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Rapid Control Prototyping in Cold Rolling using Piezoelectric Actuators

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Abstract: Precise manufacturing of cold rolled, thin, and narrow metallic strips has become more important for various applications. The overall aim is the reduction of thickness tolerances of steel and copper strips to an extent of less than 1 µm. To reach that goal, an experimental rolling mill is set up in which supplementary piezoelectric stack actuators are integrated. The setup of the machine is presented. It contains a real-time system for rapid control prototyping using model-based development. It enables a direct download of a controller from the simulation environment to the machine. Furthermore, bandwidth requirements for the actuators are derived from strip measurements and machine properties. The bandwidth of the actuators is identified by modeling the system's dynamics. The comparison of both actuators reveals that their complementary characteristics are suitable to compensate occurring disturbances.

Keywords: Cold Rolling, Piezoelectric Actuator, System Identification, Model-in-the-Loop, Rapid Control Prototyping, Model-Based Design, Bandwidth Analysis

1. INTRODUCTION

Thin cold rolled metallic strips belong to a group of products which is used in many different areas of technology. In some industries, precision of materials including metallic strips plays a major role e.g. electrical industry, space industry and medical technology. The minimal standardized tolerance for narrow steel strips with nominal thickness of $h = 1\,\text{mm}$ is $\Delta h = \pm 15\,\mu\text{m}$ (DIN EN ISO 9445-1, 2010). The tolerance for copper strips of the same extent is $\Delta h = \pm 22\,\mu\text{m}$ (DIN EN 13599, 2014). For the production of those strips, usually cold rolling is utilized in industry.

During a rolling process, the roll gap needs to be adjusted not only to compensate variations in the incoming material (as there can be variations in e.g. thickness, hardening and surface texture). Also, plant-related variations like roll eccentricities need to be compensated (Bryant, 1973). Those disturbances grow with increasing service life of the plant as they are accompanied by machine wear. Therefore, an Automatic Gauge Control (AGC) needs to be used in order to compensate those disturbances and guarantee product quality during machine life cycle. The overall aim is the reduction of thickness variations of thin and narrow metallic strips to $\Delta h = \pm 1\,\mu\text{m}$. To achieve this goal supplementary piezoelectric stack actuators will be integrated in the mill housing of a conventional rolling mill. They are expected to bear complementary dynamic capabilities in comparison to the existing actuators. In such a way it is expected to achieve the tolerance goal with ordinary roll stands which do not have to be optimized towards extreme stiffness and precision mechanically.

The piezoelectric effect describes a voltage caused by an external force which is applied to a piezoelectric ceramic. The voltage is in first approximation proportional to the deformation which results from the applied force. The so-called reciprocal piezoelectric effect achieves the opposite result (Isermann, 2005). If a voltage is applied to a piezoelectric ceramic, the material will extend. This principle is used to build piezoelectric actuators.

The possible enlargement of a piezoelectric ceramic is up to 0.2 % of its own length. As a single ceramic disk has only heights of about 1 mm, several piezoelectric ceramics are stacked in order to achieve higher enlargement. They are henceforth called stack actuators. Piezoelectric ceramics can endure relatively large pressures while they are vulnerable for tensile loads and torsion. Another property of piezoelectric ceramics is a nearly unlimited accuracy in position. In theory position discretization is limited to a single electric charge. During extension, no friction occurs within the actuator which decreases wear-out to a little extent. (Heywang et al., 2008)

The idea of using piezoelectric actuators for an increase of bandwidth is implemented in various applications. Those applications usually have in common that they work under none or only little loads. Branson et al. (2011) use them to actuate a valve in a hydraulic cylinder in order to increase its bandwidth. Other applications are injection of e.g. ink (Stemme and Larsson, 1973) or fuel (Gnad and Kasper, 2006). Another use of piezoelectric actuators is for active vibration control. A survey of different approaches was done by Moheimani (2003). In context of rolling, piezoelectric actuators were used by Zhou et al. (2011) as the only actuators for roll gap adjustment. They presented

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an experimental rolling mill for surface texturing in which micro-channels were imprinted on aluminum sheets.

While there are numerous control strategies for AGC utilizing a single pair of hydraulic actuators or electric spindle drives in rolling mills, only a few concepts were developed using different types of actuators for roll gap adjustment within a single roll stand.

An approach with two actuators was proposed and successfully tested by Zhang et al. (2014) on a plate mill at Handan Hongri Metallurgy Co. Ltd., China. They used a spindle drive for the upper roll which was counteracted by a hydraulic actuator driving the lower roll. Another approach was presented by Liu et al. (2016) where a rolling mill is adapted to be used with a linear motor instead of hydraulics.

A problem typical for manufacturing plants is that usually Programmable Logic Controllers (PLC) are used where controllers are made in hardware allowing only a few settings to change within a rigid control scheme. Developing new control strategies, hence, is often tied to simulation and cannot be easily implemented on the manufacturing plant. Therefore the need for an experimental setup enabling Rapid Control Prototyping (RCP) techniques is present.

This paper introduces a setup for an experimental rolling mill. It is shown how RCP techniques can be used to quickly develop and test various control algorithms for AGC in an industrial context. Also, the integration of piezoelectric stack actuators in the mill housing is shown. An enhancement of the dynamics of the experimental rolling mill is expected, if a piezoelectric stack actuator is used as support to an existing electromechanically actuated spindle drive. The enhancement of bandwidth will be shown.

2. SETUP OF THE EXPERIMENTAL ROLLING MILL

2.1 Components of the Rolling Mill

The particular manufacturing plant is a tandem mill which bears a 2-high roll stand as well as a 4-high stand. In this work only the second, the 2-high roll stand is used. In that stand additional piezoelectric stack actuators PSt 1000/25/150 VS35 are integrated (see fig. 1). Contemporary rolling mills are usually actuated hydraulically or have electromechanical spindle drives. The experimental rolling mill uses the latter actuators. Therefore the actuators come with mechanical properties such as self-locking which are caused by the worm gear spindle. The original machine only contains electromechanical spindle drives adjusting the upper work roll. The piezoelectric actuators are integrated in the lower part of the mill housing and drive the lower work roll. In such a way, torsion on the piezoelectric actuators caused by the spindle is avoided. Fig. 2 depicts the integration of the components in the mill housing.

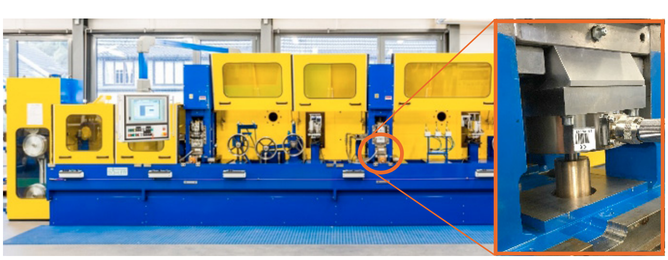

Fig. 1. Rolling mill and integration of a piezoelectric actuator

Integrating actuators in the lower part is uncommon, as the pass line of the strip is lifted which in general should be avoided. However, the maximum lift by the actuators is that small that it can be neglected ($\Delta L = 150\,\mu\text{m}$). During the rolling process high precision load cells HMB 1 C10/50kN measure the rolling force.

Additionally a strip thickness sensor (see section 3.1) and an incremental encoder WayCon A8 W 10 L 1000 KA02 for strip speed measurement are integrated on each side of the roll gap.

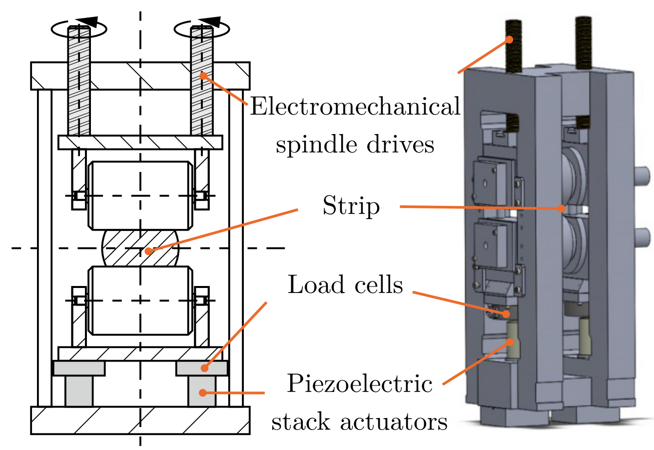

Fig. 2. Schematic of the modified mill housing

2.2 Integration of the Real-Time Control System

The central control component of the project is a dedicated dSpace Real-Time (RT) system DS1006. It will be used for RCP purposes. The system bears all relevant interfaces like PROFIBUS, Controller Area Network (CAN), Analog-Digital inputs and Digital-Analog outputs (AD/DA). When disabling the RT prototyping device, the conventional rolling mill can be used as usual. The extended 'research' mode can be activated giving the control authority to the RT system which then can set reference values for all spindle drives. Because safety functions remain in the machine's PLC, they do not have to be taken care of during developing of control strategies. The communication between the RT system and the mill's PLC is tied to certain restrictions which will be discussed in section 4.

The process variables of the spindle drive are controlled by an internal controller in the PLC of the rolling mill. The reference values as well as the measured position can be accessed by a PROFIBUS interface. The other sensors and actuators are directly connected to the RT hardware using AD/DA and CAN. It is worth noticing, that only communication via PROFIBUS bears time delays; all other components are assumed to work free of delays. Fig. 3 depicts the structure of the extended rolling mill. On the left-hand side a Model-in-the-Loop (MiL) setup is realized which has been used in a different context by e.g. Plummer (2006). MiL describes a technique in which