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Testing of an axially-actuated rotary stage for an ultra-precision machine tool

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Abstract
To compensate for the machining errors caused by process forces, vibration of machine frames, friction and motion errors of the guides, a novel actuator configuration is proposed. The actuator is designed for actuating the workpiece on a five-axis ultra-precision grinding machine in which the workpiece resides on a rotary table. The actuator consists of a voice coil actuator, positioned below the rotary table, moving the rotating workpiece in the axial direction. The position of the actuator is measured locally in six-DOF by a rotary encoder with three reading heads and three capacitive sensors. A first test set-up has been realized which is compensating for axial error motion of the rotary table. It is shown that at a rotation speed op 18 rpm, the initial error motion of 31.8 nanometer (RMS) can be reduced down to 5.6 nm (RMS).

Keywords: precision engineering, machine tools, active compensation

1. Introduction

Referring to the Taniguchi [1] law, technological evolution is characterized by an increasing accuracy of machine tools. Several concepts for precision engineering design are described and applied in various machines [2]. Dynamic machining errors in machine tools are mostly caused by process forces, friction in the guides and vibration of machine frames. Traditionally, these errors are reduced by creating high-stiffness machine frames, aerostatic or hydrostatic guides and by increasing the damping properties of the components respectively. The consequence is that for a high precision machine, ultimately large, heavy frames constructed from exotic materials and using expensive non-standard guiding systems are required. This induced the search for more compact precision machine tools [3]. Other approaches are focusing on active compensation, like e.g. in vibration isolated tables [4]. In previous research of KU Leuven, a position measurement system was developed capable of measuring the relative position of tool and workpiece as close as possible to both end-points with a measurement uncertainty of 20 nm over 100 mm [5]. In this paper, KU Leuven has also investigated how to increase the accuracy of standard multi-axis machine tools in a mechatronic way. An actuator capable of compensating the measured positioning errors by actuation of the workpiece is proposed.

2. Concept of the setup

The overall concept of the setup, here focusing on a grinding set-up is show on fig. 1.

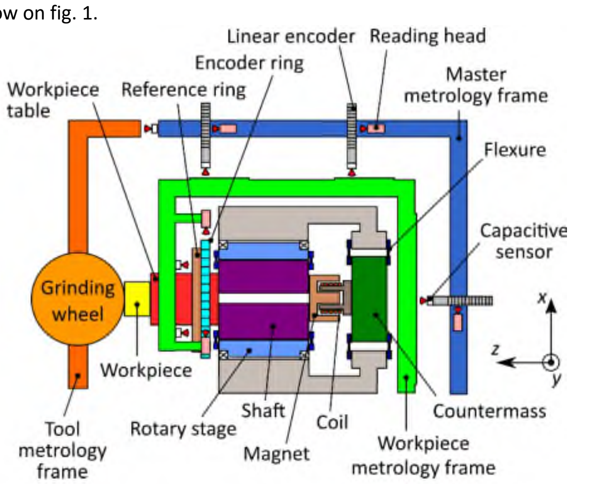

Figure 1: Overall concept of the set-up.

For a more general description of the context of this work is referred to the euspen 2017 paper [6]. The basic idea is to develop a metrology and active compensation system controlling the distance between tool tip and workpiece as this is the main distance relevant for the machining accuracy. Of course this is a multi-dimensional problem, for further details is also referred to [6].
In this concept the tool (grinding wheel) position is represented by the Tool Metrology Frame (TMF). The workpiece position is represented by a workpiece metrology frame (WMF). This WMF carries capacitive sensors and encoder reading heads measuring the workpiece spindle position (rotation angle and position) with respect to the WMF. This WMF in turn is measured by an Abbe-compliant configuration of linear encoders [7]. The metrology loop is closed though an additional master metrology frame (MMF). Errors are compensated by a combined linear-rotary actuator consisting of a voice coil actuator (VCA) and a rotary stage.

For the first tests, a reduced set-up, shown on fig. 2, has been built which differs in the fact that only a small (in green) workpiece metrology frame has been designed which in this case measures the work piece spindle rotation and position with respect to the fixed world (and not with respect to a floating WMF as depicted on fig.1). The actuator system has been constructed based on a VCA in combination with an ETEL rotary stage (DXR-TO225). The position of the actuator is measured locally in six-DOF by a rotary encoder with three reading heads and three capacitive sensors.

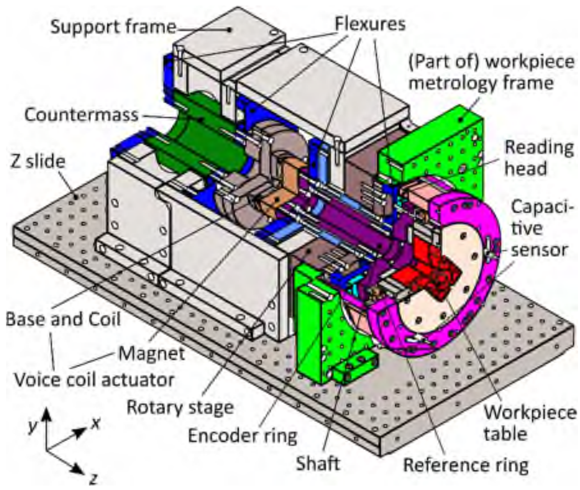

Figure 2: Detailed drawing of the first set-up

Fig. 3 shows a photographs of the overall systems, the controller is running on a dSpace data acquisition system.

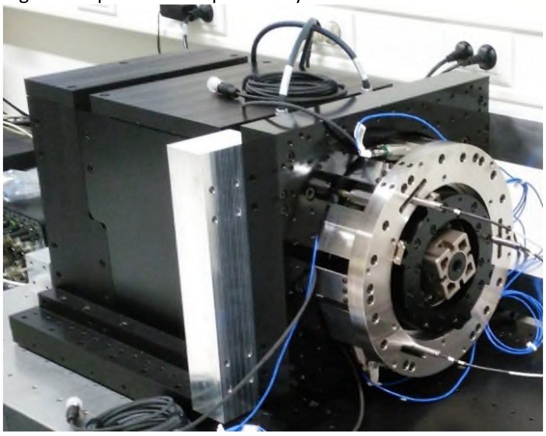

Figure 3: Photograph of the realized set-up

3. Controller design

The implemented controller is a dual-loop (velocity and position) feedback controller. The velocity controller is based on a conventional Proportional-Integral scheme. The position controller is based on an Internal Model Control concept as described in [8]. Fig. 4 shows the Bode-plot for the Plant (Voice Coil Actuator (VCA) drive signal with respect to the displacement measured by the capacitive sensor). Fig. 5 shows the closed loop system transfer function T, including the sensitivity function S.

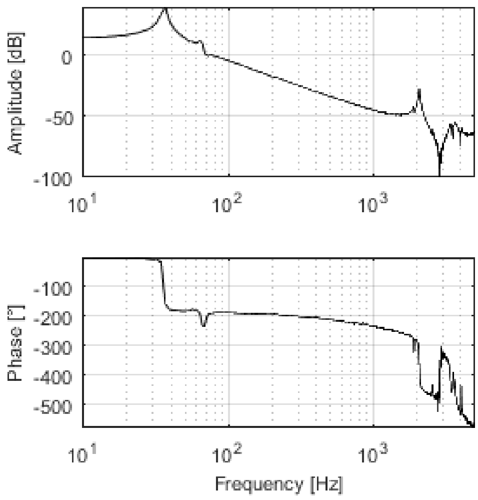

Figure 4: Bode-plot for the Plant: Voice Coil Actuator (VCA) drive signal with respect to the displacement measured by the capacitive sensor.

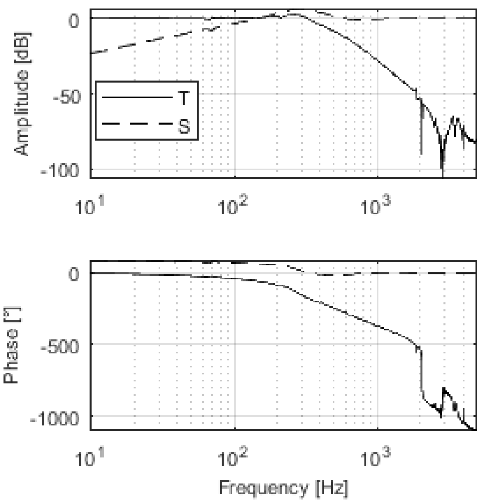

Figure 5: Transfer function T and sensitivity function S for the closed loop system.

4. Results

Fig. 6 shows the measured performance. Measurements are performed at a work piece table rotation speed of 18 rpm. Note that the actual cutting speed in this case mainly is determined by the grinding tool spindle speed. As can be seen on fig. 6, the system without compensation has an axial error motion of 31.8 nm rms. By applying the proposed active control system the compensated error motion is 5.6 nm rms.

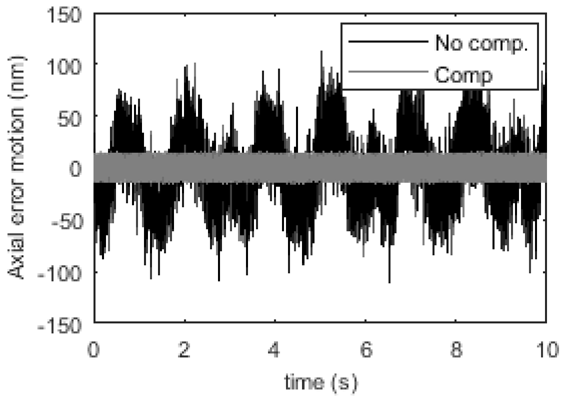

Figure 6: Measured performance

5. Conclusion

To compensate for the machining errors caused by process forces, vibration of machine frames, friction and motion errors of the guides, a novel actuator configuration is has been designed and tested. It consists of a voice coil actuator, positioned below the rotary table, moving the rotating workpiece in the axial direction. The position of the actuator is measured locally in six-DOF by a rotary encoder with three reading heads and three capacitive sensors. A first test set-up has been realized which is compensating for axial error motion of the rotary table. It is shown that at a rotation speed op 18 rpm, the initial error motion of 31.8 nanometer (RMS) can be reduced down to 5.6 nm (RMS).

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