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Mathematical Model and Stability Analysis of the Lateral Plate Motion in a Reversing Rolling Mill Stand

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Abstract: This paper deals with the stability analysis of the lateral plate motion in a reversing rolling mill for heavy plates. Lateral asymmetries in the rolling process can cause a rotation and a lateral motion of the plate in the mill stand. In the worst case, the lateral motion of the plate may lead to crashes of the plate with the mill stand. In this work, a mathematical model of the plate motion based on a time-free formulation is presented. The derivation of the equations of motion is based on the material derivative of the plate centerline. The model can capture the influence of edger rolls and side guides as well as asymmetric mill stand deflection due to asymmetric rolling forces. The stability of the plate movement is analyzed for different operating scenarios.

Keywords: Steel industry, plate rolling, lateral motion, dynamic model, stability, strip steering

1. INTRODUCTION

In heavy-plate hot rolling mills, heavy plates are produced according to customers' requirements. Typically, the thickness and the width of the plates are specified by the customer. The thickness of the plate is reduced in a rolling mill stand in successive, reversing rolling passes. The plate width is reduced with edger rolls, which are located at the entry side of the mill stand. Before each rolling pass, the plate is centered with side guides. However, it is not unusual to see the mill stand operator using the side guides as steering device during a rolling pass. Ideally, the finished plate has a straight rectangular shape. Especially, it should not have any shape defects like camber. Furthermore, the thickness profile should be uniform both in longitudinal and lateral direction.

Modeling and control of the plate contour and the plate thickness profile are covered to great extent in the literature of heavy-plate rolling. Existing camber models are reviewed in (Steinboeck et al., 2017). Concepts for camber control are described, e.g., in (Cuzzola and Dieta, 2003; Schausberger et al., 2016, 2017; Tanaka et al., 1987). In (Prinz et al., 2017a), a feedforward thickness controller for laterally asymmetrical rolling conditions is proposed.

Lateral motion and its stability, however, are mainly analyzed for strip rolling in tandem rolling mills, cf. (Gates and Tarnopolskaya, 2008; Ishikawa et al., 1988; Tarnopolskaya et al., 2005). For heavy-plate rolling, Prinz et al. (2017a) showed in simulation studies that lateral asymmetries can cause an unstable lateral plate motion. This motion may lead to crashes of the plate with the mill stand.

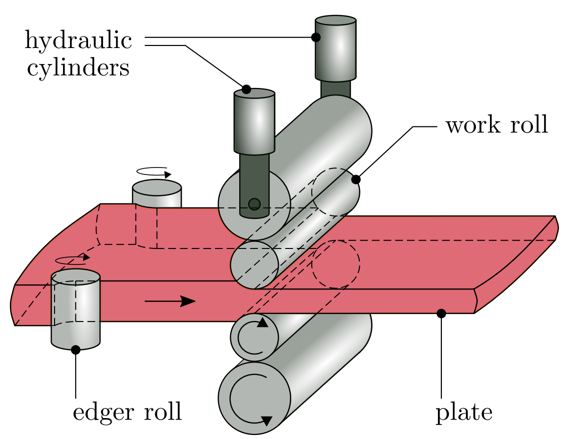

Fig. 1. Reversing rolling mill stand.

The main objective of this paper is to present a stability analysis of the lateral plate motion in heavy-plate rolling. In particular, this work presents mill stand operating scenarios which lead to a stable plate motion. Furthermore, the model may also serve as a basis for further control tasks like steering of the plate. A reversing mill stand as considered in this work is outlined in Fig. 1. The plate is deformed in the roll gap by two work rolls. While the lower roll stack is fixed at the mill stand frame, the upper roll stack can be moved by two hydraulic cylinders to adjust the roll gap height. Figure 1 also shows the edger rolls which are used to reduce the width of the plate.

This paper is structured as follows: The mill stand operating scenarios considered in this work are described in Section 2. A mathematical model of the lateral plate

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motion is derived in Section 3. In Section 4, the stability of the system is examined for the scenarios defined in Section 2. The main findings of this work are summarized in Section 5.

2. MILL STAND OPERATING SCENARIOS

The influence of different boundary conditions associated with other plant components that can touch the up- or downstream plate, e.g. edger rolls, side guides, and coil boxes, is studied in six different scenarios. The considered kinematic relations are identical in all scenarios, but the external loads acting on the plate vary. In each scenario, the cases of a strictly symmetric roll gap height and a laterally asymmetric roll gap height are distinguished. Laterally asymmetric rolling conditions and an asymmetric roll force distribution entail an asymmetric mill stretch and thus a tilt of the work rolls. A potential reason for such asymmetries is a lateral off-center position of the plate.

Figure 2 shows a top view of the plate in the mill stand and the external load acting on the plate. The external lateral load is defined in the form $F_e = F_0 - k_I w(-l)$, where F_0 is a constant force. The expression $-k_I w(-l)$ describes a force which is proportional to the lateral displacement $w(-l)$ of the plate at $z = -l$. The factor k_I thereby denotes the stiffness of the plant components that touch the plate, such as edger rolls or side guides. The six scenarios analyzed in this work are listed in Tab. 1.

Table 1. Scenarios of the plate movement.

Scenario	Operating scenario	Location of load
1	$F_0 = 0,\ k_I = 0$	-
2	$F_0 > 0,\ k_I = 0$	Entry side or exit side
3	$F_0 = 0,\ k_I \in (0, \infty)$	Entry side
4	$F_0 = 0,\ k_I \to \infty$	Entry side
5	$F_0 = 0,\ k_I \in (0, \infty)$	Exit side
6	$F_0 = 0,\ k_I \to \infty$	Exit side

Scenario 1 assumes $F_e = 0$, i.e., unrestricted motion of the plate. In this scenario, the plate outside the roll gap is considered to be a rigid body. In scenario 2, a constant force F_0 is applied to the plate by, e.g., the edger rolls. It will be shown that the stability of the plate motion in scenario 2 does not depend on the side on which the external load acts on the plate. The compliance of the hydraulic system of the edger rolls is considered in scenario 3 in form of an external load which is proportional to the lateral displacement of the plate. In scenario 4, the influence of the side guides is studied. The side guides are positioned and mechanically locked before a rolling pass. Hence, it is assumed that the lateral position of the plate is prescribed by the side guides and therefore $k_I \to \infty$. The external loads in scenarios 5 and 6 match the external loads of scenarios 3 and 4. In scenario 5 and 6, however, the external load acts on the plate at the exit side of the mill stand, i.e., at $z = l$.

3. MATHEMATICAL MODEL

In this section, a dynamical model of the lateral motion and the rotation of the plate at the mill stand is derived. The equations of motion are based on the material derivative of the plate centerline. Inputs of the model are the lateral asymmetries of the roll gap height, the plate thickness at the entry of the roll gap, and the entry-side tensile stress in the plate. For a shorter notation, the argument t is omitted throughout the whole paper.

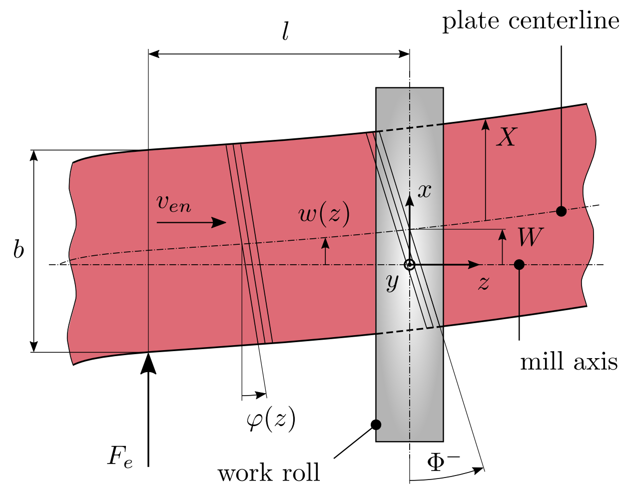

Fig. 2. Mill stand and plate in top view.

A top view of the plate and the mill stand is shown in Fig. 2. The global coordinate frame (x, y, z) is attached to the center of the mill stand. The mean entry velocity of the plate is denoted by v_{en}. Quantities at the entry side of the roll gap $(z \to 0^-)$ are denoted by a superscript $-$, quantities at the exit side of the roll gap $(z \to 0^+)$ by a superscript $+$. In the roll gap, zero lateral material flow is assumed. The lateral motion of the plate is characterized by the lateral displacement of the centerline $w(z)$ and the angular deflection of the cross section $\varphi(z)$. The Lagrangian coordinate X, which is measured from the plate centerline, is introduced for parametrizing quantities in lateral direction. It is defined in the range $X \in [-b/2, b/2]$, where b is the width of the plate. X is assumed to point into the direction of x. Throughout this paper, laterally asymmetric profiles are approximated by Taylor series expansions truncated after the linear term, i.e., terms of higher order are neglected (cf. Prinz et al., 2017b). Consequently, the roll gap height in lateral direction is defined by

$$H(X) = \bar{H} + \tilde{H}(X) = \bar{H} + \Delta H X/b, \tag{1}$$

where $\bar{H} = (H(b/2) + H(-b/2))/2$ is the mean thickness and $\Delta H = H(b/2) - H(-b/2)$. Similarly, the plate entry thickness profile in lateral direction is written in the form

$$h(X, z) = \bar{h}(z) + \tilde{h}(X, z) = \bar{h}(z) + \Delta h(z) X/b, \tag{2}$$

with $\bar{h}(z) = (h(b/2, z) + h(-b/2, z))/2$ and the so-called thickness wedge $\Delta h(z) = h(b/2, z) - h(-b/2, z)$. With the definitions (1) and (2), the mean thickness ratio in the roll gap $(X = 0)$ follows in the form

$$\lambda = \bar{h}(0^-)/\bar{H} \geqslant 1. \tag{3}$$

Let W be the lateral position of the plate at the mill stand and Φ the angular deflection at the mill stand. As explained in (Steinboeck et al., 2017), the angular deflection Φ is generally discontinuous in the roll gap, i.e., generally $\Phi^- = \lambda \Phi^+$. In this work, Φ^- is chosen to describe the rotational movement of the plate cross sections. The lateral tensile stress profile $\Sigma^-(X, z)$ at the entry side of the roll gap and $\Sigma^+(X, z)$ at the exit side of the roll gap can be written as