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Model Predictive Control with Linear Programming for the Strip Infeed in Hot Rolling Mills

Galkina, A. * **Gafur, I.** ** **Schlacher, K.** *

* *Institute of Automatic Control and Control Systems Technology, Johannes Kepler University Linz, Altenberger Strasse 69, 4040 Linz, Austria,(e-mail: anastasiia.galkina@jku.at).*
** *Primetals Technologies GmbH, Erlangen, Germany,(email: ilhom.gafur@primetals.com).*

Abstract: A model-based predictive approach is proposed for the strip head motion control during the steel strip infeed in hot rolling finishing mills. The design is based on a nonlinear simplified mathematical model in a form of ordinary differential equations. It is already shown that this model captures the behavior of FEM models for the strip and the roll gap in an excellent manner. Then the simplified time variant linear model is considered and the discrete-time model is derived in a straightforward manner. In addition the property of flatness is exploited to derive an efficient formulation for the optimization problems. We develop an optimal controller based on a linear programming and compare it with standard quadratic programming. It is shown that the proposed linear program is both more efficient than the quadratic program and the performance is equivalent. Therefore, the linear approach is convenient for the real-time application even without high performance computers. The proposed controller is tested in a co-simulation environment using FEM element model for the strip integrated in Hotint together with a highly nonlinear roll gap model. The simulation results show the excellent accordance of the controlled infeed process for both models (ODE and FEM), as well as the high performance of the closed loop.

Keywords: Advanced process control, Process optimization, Real time optimization and control

1. INTRODUCTION

In a hot rolling mill the incoming steel slabs are transformed into thin hot rolled coils. Functionally, the mill consists of two parts: roughing mill and finishing mill. The slabs are passed forwards and backwards through the roughing stand several times. During each pass the slab thickness is reduced by rolling it between two parallel rolls while moving the work rolls. Afterward the steel work piece passes through a series of finishing mill stands. One of the undesired effects, which can arise because of numerous uncontrollable factors, is strip camber (the strip forms a curve in the rolling plane) both in the roughing stand and in the finishing mill. The sources are for example: an asymmetric temperature distribution across the strip width (a temperature distribution of 100 K between both sides of the slab corresponds to a rolling force difference of about 22%, resulting in different thickness reductions on the two sides of the strip and thus leads to the strip camber Lukasson-Herzig (2007)), asymmetric input thickness profile, different wear etc. The curved strip will have not only a negative impact on the strip quality, but can even cause stops in the rolling process, due to *collision with side guides*. To avoid the collisions and therefore, quality reduction, different control strategies were proposed in recent decades. At the same time advanced control techniques, such as model predictive control, have been widely applied in industry. Model predictive control is one of few suitable methods for the process with different, sometimes contradictory, quality requirements and technical constraints.

1.1 State of the art of the camber/off-center modeling and control

The strip camber is a well-known problem in hot rolling. In most of the publications the strip camber is considered in the roughing mill and off-center, the distance between a center line of a strip and center line of the roll, is considered in finishing mill. The problem of the off-center control is often called steering control. These two effects are treated together or separately. In Lee and Choi (2014) and Kampmeijer et al. (2013) the camber is controlled at the roughing stand and steering control is implemented during rolling in the finishing mill. For camber/off-center analysis and control goals Nakajima's model is often used as a conventional model. In Okamura and Hoshino (1997) the parallel mill modulus control based on the Nakajima's model and usage of the bending force difference is proposed. In Kiyota et al. (2003) the conventional model is modified for the strip which is unconstrained both at the entry side and the exit side and the LQR control for the strip tail is proposed. Kiyota et al. (2003) assumes that only the pressure difference and the roll gap height can be measured and an observer is used to estimate the off-center value and its derivative. PID sliding mode

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control with an observer for the conventional model with tension constraint is proposed in Choi and Lee (2009). An observer-based guaranteed cost control with similar model is considered in Kim and Won (2013). Choi et al. (2008) shows the advantages of the model predictive control for the conventional linear model in hot rolling. In Schausberger et al. (2015) another mathematical model of the camber evolution of heavy plates is proposed and the optimization-based approach for reduction of the plate camber is considered in Schausberger et al. (2016). A simplified nonlinear model and model predictive control based on a quadratic program was presented in Galkina et al. (2016b) and Galkina et al. (2016a), Gafur et al. (2016) respectively.

1.2 Overview of the presented contribution

In this contribution an infeed process in finishing mill is considered. Taking into account the physical conditions we can divide the total rolling process in finishing mills into three stages: strip head has passed the upstream roll stand but does not reach yet the downstream roll stand (infeed process), see Fig. 1, strip under the tension between two roll stands and strip tail has passed the upstream roll stand, but does not reach yet the downstream roll stand. During the strip infeed the control goal is to keep the free strip head inside of the tolerance limits to avoid the rolling process interruption due to collision with the side guides (see Fig. 1) and to satisfy the strip quality requirements. In general, mathematical modeling of the strip infeed is a challenging task because the controlled system is in fact a distributed parameter system. Furthermore, measurements in this process are limited and most of the contributing factors are difficult to measure during the normal process at a plant. Thus, the control of this physical process is also challenging.

In the next Section the simplified nonlinear mathematical model in form of ordinary differential equations (ODE) is considered at first. This model is discretized with respect to time and then parameterized by the flat output to simplify the formulation of the optimization task. MPC (Model Predictive Control) based on a quadratic program was presented in Galkina et al. (2016b) and Gafur et al. (2016). MPC presented in Gafur et al. (2016) was successfully tested at the plant. This MPC has a relative short prediction horizon (0.6 s) and is implemented in a slow hardware environment. In the subsequent sections we present the formulation, which has much longer horizon (2.8 s), no waves generation and is applicable to the existing real-time system. In the third Section two model predictive strategies are proposed: stabilization of the optimal reference trajectory and step-wise recurrent generation of the new optimal trajectory. Both presented strategies are implemented as a quadratic program (QP) and linear program (LP) and then compared. It is shown that a model predictive control in form of LP is convenient for the real-time implementation in the strip infeed process, because it is more efficient in computation time and has the same dynamic performance. The last Section is devoted to the test of the designed MPC in the co-simulation environment including HOTINT with an integrated finite element model (FEM) of the strip and the roll gap model. The MPC

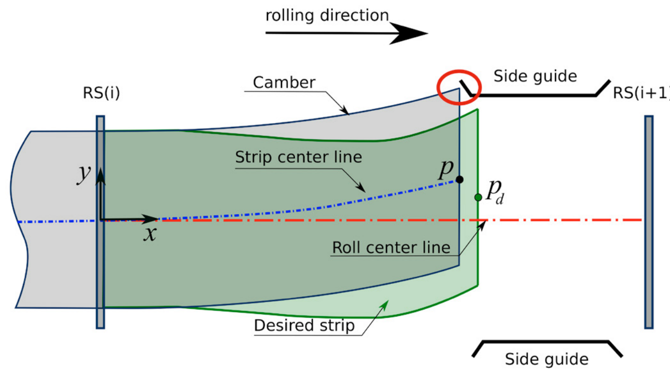

Fig. 1. Strip camber during infeed; RS(i) - upstream roll stand and RS(i+1) - downstream roll stand.

performance with the FEM model is then compared to the simulation of MPC with ODE in MATLAB.

2. MATHEMATICAL MODEL

The mathematical model convenient for the describing the infeed process must be as simple as possible from one side and allows to describe the position of the tracked free strip head quite accurate. To satisfy these contradictory requirements some assumptions must be made, which simplify the modeling. Strip is assumed to be a rigid rod deformed in the rolling direction (the plastic deformation takes place in the roll gap only). The strip mass is neglected. The steel density depends mainly on the temperature, but not on the pressure. Therefore, the density is changed by cooling down during rolling process, but not by rolling forces in the roll gap. The strip entry and output width in roll stand is assumed to be constant. The entry strip wedge is linear. If an automatic roll gap control works sufficiently well, there is no output strip wedge. Also there is no velocity in the lateral direction. We also assume that the initial strip off-center, the difference between strip center line and roll center line in the roll gap (see Fig. 1), is constant and we do not consider the influence of the strip camber from the roughing stand. With these assumptions the strip camber will be generated due to a linear asymmetric output velocity profile and the strip moves in the rolling direction and rotates.

According to the assumptions from above a pure geometric modeling is suggested. We introduce a fixed coordinate system at the center of the roll gap (see Fig. 1). Motion of any point of the strip (for example, p in Fig. 1), leaving the roll gap with the velocity $[\,v\,(t)\;\;0\,]^{\mathrm{T}}$, with $v\,(t)$ - an output velocity of the strip in the roll gap, can be described by

$$\begin{bmatrix} \dot{x}(t) \\ \dot{y}(t) \end{bmatrix} = \begin{bmatrix} v(t) \\ 0 \end{bmatrix} + \kappa(t)v(t) \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x(t) \\ y(t) \end{bmatrix}, \quad (1)$$

where $\kappa(t)$ denotes a curvature at the origin of the chosen fixed coordinate system. The model (1) can be found in Gafur et al. (2016) and Galkina et al. (2016b), Galkina et al. (2016a). Equation (1) describes a motion of an arbitrary point of the strip before the strip enters downstream roll stand. In the presented model the curvature of the strip κ depends on numerous uncontrolled and immeasurable process factors as well as on the control action, i.e. leveling in the roll stand. Leveling u is proportional to the