During this routine, the upper and lower WR are in contact (without strip). The respective values $x_h|_a$, $F_R|_a$, $h_{ex}|_a$ usually are computed for the specified strip in a more sophisticated (nonlinear) model (Level 2 setup) and provided to the subordinate controllers.

The exit thickness h_{ex} from (7) is used in the roll gap model (2) and for the deformation degree φ in (1). Consequently, the models are coupled as shown in Fig. 2. The solution of these models yields the exit thickness h_{ex} and the roll force F_R.

2.4 Forward slip model

With the presented forward slip model, the velocity of the strip as a function of the circumferential speed u_R of the WRs is obtained. The resulting strip velocity of this model will be used for material tracking. The reduction of the height of the roll gap in the direction of z from h_{en} at $z = l_d$ to h_{ex} at $z = 0$ as outlined in Fig. 3 is described with

$$h(\alpha) = h_{ex} + 2R'_{wr}\left(1 - \cos(\alpha)\right) . \tag{8}$$

According to [32], the angular position of the neutral plane in the roll gap is given by

$$\alpha_n = \sqrt{\frac{h_{ex}}{R'_{wr}}} \tan\left(\frac{1}{2}\operatorname{atan}\left(\alpha_d\sqrt{\frac{R'_{wr}}{h_{ex}}}\right)\frac{1}{4\mu}\ln\left(\frac{h_{en}(k_{fm}-p_{ex})}{h_{ex}(k_{fm}-p_{en})}\right)\sqrt{\frac{h_{ex}}{R'_{wr}}}\right) , \tag{9}$$

with the angular length α_d of the roll gap from (3), the friction coefficient μ between the strip and the WR, and R'_{wr} from (4). At the angular position α_n, the velocity of the strip equals the circumferential speed u_R of the WR and the strip thickness $h_n = h(\alpha_n)$ is obtained from (8). The continuity equation thus yields the velocities v_{en} and v_{ex} with which the strip enters and exits the roll gap,

$$v_{en} = \frac{h_n}{h_{en}} u_R \tag{10a}$$

$$v_{ex} = \frac{h_n}{h_{ex}} u_R . \tag{10b}$$

3 Thickness control concepts

One of the most challenging tasks in the process of steel rolling is thickness control. The thickness tolerances of the finished strip are often smaller than 10 µm while the roll forces are typically between 20 MN and 40 MN at each mill stand. The respective mill stand deflections due to these forces usually are between 1 mm and 3 mm at the considered rolling mill. Furthermore, the thickness of the strip cannot be measured directly at the mill stand because of the harsh environment and limited space. The strip thickness is measured before the first and after the last mill stand of the tandem rolling mill. At each mill stand, only the measurements of the hydraulic forces $F_h = \frac{F_R}{2} + F_{wrb}$ and the positions x_h of the hydraulic cylinders (at the drive side and the operator side of the mill stand) are available. These measurements are used in the automatic gauge controller (AGC) for feedback control based on estimations of the exit thickness at each mill stand. The idea of the developed feedforward control strategy is to measure and to compensate for the occurring disturbances, i. e., the temperature and the entry thickness of the strip before the first mill stand. The strips enter the tandem rolling mill with non-uniform temperature and thickness. Typically, the temperature variations are caused by non-uniform heating conditions in the upstream reheating furnace, i. e., the strips exhibit colder zones caused by the skids carrying the slabs in the furnace. These so-called skid marks entail a non-uniform strip thickness after the roughing mill.

3.1 Existing thickness controller (AGC)

The automatic gauge controller (AGC) is the standard thickness control concept used in hot strip rolling. The exit thickness of the strip is estimated based on the measured cylinder position x_h and the deflection associated with the measured roll force F_R. With (7), the estimation of $\Delta\hat{h}_{ex}$ is obtained in form of the so-called gaugemeter equation (cf. [33, 34])

$$\Delta\hat{h}_{ex} = -\Delta x_h + \frac{\Delta F_R}{m} . \tag{11}$$

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

This estimation is used by the feedback AGC for the strip thickness. Considering the desired exit thickness h_{ex}^d and the corresponding offset $\Delta h_{ex}^d = h_{ex}^d - h_{ex}|_a$, the proportional AGC law reads as

$$\begin{aligned} \Delta x_h^{agc} &= k_{agc}\left(h_{ex}|_a + \Delta\hat{h}_{ex} - h_{ex}^d\right) \\ &= k_{agc}\left(\Delta\hat{h}_{ex} - \Delta h_{ex}^d\right) . \end{aligned} \tag{12}$$

The control action Δx_h^{agc} is added to the operating point $x_h|_a$ to obtain the desired cylinder position

$$x_h^d = x_h|_a + \Delta x_h^{agc} . \tag{13}$$

This is the reference signal for the subordinate hydraulic gap controller (HGC), see [35]. For stability reasons, the gain $k_{agc} > 0$ is limited. An analysis will be shown in Appendix A. The consequence of a limited proportional feedback gain is a nonzero steady-state control error, i. e., a remaining thickness error according to (34).

Feedback control based on the measured exit thickness after the last mill stand is possible but has strong limitations. Because of the delayed measurement signal (the thickness measurement device is located $\approx 5\,\mathrm{m}$ after the last mill stand), the control action of the thickness monitor is only slow. In the considered tandem rolling mill, such a feedback controller is active only at the last three mill stands. It uses a PI feedback control law and can thus compensate the effects of constant or slowly varying disturbances. In general, the variations of the strip thickness due to the skid marks are faster disturbances and are thus still visible in the exit thickness signal of typical strips.

This means, with the existing thickness control strategies, AGC and thickness feedback controller at the end of the rolling mill, thickness errors due to temperature inhomogeneities cannot be completely compensated. This is the main motivation for proposing a new feedforward thickness control approach.

3.2 Disturbance measurement and strip tracking

Most of the inputs of the roll gap model in (2) are measured. The strip tensions p_{en} and p_{ex} can be computed based on the force measurements at the looper rolls, and the rolling velocity u_R is known from the main mill drives. In the considered processing line, there are measurements of the thickness and the temperature before the tandem rolling mill. The strip surface temperature is measured by a thermo-graphic camera (upper strip surface) and pyrometers (upper and lower strip surface). The pyrometers measure the temperatures of the upper and the lower surface in the lateral center of the strip. The mean value of these two scalar measurement signals is combined with the thermo-camera images, to get the 2-dimensional temperature distribution for the whole strip surface. Essentially, the pyrometer measurements $T_{pyro}(Z)$ are utilized to correct the absolute temperature measurement error of the thermo-camera images $T_{cam}(x,Z)$ in the form

$$T(x,Z) = T_{pyro}(Z) + \left(T_{cam}(x,Z) - T_{cam}(0,Z)\right) . \tag{14}$$

The temperature distribution over the thickness of the strip (in the direction of y) is assumed to be uniform. The thickness profile is measured with a radiometric system. For the simulations carried out in Section 4, it is assumed that these measurements exactly agree with the properties of the strip that enters the roll gap of the first finishing mill stand. The temperature measurements are placed some distance upstream of the first mill stand. Thus, the temperature decrease due to air cooling between the measurement and the first mill stand is not captured.

For feeding information of the strip or the material state to upstream or downstream entities, exact tracking of the material position is essential. This is a nontrivial task because the strip velocity changes at each mill stand, determining the strip velocity based on the rolling velocity u_R is difficult as there is slip in the roll gaps. The material tracking strategy used in this work is outlined in the following.

The Lagrangian longitudinal coordinate Z of the strip is measured with respect to the length L of the finished strip, i. e., the Lagrangian position Z of each material point of the strip is constant. Generally, the coordinate Z of a strip point that is currently at the Eulerian position z (e. g., at the mill stand, at the pyrometer) is obtained by integrating the strip velocity v at this point, starting at the time t_0 when the head end of the strip went through this point,

$$Z(t) = \int_{t_0}^{t} v(z,\tau)\frac{h(z,\tau)}{h_{ex,7}}\,\mathrm{d}\tau . \tag{15}$$

Therefore, at a certain mill stand, the strip (exit) velocity $v = v_{ex}$ at the respective mill stand is related to the circumferential velocity of the WR u_R as shown in (10). The latter term in (15) is the ratio of the exit thickness at the respective mill stand

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

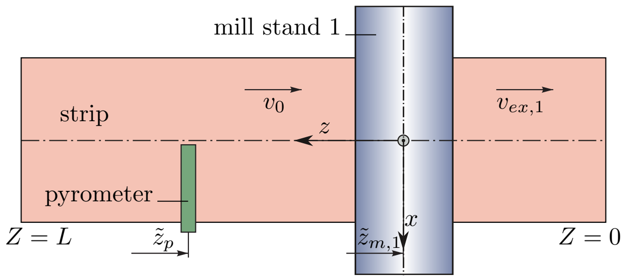

Fig. 4. Material tracking and synchronization at the pyrometer measurement.

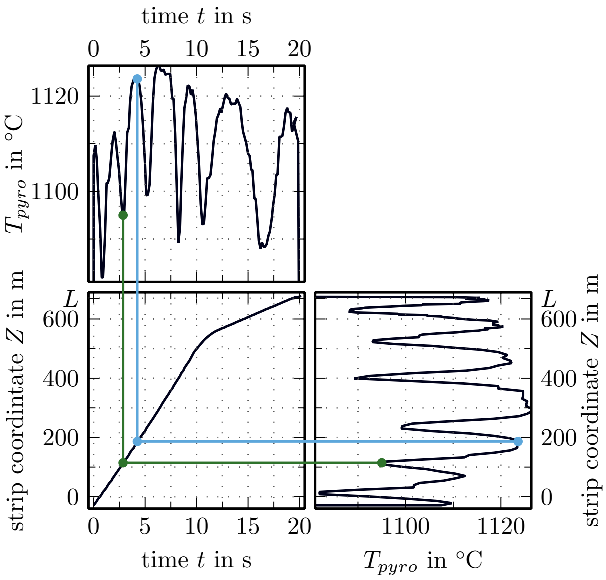

Fig. 5. Mapping of the pyrometer measurement.

to the exit thickness of the finished strip $h_{ex,7}$ (after mill stand 7). The time t_0 is detected by the rise of the measured roll force at the respective mill stand. For the proposed feedforward controller, the Lagrangian coordinate Z of the material point currently rolled in the mill stand is used to synchronize with the measured disturbances. The entry thickness and the temperature of the strip are measured at some distance upstream of the first mill stand and with varying speed. Fig. 4 shows an outline of the pyrometer measurement. The velocity at which the strip is passing the pyrometer varies. In fact, the strip is decelerated after its tail end exits the roughing mill (at $t \approx 10\,\mathrm{s}$ in Fig. 5). The relation between the time t and the Lagrangian position Z is obtained using the strip velocity $v_0(t)$ at which the strip material is passing the pyrometer and the thickness $h_{en,1}$ before the first mill stand in (15). Here, the integration of (15) is started at time t_0 when the head end of the strip is at the pyrometer. This time is detected when the temperature exceeds a certain threshold. This yields the temperature T_{pyro} as a function of the longitudinal strip coordinate Z as shown in Fig. 5. Here, the strip velocity v_0 is known from the velocity of the rolls of the roller table. Possible slip between the roller table and the strip is corrected by synchronization when the head end or the tail end of the strip pass certain photo sensors located along the line. Downstream the pyrometer measurement the crop shear cuts off the head end and the tail end of the strip. This is why the mapping in Fig. 5 starts with negative values $Z < 0$ at $t = 0$. The interval between $Z \in [0, L]$ corresponds to the finished strip. The temperature skid marks originating from the slab reheating furnace are clearly visible in Fig. 5. Thus, the rolling conditions vary over the length of the strip. This is considered in the feedforward controller developed in the following.

3.3 Nominal thickness feedforward control strategy

In general, the idea of feedforward control is to make use of known (future) information of inputs, disturbances, parameters, and reference signals of the process. The information can be various, e. g., desired output signals, known disturbances, or the known evolution of other process variables. Basically, in the feedforward controller, the model is inverted to obtain

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

the required control inputs considering the information known ahead. It is distinguished between static and dynamic feedforward control. In a static feedforward control concept, a static (nonlinear) input-output relation, which may be given in the form of a loopk-up table, is inverted. Dynamic feedforward control also takes into account the dynamics of the system. A commonly used concept belonging to the latter class is flatness-based feedforward control, where the system property of differential flatness, cf. [36], is utilized to simplify the calculation of the control input signals.

The developed feedforward control concept is a static feedforward controller using the static model of the mill stand from Section 2. For the design of the feedforward controller, it is assumed that the subordinate control loops, i. e., the HGC, are operating fast and accurate enough. As shown in the simulations in Section 4, this assumption is well satisfied. Otherwise, the dynamics of the hydraulic circuits could be included in the feedforward controller as well.

The aim of feedforward control is to compensate for known disturbances on the plant such that the system output still follows its reference. For the considered rolling mill, the disturbances are described in Section 3.2, i. e., inhomogeneities of the strip entry temperature and the strip entry thickness. The reference signal is the desired exit thickness profile $h_{ex}^d(Z)$. For an exact model with known disturbances, the output follows its reference without deviations. In reality, however, there are model-plant mismatches and unknown disturbances. This is why there can remain a small output control error if only the nominal feedforward controller is used.

The static disturbance and reference thickness feedforward control concept for a single mill stand is explained in the next paragraphs for the first mill stand. The considered control input is a symmetric adjustment Δx_h^{ff} of the hydraulic cylinders and the controlled variable is the mean exit thickness h_{ex}. That is, the control concept belongs to the category of SISO (single input, single output) feedforward controllers. In [2], a MIMO (multiple input, multiple output) feedforward controller was developed, where all the control inputs available, i. e., the cylinder positions and the bending forces at both sides of the mill stand, are simultaneously used in an optimization-based approach.

Using the measured disturbances h_{en} and T, the measurements for u_R, p_{en}, and p_{ex}, and the desired thickness profile h_{ex}^d in the roll gap model (2) yields the expected total roll force F_R^{ff} as a solution of

$$f_R(F_R^{ff}, h_{en}, h_{ex}^d, b_R, p_{en}, p_{ex}, u_R, k_{fm}) = 0 \,, \tag{16}$$

with the yield stress k_{fm} according to (1). F_R^{ff} is used in the linearized machine model (7) with $h_{ex} = h_{ex}^d$ to obtain the required additional cylinder position

$$\Delta x_h^{ff} = \frac{\Delta F_R^{ff}}{m} - \Delta h_{ex}^d \,. \tag{17}$$

The term $\frac{\Delta F_R^{ff}}{m}$ compensates for the expected extra mill stretch. In (17), the deviations from the nominal operating point a are used, i. e.,

$$\Delta F_R^{ff} = F_R^{ff} - F_R|_a \,. \tag{18}$$

The extra feedforward control input Δx_h^{ff} is simply added to the HGC set-point. Together with the AGC, this yields a two-degrees-of-freedom control structure, i. e., (13) is replaced by

$$x_h^d = x_h|_a + \Delta x_h^{ff} + \Delta x_h^{agc} \,. \tag{19}$$

In the ideal case when the disturbances are exactly known and there is no model-plant mismatch Δx_h^{agc} will be exactly zero, see also (35).

3.4 Parameter estimation

For the nominal feedforward control strategy developed in the previous section, it would be ideal if the parameters k_0, m_1, m_2, and m_3 of the material model (1) were exactly known and if the measurements of the incoming strip thickness and temperature were exact. These material parameters and measurement signals are required for the calculation of the feedforward control inputs in (16). Furthermore, an essential requirement of the presented feedforward control strategy is that the material tracking as described in Section 3.2 is working properly. That is, temperature and thickness signals need to be correctly mapped to the material cross section that is currently in the respective roll gap. In reality, the material

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575

parameters k_0, m_1, m_2, and m_3 are uncertain, the measurement signals may be inaccurate, especially the temperature signal which depends on the uncertain emissivity of the strip surface, and the material tracking can be erroneous. As discussed in [2], wrong material parameters deteriorate the accuracy of the exit thickness using the nominal feedforward controller combined with the AGC. However, the simulation scenario presented in [2] showed that this controller is still superior to the AGC without feedforward control. To reduce the impact of inexact model parameters, here, an adaptive feedforward control approach is proposed. In general, the idea is to adaptively correct specific parameters based on the deviation between the measured roll force and the roll force predicted by the roll gap model (16). The approach may also reduce the impact of inaccurate measurement signals. For instance, gain or offset errors of the measurements can be compensated by modifying specific model parameters. Moreover, tracking errors can be corrected by shifting the signals by an adaptively identified position offset.

First, multiplicative adaption parameters $\hat{k}_k$ and $\hat{k}_T$ for the nominal material parameters k_0 and m_1 are introduced, i. e., $\hat{k}_k k_0$ and $\hat{k}_T m_1$ are used instead of k_0 and m_1 in (1). Similarly, an additive offset $\hat{k}_Z$ is introduced to distinguish between the nominal Lagrangian coordinate Z and its true counterpart $Z+\hat{k}_Z$ for the measurements of the entry properties of the strip. For all other model parameters, i. e., m_2 and m_3, it is assumed that they are exactly known. Using these adaption parameters, the material model (1) for the mean yield stress can be rewritten in the form

$$\hat{k}_{fm}(Z+\hat{k}_Z) = \hat{k}_k k_0 \mathrm{e}^{\hat{k}_T m_1 T(Z+\hat{k}_Z)} \left(\varphi(Z+\hat{k}_Z)\right)^{m_2} \left(\dot{\varphi}(Z+\hat{k}_Z)\right)^{m_3} , \tag{20}$$

with the Lagrangian strip coordinate Z at the first mill stand. The estimated exit thickness $\hat{h}_{ex}$ from (11) and the roll gap model

$$f_R(\hat{F}_R(Z,\hat{\mathbf{k}}), h_{en}(Z+\hat{k}_Z), \hat{h}_{ex}(Z), b_R, p_{en}(Z), p_{ex}(Z), u_R(Z), \hat{k}_{fm}(Z+\hat{k}_Z)) = 0 , \tag{21}$$

can be used to compute the expected roll force $\hat{F}_R(Z,\hat{\mathbf{k}})$ based on the parameter vector $\hat{\mathbf{k}} = \left[\hat{k}_k, \hat{k}_T, \hat{k}_Z\right]$. In (20) and (21), $Z+\hat{k}_Z$ is the independent variable of the incoming measurement signals h_{en} and T that are recorded a few meters upstream of the mill stand. All other measurement signals needed for the adaptive feedforward control strategy, i. e., the exit thickness $\hat{h}_{ex}$, the strip tensions p_{en} and p_{ex}, the rolling velocity u_R, and the roll force F_R, are not shifted because they are measured directly at the first mill stand and they all undergo exactly the same transformation from the time t to the coordinate Z, cf. (15).

To estimate the parameters $\hat{\mathbf{k}}$, the optimization problem

$$\min_{\hat{\mathbf{k}}_i \in \kappa} \quad \int_{Z_i - Z_{hor}}^{Z_i} \left(\hat{F}_R(\zeta,\hat{\mathbf{k}}_i) - F_R(\zeta)\right)^2 \mathrm{d}\zeta + \left(\hat{\mathbf{k}}_i - \hat{\mathbf{k}}_{i-1}\right)^{\mathrm{T}} \mathbf{K} \left(\hat{\mathbf{k}}_i - \hat{\mathbf{k}}_{i-1}\right) \tag{22a}$$

$$\text{s. t.} \quad \hat{F}_R(\zeta,\hat{\mathbf{k}}_i) \text{ from (20) and (21)} \tag{22b}$$

is formulated. The aim is to minimize the difference between the measured total roll force $F_R(\zeta)$ and the predicted roll force $\hat{F}_R(\zeta,\hat{\mathbf{k}}_i)$ during an estimation horizon $[Z_i - Z_{hor}, Z_i]$ with the length Z_{hor} by adapting the parameter vector $\hat{\mathbf{k}}_i$. For robustness, (box) constraints κ can be defined for the adaption parameters $\hat{\mathbf{k}}$. The estimation (22) is carried out at discrete time points t_i where the respective strip position according to (15) is $Z_i = Z(t_i)$. With the positive definite weighting matrix $\mathbf{K}$, changes of the adaption parameters $\hat{\mathbf{k}}$ between two subsequent solutions i and $i-1$ are penalized to avoid fast fluctuations of $\hat{\mathbf{k}}$. With (22), a moving horizon estimation (MHE) or receding horizon estimation (RHE) approach is realized because the error between the measured roll force and the roll force predicted by the model is minimized over the moving estimation horizon $[Z_i - Z_{hor}, Z_i]$, cf. [37].

The optimization problem (22) can be numerically solved utilizing the Gauss-Newton method. To compute the gradient of (22a) with respect to $\hat{\mathbf{k}}_i$, partial derivatives of (20) and (21) are analytically calculated. The derivatives of the measured entry thickness profile h_{en} and the entry temperature profile T with respect to $\hat{k}_Z$ are numerically approximated by central differences. The algorithm terminates if the relative change of the objective function (22a) is below a certain threshold.

3.5 Adaptive thickness feedforward control strategy

In the adaptive feedforward control strategy, the extended model (20) and (21) is used instead of (1) and (2). In fact, the estimation result $\hat{\mathbf{k}}_i$ from (22) is used in the model (20) and

$$f_R(F_R^{ff}, h_{en}, h_{ex}^d, b_R, p_{en}, p_{ex}, u_R, \hat{k}_{fm}) = 0 \tag{23}$$

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575

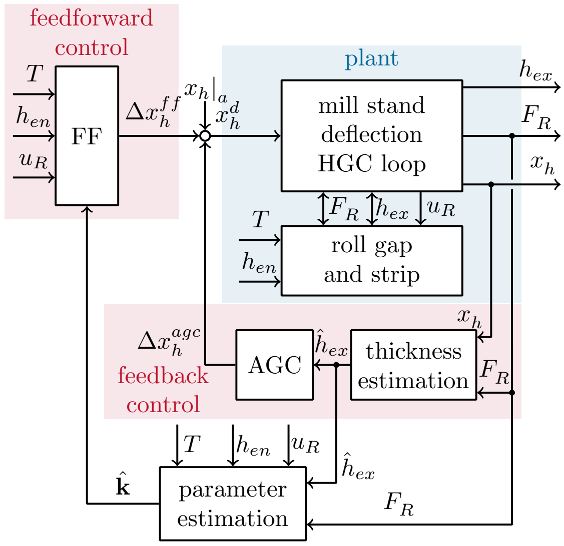

Fig. 6. Closed-loop control structure with the adaptive feedforward control strategy.

to compute the expected roll force F_R^{ff}, which is then used in the feedforward control law (17) and (19).

Fig. 6 shows the control structure with the closed-loop identification of $\hat{\mathbf{k}}$ integrated in the two-degrees-of-freedom control structure. An advantage of this approach is that both the nonlinearities of the model and a possible shift of the longitudinal strip position Z are properly considered. The drawback of this nonlinear approach is the high computational time required to solve the optimization problem (22). The estimation of $\hat{\mathbf{k}}$ does not necessarily have to be executed with the same (fast) sampling rate as the feedforward controller (17). If (22) is solved for instance only every 2 m of the strip, approximately 250 ms are available for updating the parameters $\hat{\mathbf{k}}_i$. The previously estimated values of $\hat{\mathbf{k}}_{i-1}$ are used in the feedforward controller until updated estimations $\hat{\mathbf{k}}_i$ are available.

The proposed feedforward control concept essentially relies on the knowledge of the mill modulus m. This parameter also needs to be correctly known for the estimation of the exit thickness $\hat{h}_{ex}$ in the AGC (11). However, with suitable calibration routines, the correct value of m can be identified for the respective mill configuration. The main advantage of the proposed (adaptive) feedforward control concept is that the steady-state error of the exit thickness is zero, $\hat{h}_{ex} - h_{ex}^d = 0$, whereas for the AGC there is a remaining thickness error for strip entry properties or rolling conditions not equal to the operating point a, cf. Appendix A.

4 Simulation results

To test the presented adaptive feedforward control strategy, a simulation scenario with model-plant mismatch is considered. Here, 10 % error in the temperature coefficient m_1 of k_{fm} from (1) and a shifting error of 1 % in the longitudinal strip position are assumed, i. e., the parameters of (20) and (21) are constant over the strip length L and have the following values: $k_k = 1$, $k_T = 1.1$, and $k_Z = 0.01L$. In the simulation, the measured signals of the disturbances h_{en}, T and u_R from a real strip are used as inputs, cf. Fig. 2. For this scenario, Fig. 7 shows the simulation results of the adaptive feedforward control strategy with AGC compared to the nominal feedforward controller with AGC, and the AGC only. The adaptive feedforward controller achieves a significantly more accurate exit thickness h_{ex} than the feedforward controller with nominal parameters. Because the nominal parameter m_1 is not exact, there are small thickness errors with the nominal feedforward controller (black lines). Additionally, the longitudinal position of the feedforward controller with nominal parameters is inaccurate, i. e., the compensation of the skid marks is not exactly at the correct longitudinal position. The remaining thickness errors of the feedforward controllers are just partly corrected by Δx_h^{agc} of the AGC. The resulting inhomogeneous average exit thickness h_{ex} is shown in Fig. 7.

Fig. 8 shows that the expected roll force F_R^{ff} of the nominal feedforward controller from (16) (dash-dotted black line) does not match the simulated true roll force F_R (solid black line). The resulting roll force F_R of both the nominal and the adaptive feedforward control approach are virtually equal (solid black and solid blue lines) because the influence of the small differences of the exit thickness h_{ex} between the controllers on the roll force is rather small. The adaptive feedforward controller (blue lines in Fig. 8) utilizes the difference between the estimated roll force $\hat{F}_R$ and the actual roll force F_R in the optimization problem (22) to estimate the three uncertain parameters $\hat{\mathbf{k}} = \left[\hat{k}_k, \hat{k}_T, \hat{k}_Z\right]$. The values are initialized with their nominal values, i. e., $\hat{\mathbf{k}}_0 = [1, 1, 0]$. The optimization starts at $Z \approx 70$ m, when enough data from the measurements of this

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575

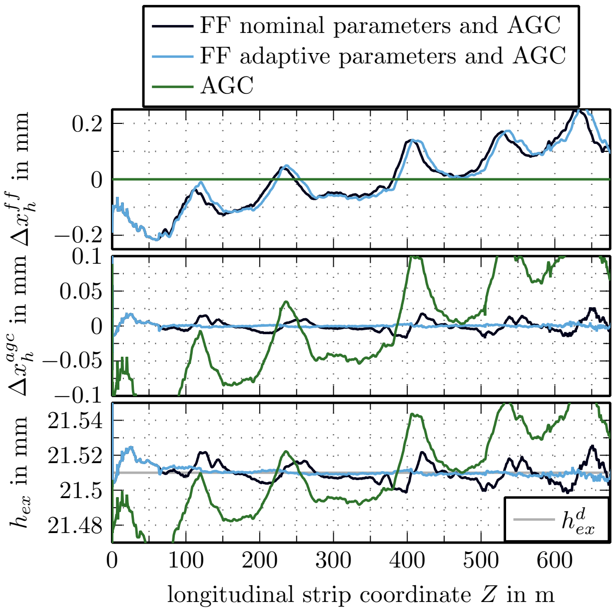

Fig. 7. Simulation results with a model-plant mismatch ($10\,\%$ error in m_1 of (1) and $1\,\%$ of L in Z).

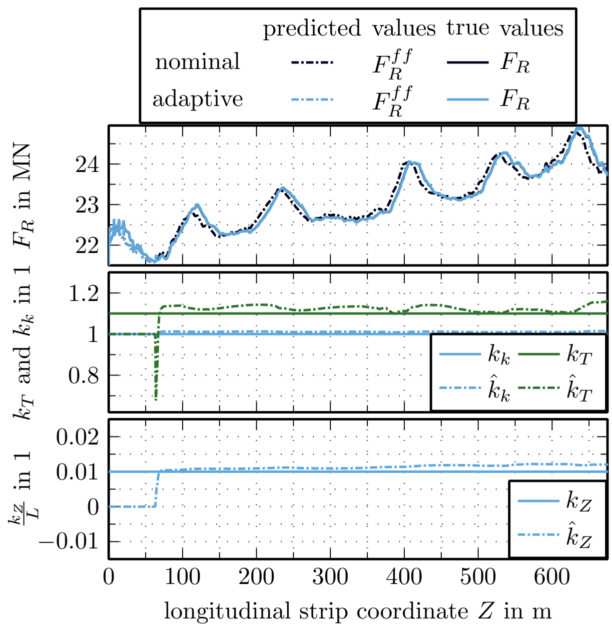

Fig. 8. Predicted roll force and identified parameters with a model-plant mismatch ($10\,\%$ error in m_1 of (1) and $1\,\%$ of L in Z).

strip are available. The estimated parameters $\hat{k}_k$, $\hat{k}_T$, and $\hat{k}_Z$ are also shown in Fig. 8. In the very first place, the estimation of $\hat{k}_T$ shows some error. It converges towards its correct value $k_T = 1.1$ only after the estimation of $\hat{k}_Z$ has converged to its true value $k_Z = 0.01L$. In Fig. 9, the roll force over one exemplary estimation horizon with the length $Z_{hor} = 105\,\mathrm{m}$ is shown in detail. The roll force $\hat{F}_R^{nom}$ estimated with nominal parameters $\hat{\mathbf{k}} = [1, 1, 0]$ is shown as black dash-dotted line. It is shifted left compared to the true roll force F_R (black solid line). With the parameters $\hat{\mathbf{k}}$ estimated as $\hat{k}_k = 1.013$, $\hat{k}_T = 1.119$, and $\hat{k}_Z = 0.011L$ based on (22), the expected roll force $\hat{F}_R$ (blue dash-dotted line) and the true roll force F_R (black solid line) match very accurately.

The estimated parameters $\hat{\mathbf{k}}$ are used to predict the roll force F_R^{ff} in the adaptive feedforward controller. Based on the feedforward control law (17), the expected roll force F_R^{ff} yields the feedforward control signal Δx_h^{ff} shown in blue in Fig. 7.

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

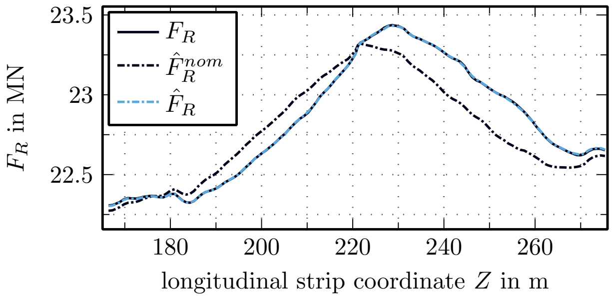

Fig. 9. Simulation results of the roll force F_R for a single estimation horizon with a model-plant mismatch ($10\,\%$ error in m_1 of (1) and $1\,\%$ of L in Z).

For the first few meters, the adaptive feedforward signal equals the nominal feedforward signal. After the estimation has started, the feedforward control signal Δx_h^{ff} is correctly delayed. Because the adaptive feedforward controller accurately predicts the roll force F_R, its control signal Δx_h^{ff} is almost ideal and there remains only a very small thickness error to be corrected by the AGC. Consequently, the mean exit thickness h_{ex} almost equals the desired exit thickness h_{ex}^d. Fig. 7 clearly shows the benefit of the adaptive feedforward control concept (blue line) compared to the nominal feedforward controller (black line).

5 Implementation on an industrial hot strip rolling mill

First simplified versions of the nominal and of the adaptive feedforward control strategy were implemented at the first mill stand of the finishing mill of voestalpine in Linz, Austria.

5.1 Nominal feedforward control strategy

This implementation uses the inversion-based feedforward control concept for the mean strip thickness as proposed in Section 3.3. Instead of the nonlinear roll force model (16), a linearized version of (16) is used to compute the deviation of the expected roll force ΔF_R^{ff} from the nominal operating point a. That is, the influence of the strip temperature T, the strip entry thickness h_{en}, and the strip exit thickness h_{ex} on the total roll force F_R is linearized. Thus, the nominal scalar sensitivities $\frac{\partial F_R}{\partial h_{en}}\Big|_a$, $\frac{\partial F_R}{\partial T}\Big|_a$, and $\frac{\partial F_R}{\partial h_{ex}}\Big|_a$ are utilized for the implementation. These nominal sensitivities can be numerically obtained for each rolled strip from the roll gap model (5) using difference quotients. The scalar feedforward control action is then obtained from (17) in the form

$$\Delta F_R^{ff} = \Delta h_{en} \frac{\partial F_R}{\partial h_{en}}\Big|_a + \Delta T \frac{\partial F_R}{\partial T}\Big|_a + \Delta h_{ex}^d \frac{\partial F_R}{\partial h_{ex}}\Big|_a \tag{24a}$$

$$\Delta x_h^{ff} = \frac{\Delta F_R^{ff}}{m} \,. \tag{24b}$$

With $\Delta h_{ex}^d = 0$, the last term in (24a) vanishes. Hence, the expected variations of the roll force ΔF_R^{ff} are calculated based on the measured differences Δh_{en} and ΔT of the entry thickness and temperature, respectively, from their values at the nominal operating point a. The strip velocity or other variations that influence the roll force are not considered in the current implementation.

5.2 Adaptive feedforward control strategy

The basic concept of the adaptive feedforward controller developed in Section 3.4 also serves as the basis for extending the nominal feedforward controller of the previous section. Again, the linearized roll gap model (24a) is used for the estimation of the roll force. To get an accurate estimation of the roll force despite the missing sensitivity terms for the increased rolling velocity and cool-down towards the tail end of the strip, a constant $\hat{k}_0$ and a linear term $\hat{k}_1 Z$ are added to the linearized model (24a). Hence, the identification model takes the form

$$\Delta\hat{F}_R(Z) = \hat{k}_0 + \hat{k}_1 Z + \Delta h_{en}(Z+\hat{k}_Z) \frac{\partial F_R}{\partial h_{en}}\Big|_a + \Delta T(Z+\hat{k}_Z)\hat{k}_T \frac{\partial F_R}{\partial T}\Big|_a + \Delta\hat{h}_{ex}(Z) \frac{\partial F_R}{\partial h_{ex}}\Big|_a \,, \tag{25}$$

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

with the estimation parameters $\hat{\mathbf{k}} = [\hat{k}_0, \hat{k}_1, \hat{k}_T, \hat{k}_Z]$. Similar to (20), the factor $\hat{k}_T$ amplifies the nominal sensitivity $\left.\frac{\partial F_R}{\partial T}\right|_a$ of the roll force with respect to the strip temperature. The sensitivities with respect to the entry thickness $\left.\frac{\partial F_R}{\partial h_{en}}\right|_a$ and the exit thickness $\left.\frac{\partial F_R}{\partial h_{ex}}\right|_a$ are assumed to be exactly known. Again, the parameter $\hat{k}_Z$ is used to shift the position Z of measurement signals in order to correct strip tracking errors. The parameters $\hat{\mathbf{k}}$ are identified by solving the optimization problem

$$\min_{\hat{\mathbf{k}}_i \in \kappa} \quad \int_{Z_i - Z_{hor}}^{Z_i} \left(\Delta\hat{F}_R(\zeta, \hat{\mathbf{k}}_i) - \Delta F_R(\zeta)\right)^2 \mathrm{d}\zeta + \left(\hat{\mathbf{k}}_i - \hat{\mathbf{k}}_{i-1}\right)^{\mathrm{T}} \mathbf{K} \left(\hat{\mathbf{k}}_i - \hat{\mathbf{k}}_{i-1}\right) \tag{26a}$$

$$\text{s. t.} \quad \Delta\hat{F}_R(\zeta, \hat{\mathbf{k}}_i) \text{ from (25)} , \tag{26b}$$

which is similar to (22). In the adaptive feedforward controller, the identified parameters $\hat{k}_T$ and $\hat{k}_Z$ are used in the control law (24) with $\Delta h_{ex}^d(Z) = 0$,

$$\Delta F_R^{ff}(Z) = \Delta h_{en}(Z + \hat{k}_Z) \left.\frac{\partial F_R}{\partial h_{en}}\right|_a + \Delta T(Z + \hat{k}_Z)\hat{k}_T \left.\frac{\partial F_R}{\partial T}\right|_a \tag{27a}$$

$$\Delta x_h^{ff}(Z) = \frac{\Delta F_R^{ff}(Z)}{m} . \tag{27b}$$

Note that only variations of Δh_{en} and ΔT are considered in the adaptive feedforward controller implemented on the plant. Thus, the term $\hat{k}_0 + \hat{k}_1 Z$ appearing in (25) is omitted in (27a).

6 Measurement results

Fig. 10 shows measurement results from the pilot installation of the nominal feedforward control strategy presented in Section 5.1. The influence of the skid marks on the roll force ΔF_R^{ff} predicted by the feedforward controller is slightly too high for this strip. Hence, the feedforward control input Δx_h^{ff} from (24b) is overcompensating the inhomogeneities of ΔT and Δh_{en}. Consequently, the exit thickness h_{ex} (not shown in Fig. 10) is also inhomogeneous and the AGC corrections have to counteract the feedforward signal. This behavior can be observed by comparing the nominal feedforward control signal Δx_h^{ff} and the AGC signal Δx_h^{agc}, especially at the skid marks $Z \approx 0.4L$ and $Z \approx 0.62L$ in Fig. 10. Because of the cool-down towards the tail end of the strip and the increasing rolling velocity, the measured roll force ΔF_R (green line) is increasing with increasing strip position Z. These effects are not considered in the implemented feedforward control strategy (24). Thus, the predicted roll force ΔF_R^{ff} (black line) contains only local variations, which are mainly due to the skid marks. The negative spike of the measured roll forces at $Z \approx 0.85L$ is associated with clamping of the strip for a short time in the crop shear, which cuts off the tail end of the strip. This entails a peak in the entry-side strip tension and a temporary reduction of the roll force.

The identification result for an estimation horizon of length $Z_{hor} = 0.25L$ is shown in Fig. 11. The same strip as in Fig. 10 was used for this identification. The measured roll force ΔF_R is shown as a black line. The estimated roll force $\Delta\hat{F}_R$

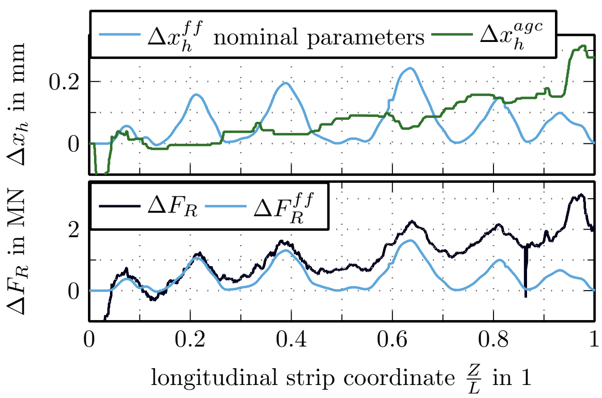

Fig. 10. Behavior of the nominal feedforward controller (combined with AGC) at the industrial plant with incorrect nominal sensitivities in the roll force model (24).

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

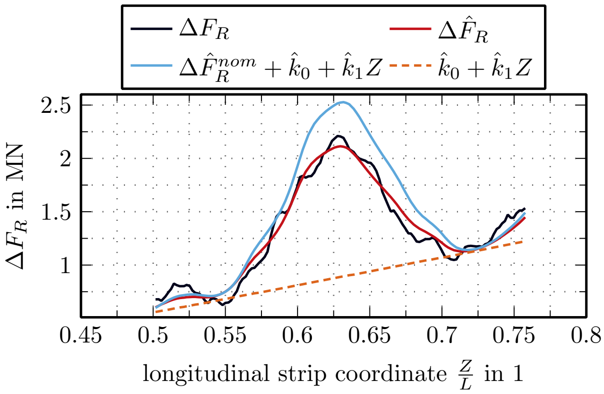

Fig. 11. Estimation of the roll force for a single estimation horizon (length $Z_{hor} = 0.25L$) with $\hat{k}_T = 0.716$ and $\hat{k}_Z = -0.0022L$ for the strip shown in Fig. 10.

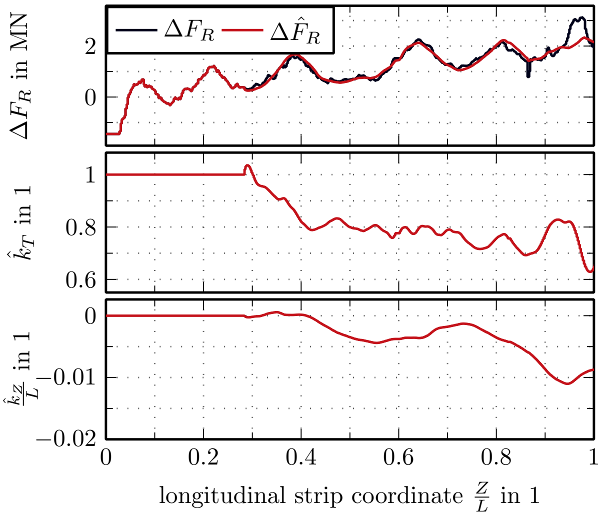

Fig. 12. Parameter estimation at the first mill stand for the strip of Fig. 10.

with parameters $\hat{\mathbf{k}}$ identified based on (26) is shown as a red line. The dashed orange line shows the estimated linear function $\hat{k}_0 + \hat{k}_1 Z$. This linear approximation is also added to the roll force $\Delta\hat{F}_R^{nom}$ estimated based on nominal parameters $k_T = 1$ and $k_Z = 0$, which gives the blue line in Fig. 10. The inaccuracy of the estimation $\Delta\hat{F}_R^{nom}$ with nominal parameters (blue line) can be clearly seen, while the adaptive estimation $\Delta\hat{F}_R$ (red line) is accurately following the measured roll force ΔF_R (black line).

The estimation results for the complete strip length are shown in Fig. 12. All estimation parameters are initialized with their nominal values. Both parameters $\hat{k}_T$ and $\hat{k}_Z$ are then decreasing. Generally, the measured roll force ΔF_R (black line) can be accurately approximated by the estimated roll force $\Delta\hat{F}_R$ from the linear model (25) (red line). Based on the estimated value $\hat{k}_T < 1$ in Fig. 12, the feedforward control input is reduced by the adaptive feedforward controller. Consequently, a more accurate strip exit thickness can be expected with the adaptive feedforward control strategy.

Fig. 13 shows measurement results of the adaptive feedforward control stategy presented in Section 5.2, see also Fig. 6 for the overall control structure. The chosen estimation horizon has the length $Z_{hor} = 0.25L$, meaning that the estimation is started after $Z_{hor} = 0.25L$ of the strip length has been rolled. The parameters $\hat{k}_T$ and $\hat{k}_Z$ are restricted by the box constraints $0.5 \leq \hat{k}_T \leq 2$ and $-0.03L \leq \hat{k}_Z \leq 0.03L$, respectively. However, in the scenario shown in Fig. 13, these constraints are never active. Fig. 13 shows the control inputs of the nominal and the adaptive feedforward controller Δx_h^{ff} (with the adaptive one being actually used), the AGC feedback signal Δx_h^{agc}, the measured roll force ΔF_R, the estimated roll force $\Delta\hat{F}_R$, the expected roll force ΔF_R^{ff} according to the nominal and to the adaptive feedforward controller, the estimated parameters $\hat{k}_T$ and $\hat{k}_Z$, the exit thickness $\Delta\hat{h}_{ex}$ (normalized with respect to the average exit thickness after the first mill stand), and the slope-corrected exit thickness $\Delta\hat{h}_{ex} - p_h(Z)$. With the adaptive feedforward controller, the variations of the exit thickness are further reduced

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

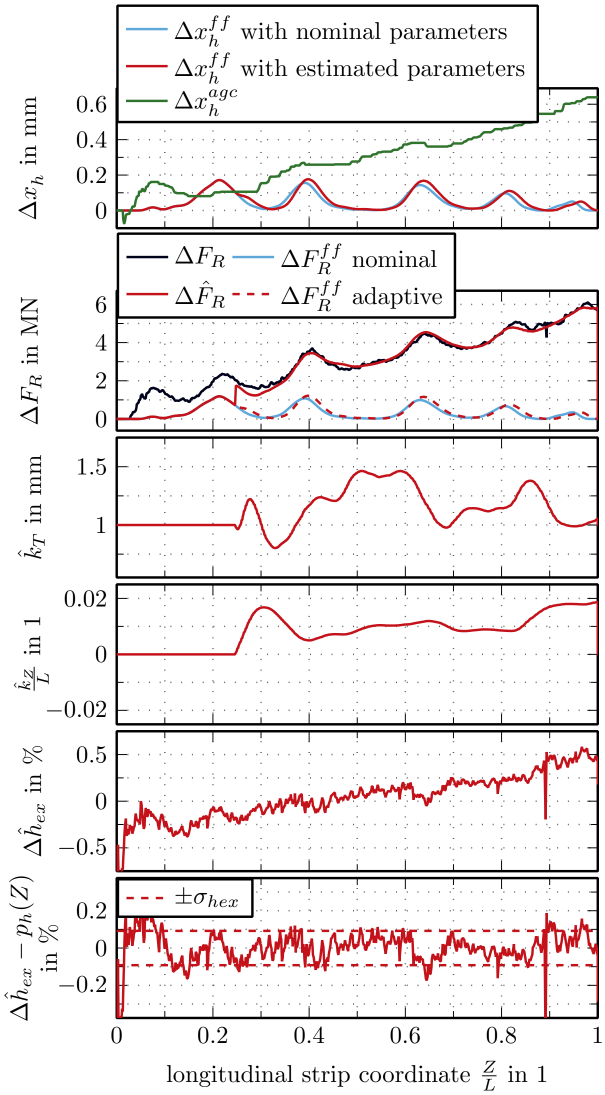

Fig. 13. Estimated parameters and results of the adaptive feedforward controller for a sample strip at the first mill stand.

compared to the nominal feedforward control strategy. Therefore, the AGC is correcting only a slowly changing (increasing) thickness error. The correction of the slope of the exit thickness h_{ex} with the 1st-order polynomial $p_h(Z)$ is required for a fair comparison of the accuracy of the thickness control approaches. For safety reasons, the feedforward control input Δx_h^{ff} is limited in this pilot installation to the range $-0.3\,\mathrm{mm} \leq \Delta x_h^{ff} \leq 0.3\,\mathrm{mm}$. This is why, in the currently implemented feedforward control concepts, the increase of the roll force over the strip length due to cool-down of the strip and increasing rolling speed is still left out. Only the high-frequency disturbances, e. g. caused by the skid marks, are compensated. This yields the slowly increasing exit thickness $\Delta\hat{h}_{ex}$ as shown in Fig. 13. As discussed in Section 3.1, it is possible to correct the remaining low-frequency thickness errors of the (adaptive) feedforward controller (constant or changing very slowly) with a proportional and integral feedback thickness controller at the end of the tandem rolling mill.

The control strategies were also tested with other strips. The population standard deviation σ_{hex} of the slope-corrected thickness error $\Delta\hat{h}_{ex} - p_h(Z)$ computed for the whole strip length L is used as an aggregate measure of the accuracy of the exit thickness of each strip,

$$\sigma_{hex} = \sqrt{\frac{1}{L}\int_0^L \left(\Delta\hat{h}_{ex}(Z) - p_h(Z)\right)^2 \mathrm{d}Z}\,. \tag{28}$$

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

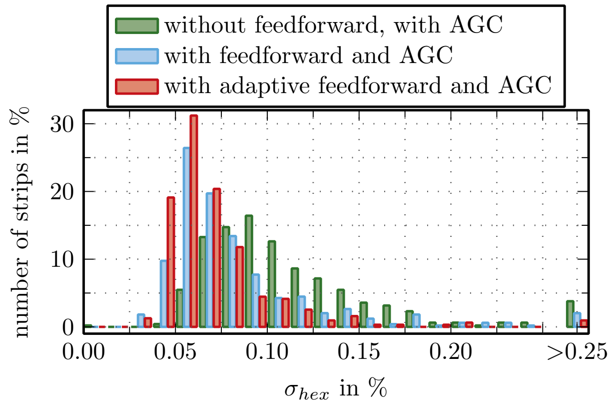

Fig. 14. Frequency distribution of the standard deviation (28) of the slope-corrected exit thickness at the first mill stand of an industrial finishing mill with linearized nominal feedforward thickness controller and AGC (blue bars, 492 strips), with AGC alone (green bars, 475 strips), and with adaptive feedforward thickness controller and AGC (red bars, 314 strips).

The standard deviation for the strip is shown with dashed lines in the bottom part of Fig. 13. The standard deviation σ_{hex} was calculated for 492 strips rolled with the nominal feedforward controller (24) and AGC, for 314 strips with the adaptive feedforward controller (27) and AGC, and for 475 strips with AGC (12) only. Fig. 14 shows the frequency distribution of the standard deviations for these strips. This demonstrates that σ_{hex} is significantly lower with the nominal feedforward control strategy (mean value 0.085 %) compared to the situation without feedforward control (mean value 0.115 %). The adaptive feedforward controller (red bars in Fig. 14) even further reduces the standard deviations (mean value 0.072 %). The number of strips with large standard deviations is drastically reduced with the feedforward controllers. The adaptive feedforward controller is now in continuous operation hot strip rolling mill of voestalpine in Linz, Austria.

7 Conclusions and outlook

An adaptive feedforward control strategy for thickness control in a hot strip tandem rolling mill was developed. Parameters of the mean yield stress model and a shift of the longitudinal position of the measurement signals are identified. This approach proved useful for uncertain material parameters, possibly wrong measurements, and material tracking errors. In simulation scenarios, the estimation and control approach was validated and the adaptive feedforward control strategy with AGC was shown to achieve a higher accuracy of the strip exit thickness compared to the nominal feedforward controller with AGC and AGC alone. A first simplified version of the parameter estimation strategy has already been implemented at the first mill stand of the considered hot strip rolling mill of voestalpine in Linz, Austria. The developed ideas for the extension with a parameter estimator are straightforwardly transferable to other feedforward control approaches.

Measurement results comparing the standard AGC with the proposed nominal and adaptive feedforward control strategies show how the accuracy of the exit thickness can be improved by the proposed concepts. The adaptive feedforward control strategy is especially interesting for rolling new steel grades with yet unknown material parameters. The estimated values of the material parameters could also be recorded to build and train a database of material parameters for different steel grades.

The measurement results obtained so far from the industrial pilot installation clearly validate the proposed feedforward control concept and encourage the implementation of more features of the proposed feedforward control strategies. The accuracy of the exit thickness after the first mill stand significantly improves if the variations of the entry thickness and strip temperature are systematically compensated by feedforward control. Based on these results, it is planned to implement the feedforward control strategy also at consecutive mill stands, which have a greater effect on the quality of the final strip.

Acknowledgements

The financial support by the Austrian Federal Ministry of Science, Research and Economy, the National Foundation for Research, Technology and Development and voestalpine Stahl GmbH is gratefully acknowledged.

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

Appendix A: Stability and steady-state analysis of the automatic gauge control (AGC) and the feedforward control

The idea of this analysis is based on [38]. For this discussion, a linearized material and roll gap model is assumed, i. e., the roll force is approximated by

$$F_R = F_R|_a - c_m (h_{ex} - h_{ex}|_a) + \delta F_R \,, \tag{29}$$

with the material modulus $c_m > 0$ and the (constant) disturbance δF_R. For a discrete time kT_s with the sampling time T_s, the deflection model (7) with (29) reads as

$$h_{ex,k} = h_{ex}|_a + \frac{1}{m+c_m}\delta F_R - \frac{m}{m+c_m}\Delta x_{h,k} \,, \tag{30}$$

where $h_{ex,k} = h_{ex}(kT_s)$ and $\Delta x_{h,k} = \Delta x_h(kT_s)$. For the subsequent considerations, it is assumed that the subordinate HGC loop for the cylinder position is ideal and the reference position $x^d_{h,k}$ is realized with only one sampling internal delay, i. e., $x_{h,k+1} = x^d_{h,k}$. Thus from (12) and (13), we get

$$\Delta x_{h,k+1} = -\frac{k_{agc} m}{m+c_m}\Delta x_{h,k} + \frac{k_{agc}}{m+c_m}\delta F_R - k_{agc}\Delta h^d_{ex} \tag{31}$$

From (31) it can be immediately deduced that the time-discrete closed-loop system is stable if the condition

$$\left|\frac{k_{agc} m}{m+c_m}\right| \leq 1 \tag{32}$$

is fulfilled, which gives an upper limit for the proportional gain k_{agc} of the AGC law (12). This finite gain also entails a nonzero steady-state error of the exit thickness. The steady-state position follows from (31) with $\Delta x_{h,k+1} = \Delta x_{h,k} = \Delta x^{ss}_h$ in the form

$$\Delta x^{ss}_h = \frac{k_{agc}}{1+\frac{c_m}{m}+k_{agc}}\frac{\delta F_R}{m} - \frac{k_{agc}\left(1+\frac{c_m}{m}\right)}{1+\frac{c_m}{m}+k_{agc}}\Delta h^d_{ex} \,. \tag{33}$$

Inserting this result into (30) yields the steady-state exit thickness

$$h^{ss}_{ex} = h_{ex}|_a + \frac{1}{1+\frac{c_m}{m}+k_{agc}}\frac{\delta F_R}{m} + \frac{k_{agc}}{1+\frac{c_m}{m}+k_{agc}}\Delta h^d_{ex} \,. \tag{34}$$

Simulation results (including the dynamics of the hydraulic cylinder and the servo valves as well as the subordinate control loops) confirm the validity of the relations (32) and (34). The steady-state thickness h^{ss}_{ex} in (34) equals the desired exit thickness $h_{ex}|_a + \Delta h^d_{ex}$ for $k_{agc} \to \infty$, but (32) limits the gain of the AGC.

With the feedforward control law (17) and (19), (30) takes the form

$$\begin{aligned} h^{ss}_{ex} &= h_{ex}|_a + \frac{1}{m+c_m}\delta F_R - \frac{m}{m+c_m}\underbrace{\left(\frac{\delta F_R - c_m\Delta h^d_{ex}}{m} - \Delta h^d_{ex}\right)}_{\Delta x^{ff}_h} \\ &= h_{ex}|_a + \Delta h^d_{ex} = h^d_{ex} \end{aligned} \tag{35}$$

Here, it is assumed that the model used in the feedforward controller can predict the correct roll force, i. e., $\Delta F^{ff}_R = \delta F_R - c_m\Delta h^d_{ex}$. This means that the disturbance δF_R is supposed to be exactly known. Similar considerations can be made for model-plant mismatch due to inaccurately known material and mill moduli, c_m and m, respectively.

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575

References

[1] Prinz, K., 2017. *Model-based control of the thickness profile in hot strip rolling*, Vol. 37 of *Modellierung und Regelung komplexer dynamischer Systeme*. Shaker Verlag, Aachen.

[2] Prinz, K., Steinboeck, A., and Kugi, A., 2018. "Optimization-based feedforward control of the strip thickness profile in hot strip rolling". *Journal of Process Control,* **64**, pp. 100–111.

[3] Prinz, K., Schausberger, F., Steinboeck, A., and Kugi, A., 2017. "Feedforward control of lateral asymmetries in heavy-plate hot rolling using vision-based position estimation". In Proceedings of the 20th IFAC World Congress, Vol. 50, pp. 11307–11312.

[4] Ginzburg, V., 1993. *High-Quality Steel Rolling*. CRC Press, New York.

[5] Ferguson, I. J., and De Tina, R. F., 1986. "Modern hot-strip mill thickness control". *IEEE Transactions on Industry Applications,* **22**(5), pp. 934–940.

[6] Bilkhu, T. S., 2010. "Hot strip mill gauge control". In UKACC International Conference on Control, pp. 150–155.

[7] Hearns, G., and Grimble, M. J., 2000. "Robust multivariable control for hot strip mills". *Iron and Steel Institute of Japan (ISIJ) International,* **40**(10), pp. 995–1002.

[8] Randall, A., Reeve, P. J., and MacAlister, A. F., 1996. "Disturbance attenuation in a hot strip rolling mill via feedforward adaptive control". In Proceedings of the 13th IFAC World Congress, Vol. 29, pp. 6257–6262.

[9] Rigler, G., Aberl, H., Staufer, W., Aistleitner, K., and Weinberger, K., 1996. "Improved rolling mill automation by means of advanced control techniques and dynamic simulation". *IEEE Transactions on Industry Applications,* **32**(3), pp. 599–607.

[10] Heeg, R., Kiefer, T., Kugi, A., Fichet, O., and Irastorza, L., 2007. "Feedforward control of plate thickness in reversing plate mills". *IEEE Transactions on Industry Applications,* **43**(2), pp. 386–394.

[11] Zárate, L. E., and Bittencout, F. R., 2008. "Representation and control of the cold rolling process through artificial neural networks via sensitivity factors". *Journal of Materials Processing Technology,* **197**(1–3), pp. 344–362.

[12] Wehr, M., Stockert, S., Abel, D., and Hirt, G., 2018. "Model predictive roll gap control in cold rolling with piezoelectric actuators". In Proceedings of the IEEE Conference on Control Technology and Applications (CCTA), pp. 1377–1382.

[13] Stephens, R. I., and Randall, A., 1997. "On-line adaptive control in the hot rolling of steel". *IEE Proceedings - Control Theory and Applications,* **144**(1), pp. 15–24.

[14] Stephens, R. I., Bilkhu, T. S., MacAlister, A. F., and Reeve, P. J., 1999. "Adaptive control for industry: Feedforward control for metal rolling mills". *International Journal of Adaptive Control and Signal Processing,* **13**(2), pp. 71–83.

[15] Wang, J. S., Jiang, Z. Y., Tieu, A. K., Lui, X. H., and Wang, G. D., 2005. "Adaptive calculation of deformation resistance model of online process control in tandem cold mill". *Journal of Materials Processing Technology,* **162–163**, pp. 585–590.

[16] Bai, J. L., Li, X., and Wang, J. S., 2013. "Model adaptive learning in process control of strip cold rolling". *Applied Mechanics and Materials,* **423–426**, pp. 775–779.

[17] Bu, H. N., Yan, Z. W., Zhang, C. M., and Zhang, D. H., 2014. "Comprehensive parameters adaption of rolling force model based on objective function in tandem cold mill". *Applied Mechanics and Materials,* **551**, pp. 296–301.

[18] Pires, C. T. d. A., Ferreira, H. C., and Sales, R. M., 2009. "Adaption for tandem cold mill models". *Journal of Materials Processing Technology,* **209**, pp. 3592–3596.

[19] Atack, P. A., and Robinson, I. S., 1996. "Adaptation of hot mill process models". *Journal of Materials Processing Technology,* **60**(1–4), pp. 535–542.

[20] Cuzzola, F. A., 2008. "A multivariable and multi-objective approach for the control of hot-strip mills". *ASME Journal of Dynamic Systems, Measurement, and Control,* **128**(4), pp. 856–868.

[21] Pittner, J., and Simaan, M. A., 2008. "Optimal control of tandem cold rolling using a pointwise linear quadratic technique with trims". *ASME Journal of Dynamic Systems, Measurement, and Control,* **130**(2), pp. 021006–1–021006–11.

[22] Müller, M., Steinboeck, A., Prinz, K., Ettl, A., Kugi, A., Etzelsdorfer, K., Fuchshumer, S., and Seyrkammer, H., 2019. "Asymmetric hydrodynamic roll gap model and its experimental validation". *International Journal of Advanced Manufacturing Technology,* **100**(9-12), pp. 3101–3111.

[23] Müller, M., Steinboeck, A., Prinz, K., and Kugi, A., 2018. "Optimal parameter identification for a hydrodynamic roll gap model in hot strip rolling". In Proceedings of the 5th IFAC Workshop on Mining, Mineral and Metal Processing (MMM), Vol. 51, pp. 195–200.

[24] Hensel, A., and Spittel, T., 1978. *Kraft- und Arbeitsbedarf bildsamer Formgebungsverfahren*. VEB Deutscher Verlag für Grundstoffindustrie, Leipzig.

[25] Sellars, C., 1978. "Recrystallization of metals during hot deformation". *Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences,* **288**(1350), pp. 147–158.

[26] Sims, R., 1954. "The calculation of roll force and torque in hot rolling mills". *Proceedings of the Institute of Mechanical Engineers,* **168**, pp. 191–200 and 209–214.

[27] Bland, D., and Ford, H., 1948. "The calculation of roll force and torque in cold strip rolling with tensions". *Proceedings*

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.

of the Institution of Mechanical Engineers, **159**, pp. 144–163.
[28] Hosford, W. F., and Caddell, R. M., 2007. *Metal Forming, Mechanics and Metallurgy*. Cambridge University Press, Cambridge, UK.
[29] Orowan, E., 1943. "The calculation of roll pressure in hot and cold flat rolling". *Proceedings of the Institution of Mechanical Engineers,* **150**, pp. 140–167.
[30] Malik, A., and Hinton, J., 2012. "Displacement of multiple, coupled Timoshenko beams in discontinuous nonlinear elastic contact, with application to rolling mills". *ASME Journal of Manufacturing Science and Engineering,* **134**(5), pp. 051009 1–10.
[31] Zhang, F., and Malik, A., 2018. "A roll-stack contact mechanics model to predict strip profile in rolling mills with asymmetric CVC roll crowns". *ASME Journal of Manufacturing Science and Engineering,* **140**(1), pp. 011008–1–011008–15.
[32] Montmitonnet, P., 2006. "Hot and cold strip rolling processes". *Computer Methods in Applied Mechanics and Engineering,* **195**, pp. 6604–6625.
[33] Pittner, J., and Simaan, M. A., 2011. *Tandem Cold Metal Rolling Mill Control; Using Practical Advanced Methods*. Springer, London.
[34] Prinz, K., Steinboeck, A., Müller, M., Ettl, A., and Kugi, A., 2017. "Automatic gauge control under laterally asymmetric rolling conditions combined with feedforward". *IEEE Transactions on Industry Applications,* **53**(3), pp. 2560–2568.
[35] Kugi, A., Schlacher, K., and Novak, R., 2001. "Nonlinear control in rolling mills: A new perspective". *IEEE Transactions on Industry Applications,* **37**(5), pp. 1394–1402.
[36] Fliess, M., Lévine, J., Martin, P., and Rouchon, P., 1995. "Flatness and defect of non-linear systems: introductory theory and examples". *International Journal of Control,* **61**(6), pp. 1327–1361.
[37] Allgöwer, F., Badgwell, T. A., Qin, J. S., Rawlings, J. B., and Wright, S. J., 1999. *Nonlinear Predictive Control and Moving Horizon Estimation – An Introductory Overview*. Springer, London, UK, pp. 391–449.
[38] Heeg, R., 2009. *Modellierung und Dickenregelung beim Warmwalzen*, Vol. 5 of *Modellierung und Regelung komplexer dynamischer Systeme*. Shaker Verlag, Aachen.

List of Figures

Post-print version of the article: K. Prinz, A. Steinboeck, M. Müller, A. Ettl, F. Schausberger, and A. Kugi, "Online parameter estimation for adaptive feedforward control of the strip thickness in a hot strip rolling mill", *Journal of Manufacturing Science and Engineering*, vol. 141, no. 7, pp. 071005-1–071005-12, 2019. DOI: 10.1115/1.4043575
The content of this post-print version is identical to the published paper but without the publisher's final layout or copy editing.