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Design 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. An eigenfrequency analysis of the actuator revealed that the first resonance frequency that is excited by the voice coil actuator resides at 2663 Hz, which indicates that a closed-loop control bandwidth of 532 Hz is within reach.

Actuator, Ultra-Precision, Machine tool, Mechatronic, Positioning

1. Introduction

Technological evolution is propelled by continuously increasing the accuracy of machine tools. 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 frame materials respectively. If a high precision is required, ultimately a machine tool would require large, heavy frames constructed from exotic materials and using expensive non-standard guiding systems. KU Leuven has investigated how to increase the accuracy of standard multi-axis machine tools in a mechatronic way. In previous research, 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 [1]. This paper proposes the design of an actuator capable of compensating the measured positioning errors by actuation of the workpiece.

2. Actuator concept

Figure 1 shows the configuration of the slides of a five-axis ultra-precision grinding machine that is under development at KU Leuven [2]. The tool spindle, which holds a spherical grinding wheel, rotates about the A-axis. The workpiece is placed on top of a rotary stage (C-axis) which is mounted on the stacked X-, Y- and Z- slides. All slides use precision ball bearings as means of guiding.

Motion errors in the *x*-, *y*- and *z*-direction cause machining errors in the direction normal to the surface of the workpiece. As the tool is spherical and the workpiece surface normal always has a component in *z*-direction, these motion errors can be compensated by a motion in *z*-direction as shown in Figure 2. For decreasing the machining errors caused by process forces, vibration of the machine frames, friction and motion errors of the guides below 0.1 µm, the control bandwidth of the actuator in *z*-direction should be higher than 500 Hz [3]. As actuation of the spherical grinding wheel is cumbersome, it has been decided to integrate an actuator below the workpiece table to drive the axial movement of the rotary stage.

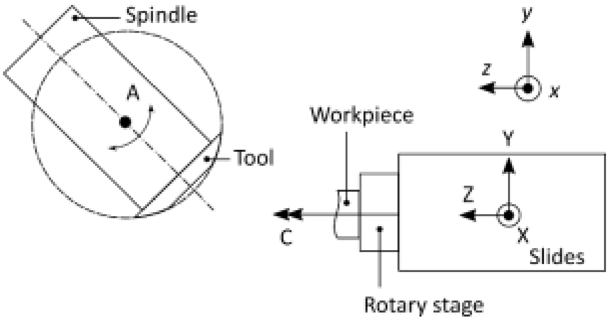

Figure 1: Configuration of the five-axis grinding machine [DH]

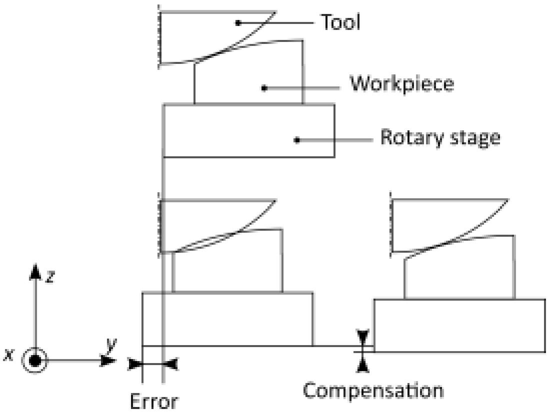

Figure 2: Error compensation of X and Y movement

3. Conceptual layout and mechanical layout

The conceptual layout of the actuator and rotary stage is shown in Figure 3. The 3D mechanical design of the Z-slide including the actuator and its position measurement is depicted in Figure 4. Fast actuation of the workpiece in *z*-direction is achieved by a voice coil actuator (VCA). The magnet of the VCA is connected to a rotating shaft. The shaft moves in the axial direction through a rotary table with a hollow rotor

(DXR-TO225). Because motion is limited to a few tens of micrometres and to avoid friction and backlash, flexures are used to guide motion in z-direction. These flexures are connected to the rotational part of the rotary table. The axial and radial stiffness of the flexures of the rotary stage are 0.167 N/μm and 208 N/μm respectively. The coils of the VCA are mounted on a counter-mass behind the actuator, which is also guided by flexures. The counter-mass reduces the transfer of forces to the underlying slides, which improves the control characteristics. The axial and radial stiffness of the counter-mass flexures are 0.795 N/μm and 33 N/μm.

All six degrees of freedom of the rotary stage are measured. The x- and y-displacement and θ_z-position is measured using a rotary encoder (Heidenhain ECA 4000) with 3 reading heads. A reference ring is connected to the rotary stage, of which z-, θ_x- and θ_y-displacement is measured by three capacitive sensors. The capacitive sensors and encoder reading heads are connected to a workpiece metrology frame (WMF). This WMF in turn is measured by an Abbe-compliant configuration of linear encoders [1]. The metrology loop is closed though an additional master metrology frame (MMF) and a tool metrology frame (TMF) that is connected to the A-axis holding the tool spindle.

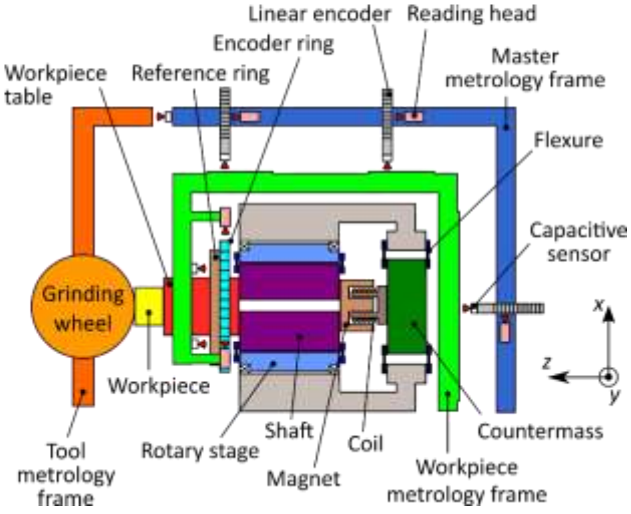

Figure 3: Conceptual layout of the actuator and associated position measurement systems.

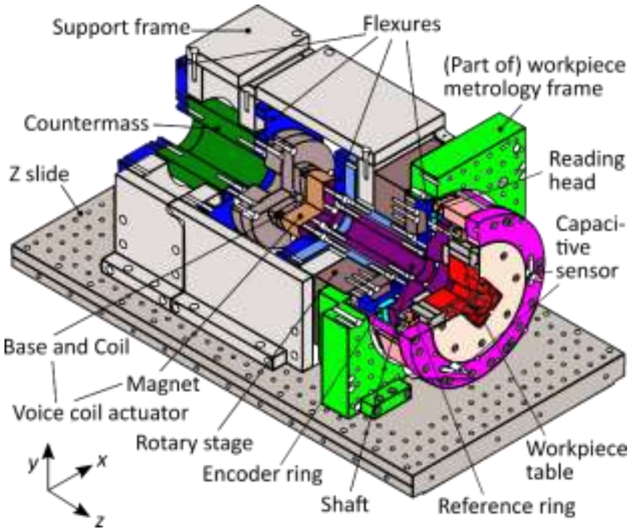

Figure 4: Mechanical layout of the Z-slide, including the rotary stage, actuator and position measurement systems.

4. Control bandwidth estimation

The maximum achievable bandwidth of the control loop of the actuator is determined by the first frequency of the transfer function between the VCA force and the displacement of the reference ring where the phase drops below 180°. Rankers [4] indicates that for a non-collocated control configuration, the control bandwidth will be at least five times lower than this frequency.

An FEA, of which the result is shown in Figure 5, shows that the first eigenfrequency of the assembly of workpiece, shaft, VCA, reference ring and encoder ring that will be excited by the VCA equals 2663 Hz. Therefore, it can be derived that the maximum achievable bandwidth will be below 532 Hz, which is within specifications.

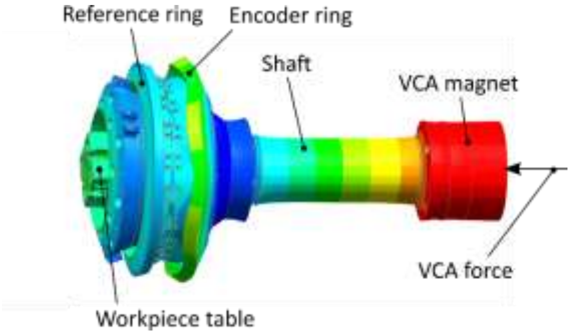

Figure 5: Eigenfrequency analysis of the actuated rotary shaft.

5. Summary, conclusion and future work

This paper proposed the design of an actuator capable of compensating the machining errors due to process forces, vibration of the machine frames, friction and motion errors of an ultra-precision five-axis grinding machine. Resulting from an analysis of the eigenfrequencies, the actuator control bandwidth has been estimated at 532 Hz. This actuator, in combination with improved position measurement enables the dynamic compensation of machining errors on normal machine tools to bring these machines to a level of accuracy of ultra-precision machine tools. As a next step, a prototype of the designed actuator will be developed to verify its performance.

Acknowledgements

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References

[1] Bosmans N, Qian J and Reynaerts D 2017 Design and experimental validation of an ultra-precision Abbe-compliant linear encoder-based position measurement system *Precision Engineering,* **47** 197-211

[2] Hemschoote D, Qian J, Van Brussel H, Reynaerts D 2006 The use of metrology frames in an ultra-precision 5-axis machine for ELID-grinding *Euspen 6th International Conference proceedings* **1** 249-252

[3] Neyens D and Van Campen Z 2015 Design of a combined rotary linear actuator for a nanometer precision five-axis grinding machine *Master's thesis* KU Leuven

[4] Rankers A M 1997 Machine dynamics in mechatronic systems: an engineering approach *PhD thesis* TU Twente