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Optimization-based feedforward control of the strip thickness profile in hot strip rolling

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ABSTRACT

A new feedforward control approach for the thickness profile of the strip in a tandem hot rolling mill is developed. In industry, the automatic gauge control (AGC) concept is widely used for thickness control. The AGC has the disadvantage that it does not consider known disturbances from upstream entities. This is why a number of disturbance feedforward control concepts have been proposed in the literature. These feedforward control strategies typically rely on linearized models and only provide symmetric control inputs for the mean thickness to the hydraulic adjustment system. In this work, an optimization-based feedforward controller for the lateral thickness profile is proposed that fully exploits all degrees of freedom available, i.e., the hydraulic cylinder positions and the bending forces at the drive side and at the operator side of the mill stand. Moreover, it is shown that by linearizing the mill stand model while keeping the nonlinearities from the roll gap model leads to a numerically efficient optimization problem, which is a good compromise between accuracy and computational efficiency. The feedforward controllers are further combined with the AGC in the feedback path in a two-degree-of-freedom controller structure to account for model-plant mismatch. Simulation results for a validated mathematical model and first experimental results from an industrial pilot installation show a significant benefit compared to the existing AGC without feedforward control.

1. Introduction

In hot strip rolling, a central objective is the production of strips with an accurate and uniform thickness. Therefore, at each mill stand of the tandem hot rolling mill considered in this paper, the strip thickness can be adjusted by hydraulic cylinders that move the upper roll stack. Additionally, the mill stands are equipped with a work roll bending system (WRB) to compensate for the bending deflection of the work rolls and to control the strip crown.

1.1. Literature review

The widely used automatic gauge controller (AGC) causes a non-zero steady-state control error of the strip exit thickness for any entry disturbance or deviation from its operating point because of its limited feedback gain [3,7,10]. The disturbance feedforward control concept proposed in [24] estimates the strip temperature and thickness at upstream mill stands and adjusts the setpoint for the hydraulic cylinder position at downstream mill stands. This position adjustment is derived from a linearized model, where only the mean thickness value but not the lateral profile is considered. An additional cylinder position that is equal for both sides of the mill stand is used as control input (SISO FF). In [14], it is suggested to additionally use the bending force in feedforward control.

In other feedforward concepts, the additional hydraulic cylinder position is obtained based on an estimation of the yield stress of the strip material [5,11]. In [17,18], the variations of rolling conditions, e.g., the measured roll force, are divided into variations caused by the roll eccentricities and those caused by strip temperature inhomogeneities. It is possible to identify and distinguish the root of these variations in the frequency domain because the distance between the skid marks and the revolution speed of the rolls are known.

The control concepts known from literature targeting the strip shape, including the flatness of the strip, are merely feedback control structures. In [2], the measurement from a downstream shape meter is used to control the strip flatness using an actuator influence matrix. This causes a dead time (transport delay) in the controlled plant. In fact, the distance between measurement

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Nomenclature

Abbreviations

AGC	automatic gauge control
BR	backup roll
CVC	continuous variable crown
DS	drive side
FF	feedforward control
HGC	hydraulic gap control
MIMO	multiple input, multiple output
OS	operator side
SISO	single input, single output
TCW	thermal and wear crown
WR	work roll
WRB	work roll bending
WRS	work roll shifting

Variables

x, y, z	Cartesian coordinates
$\tilde{b}$	parameter used in cost function
b_{br}	distance between hydraulic cylinders
b_c	face length of backup roll
b_R	material width
b_{wrb}	distance between hydraulic WRB cylinders
c_m	mill modulus
c_i	crown of the roll
e	thickness error defined in cost function
F_B	force applied to the BR bearing
F_f	frictional force
F_R	roll force
F_{bal}	balancing force
F_h	force of the hydraulic main cylinder
f_R	roll gap model
f_s	static mill stand model
F_{wrb}	work roll bending force
g	gravitational acceleration
h_0	height of unloaded roll gap
h_{en}	material entry thickness
h_{ex}	material exit thickness
k_B	feedback gain of AGC
k_0, m_1, m_2, m_3	coefficients for yield stress
$K_{B,i}$	bending stiffness of the beam i
k_{fm}	yield stress
$K_{S,i}$	shear stiffness of the beam i
L	length of the finished strip
l_d	length of the contact arc
m	mass of the moving parts (upper roll stack)
M_i	bending moment of the beam i
N	number of discretization elements
N_z	number of discretization elements
p_{en}	strip tension at entry side
p_{ex}	strip tension at exit side
$p_h(z)$	polynomial approximating the exit thickness
Q_i	shear force of the beam i
q_c	local contact force
q_{roll}	local roll force
s_{wrs}	WR shifting position
T_{en}	material entry temperature
u_R	rolling velocity
v_i	deflection of the beam i
w	exit thickness wedge
x_h	HGC cylinder position
$\boldsymbol{\Phi}_k, \boldsymbol{\Gamma}_k$	solution of linearized ODE
$\mathbf{A}, \mathbf{b}$	system of linearized static mill stand model
$\mathbf{A}_k, \mathbf{b}_k$	linearized ODE
$\mathbf{u}$	vector of inputs
$\mathbf{y}_k$	state vector for boundary value problem
δ_{bw}	compression between WR and BR
δ_B	displacement of the hydrodynamic bearing
δ_{wr}	flattening of the WR
σ_{hex}	standard deviation of the thickness error
φ	degree of deformation
φ_i	angle of rotation of the beam i
ξ_{cal}	calibration offset of roll gap height

Subscripts and superscripts

$_{AGC}$	output of AGC
$_{br}$	backup roll
$_{cal}$	calibration parameter
$_{DS}$	drive side
$_{en}$	entry side of roll gap
$_{ex}$	exit side of roll gap
$_{FF}$	output of feedforward
$_{l}$	lower roll
$_{opt}$	output of optimization
$_{OS}$	operator side
$_{u}$	upper roll
$_{d}$	desired values
	operating point
*	optimal values
Δ	difference to operating point
$\dot{}$	time derivative
$\hat{}$	estimated values
$\vert_A$	operating point
$'$	derivative with respect to x
†	matrix pseudoinverse

and control input can be very large, like in tandem rolling, where the shape meter measurement is typically located several meters after the last mill stand. A model predictive control (MPC) approach is used in [2] to obtain the control inputs for each mill stand. The system synchronizes the control action to compensate for the transport delay of the strip. A MIMO control method for the strip flatness based on roll bending is discussed in [21].

Other research works, see, e.g., [8,20], deal with finding the optimal interstand crowns. The aim is to prevent wavy edges and center buckles and to determine the control parameters for the Level 2 setup. These setup control parameters are constant within each strip and thus disregard inhomogeneities of the strip in longitudinal direction.

1.2. *Motivation and objective of this paper*

The main goal of this paper is to develop a thickness control strategy that realizes the desired target exit thickness profile over the complete length of the strip as accurately as possible. The deviation of the lateral exit thickness profile from a desired profile should be systematically minimized using all available control inputs, i.e., the hydraulic cylinder position of the backup rolls at both sides of the mill stand, operator and drive side, and the bending forces at both sides of the work rolls. The proposed concept is a multi-input multi-output feedforward (MIMO FF) controller that yields the optimal transient control inputs, and will be described in Section 4. To calculate the (expected) exit thickness profile for the measured disturbances, a mathematical model of the mill stand is required. The model presented in Section 2 uses well-known sub-models (Sims roll gap model, Hensel–Spittel material model, Hertzian contact model, Timoshenko beam model).