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A Sensor-Based Method for Diagnostics of Geometric Performance of Machine Tool Linear Axes

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Abstract

A linear axis is a vital subsystem of machine tools, and when installed and operating within a manufacturing facility, a machine tool needs to stay in good condition for parts production. All machine tools degrade during operations, yet knowledge of that degradation is elusive; accurate detection of linear axis degradation is a manual and time-consuming process. Thus, manufacturers need automated and efficient methods to diagnose the condition of their machine tool linear axes without disruptions to production. Towards this end, a sensor-based method was developed to quickly estimate the performance degradation of linear axes. The multi-sensor-based method uses data from inclinometers, accelerometers, and rate gyroscopes to identify changes in linear and angular errors due to axis degradation. A linear axis testbed, developed for verification and validation of the sensor-based method, contains a linear axis and a reference laser-based system for measurement of the axis geometric performance. Comparison of the sensor-based results and the laser-based results shows that the sensor-based method is capable of detecting micrometer-level and microradian-level degradation of linear axes. Consequently, if a sensor box resides on a machine tool, then the degradation of the linear axes can be periodically measured and used to help optimize maintenance.

Keywords: Machine tool, Linear Axis, Error, Wear, Degradation, Sensor, Diagnostics, Maintenance

1 Introduction

Linear axes are used to move components of machine tools that carry the cutting tool and workpiece to their desired positions for parts production (Altintas, Verl, Brecher, Uriarte, & Pritschow, 2011). Because a typical machine tool has three linear axes, their positional accuracies directly impact load capacity, quality, and efficiency of manufacturing processes. However, as a machine tool is utilized for parts production, emerging faults lead to performance degradation that lowers control precision and

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accuracy (Li, Wang, Lin, & Shi, 2014). Typical faults within feed systems are due to pitting, wear, corrosion, cracks, and backlash (Zhou, Mei, Zhang, Jiang, & Sun, 2009). As degradation increases, tool-to-workpiece errors become more likely, and eventually, linear axes of computer numerical controlled (CNC) machines may undergo significant wear that results in a failure and/or a loss of production quality (Uhlmann, Geisert, & Hohwieler, 2008). Faults and failures may become more common as higher levels of manufacturing productivity can result in greater wear on machine components. Machine tool faults account for yearly economic losses of tens of billions of US dollars (Shi, Guo, Song, & Yan, 2012).

Machine tools must be maintained and available for cost-effective production (Verl, Heisel, Walther, & Maier, 2009), yet knowledge of degradation is illusive. While direct methods for machine tool calibration are well-established (International Organization for Standardization, 2012) for position-dependent error quantification, measurements for these methods typically halt production and take "a long time" (Khan & Chen, 2009). The "extensive experimental and analytical efforts" for conventional error measurement methods usually requires expensive equipment, hindering widespread commercial adoption (Ouafi & Barka, 2013). Because degradation differs along a linear axis and the wear changes with production time (Uhlmann et al., 2008), the particular condition of an axis is usually unknown.

Manufacturers need automated and efficient methods for continual diagnosis of the condition of machine tool linear axes without disruptions to production. Efforts to monitor the condition of linear axes components have utilized various sensors:

- Built-in linear and motor encoders (Plapper & Weck, 2001; Zhou, Tao, Mei, Jiang, & Sun, 2011; Zhou, Xu, Liu, & Zhang, 2014) with laser interferometer (Verl et al., 2009)
- Motor torque via current sensors (Li et al., 2014; Uhlmann et al., 2008; Zhou et al., 2009), accelerometers (Feng & Pan, 2012; Huang et al., 2010; Liao & Lee, 2009)
- Accelerometers, thermocouples, and analog controller outputs (torque, speed, and encoder position) (Liao & Pavel, 2012)
- Hall effect sensors (Garinei & Marsili, 2012)
- Piezoresistive thin films (Biehl, Staufenbiel, Recknagel, Denkena, & Bertram, 2012; Möhring & Bertram, 2012)
- Piezoelectric ceramics (Ehrmann & Herder, 2013).

These attempts at condition monitoring of linear axes were limited in success, largely because both external sensors and built-in sensors have limitations. Built-in position sensors are usually highly accurate (Zhou et al., 2011), yet controller signals have problems such as low sample rate, limited sensitivity due to sensors being far from monitored components, and unwanted influences from multiple sources (Plapper & Weck, 2001). On the other hand, external sensors can be more direct and physically sensitive, but high costs and required bandwidths have impeded their application for online monitoring of linear axes (Zhou et al., 2009).

In this paper, a new sensor-based method for diagnostics of machine tool linear axes is presented. The sensor-based method was developed to quickly estimate the performance degradation of linear axes, based on the use of external sensors for high-bandwidth measurements of changes in translational and angular errors of linear axes. The sensors are contained within a sensor box for ease of installation and periodic use on a machine tool, resulting in data collection and analysis with minimal disruption to production. The diagnostics and prognostics of the linear axes can be used to help optimize maintenance and production schedules. The cost-effective sensors are expected to be an overall net positive when factoring in the expected savings in production losses and scrapped parts for a machine tool.