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Experimental investigation of an electromagnetic linear guide for ultra-precision high performance machining

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Abstract
Machine tools for ultra-precision cutting are specifically designed to achieve the highest degree of working accuracy. In fact, this is often accomplished at the expense of machining speed and productivity. In order to increase the overall machining performance while maintaining the required position accuracy, a novel electromagnetic ultra-precision linear guide is developed.
This paper presents the first experimental investigation of the electromagnetic guide for use in ultra-precision cutting with increased machining performance. The guiding system's mechanical setup and control environment as well as its implementation in a high-precision cross table are briefly introduced. Initially, the positioning capability of the electromagnetic actuators is investigated. Then, the functionality of the active magnetic guide is verified via decoupled control of the slide's five degrees of freedom. Following the commissioning, the electromagnetic guide demonstrates a submicrometre positioning accuracy.

Keywords: Active magnetic guide, motion control, ultra-precision machining

1. Introduction

Ultra-precision machining is primarily used to manufacture optical, electronical and mechanical high-precision components, thus, driving various industrial sectors such as aerospace, automotive, laser technology, medical engineering, metrology and optical production [1, 2].

Recent research activities in the field of ultra-precision machining exhibit two key objectives: On the one hand the increase of the overall machining accuracy, on the other hand the production of increasingly complex workpiece and surface geometries. The aspect of manufacturing productivity in ultra-precision machining has not been addressed yet. Hence, respective machining processes are usually characterised by disproportionately long machining times and limited economic applicability. Productivity restrictions can be traced back to the machine tools' feed axes, among other things, because they are designed to operate solely at low feed rates to ensure a high position accuracy.

In order to overcome present limitations, a novel electromagnetic ultra-precision linear guide is developed. This new development presents the first approach to design an active magnetic guide which provides nanometre positioning capability and sufficient stiffness for ultra-precision machining. Electromagnetic levitation technology provides friction-free movement and fine positioning in five degrees of freedom (DOFs) allowing for high feed rates and high position accuracy.

This paper introduces the prototype of the new electromagnetic linear guide and its implementation in an ultra-precision cross table (chapter 2) as well as the results obtained from the initial operation of the guiding system (chapter 4).

2. Experimental setup

2.1 Electromagnetic ultra-precision linear guide

The design of the guiding system is determined by the differential arrangement of the electromagnets (Figure 1a). Each electromagnet consists of an E-shaped core unit with an attached capacitive probe for air gap measurement and a back iron to close the iron circuit [3] (Figure 1b). A pair of ironless linear motors drives the slide in feed direction (x-direction) utilising an exposed linear encoder for position feedback. All feedback systems feature a dynamic resolution of 1 nm.

Electromagnets and linear direct drives are placed near the horizontal centre of gravity plane for an effective force application. Further, the guiding system's active components are mounted on the frame to avoid supply lines to the levitating slide as a source of non-linear friction. The slide body is made of natural granite for high thermal stability and material damping.

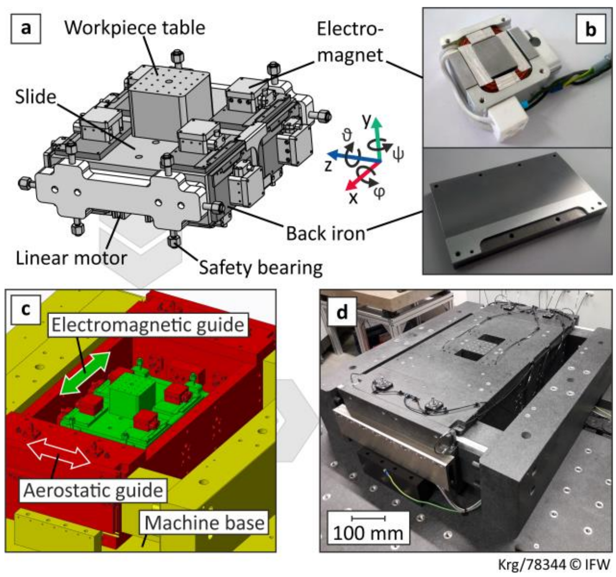

Figure 1. Implementation of the electromagnetic ultra-precision linear guide in a high-precision cross table prototype

2.2. Ultra-precision cross table

The new electromagnetic guide is integrated in a cross table with a secondary machine axis (Figure 1c). The secondary axis (z-direction) features aerostatic guideways and ironless linear motors in a gantry configuration with individual linear encoders.

A box-in-a-box construction is applied in order to minimise the error budget of the two-axis stage. Again, natural granite is used as the main construction material to reduce the effects of thermal load. Figure 1d shows the cross table prototype at the IFW.

2.3. Control environment

Due to its inherently unstable properties, an electromagnetic guide requires a control system consisting of a sensor system, a suitable control algorithm and power electronics for stable operation. Figure 2 outlines the hardware structure for the control application at hand.

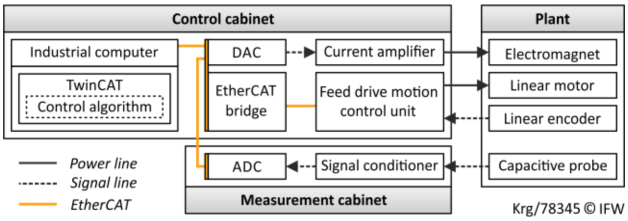

Figure 2. Hardware structure of the control environment

The control algorithm runs on an industrial computer using TwinCAT automation software. The position data from the capacitive probes' signal conditioners and the set values for the electromagnets' current amplifiers are included in the control environment through data conversion terminals. The linear motors of both axes are driven by a separate multi-axis control unit. Communication between industrial computer, terminals and feed drive control unit is realised via EtherCAT protocol.

3. Methodology

An observer-based state space controller was developed and verified by closed loop feedback simulation during the design and construction of the electromagnetic guide [4]. However, under more practical conditions the performance of the developed state space controller is limited due to manufacturing and mounting tolerances which compromise the accuracy of the plant's state space model. Hence, an alternative approach was chosen for the commissioning and plant identification.

First, the functionality of the installed electromagnets was investigated. For this purpose, two opposing magnets were considered as one bi-directional actuator that is individually controlled by a PID feedback mechanism with a control frequency of 10 kHz. Control parameters were calculated based on a linearization of the electromagnets' characteristic diagram for an operating point with an air gap of 200 µm and a bias current of 5 A.

Then, a control mechanism to manipulate the slide's five DOFs was implemented. The mechanism is based on the decoupling of the slide's DOFs by Jacobian matrices and independent PID controllers per DOF.

Control accuracy and robustness were evaluated through step response analysis. The internal sensors of the electromagnetic guide were used to monitor the position and orientation of the slide. Besides the aliasing filters of the measurement electronics, no additional filters were used to avoid any effects on the control loop's dynamic properties.

4. Results

The use of PID feedback mechanisms enables stable position control of the electromagnetic actuators. Overshoots occur at large set point steps (Figure 3a) due to the linear estimation of the magnet forces as well as the control parameter optimisation for smaller step sizes in the submicron range (Figure 3b). Currently, overall gain, stiffness and position accuracy are limited by the sensor noise which is amplified by the derivative term of the PID controller. This results in a position noise of approximately 200 nm. Nonetheless, the derivative term of the feedback system is necessary to stabilise the control loop.

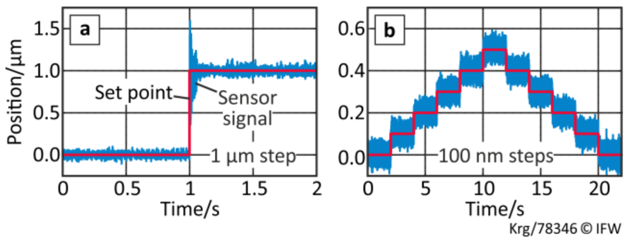

Figure 3. Position control of a single electromagnetic actuator

Furthermore, it is possible to stabilise the levitating slide by decoupling the slide's DOFs and applying five independent PID controllers. Figure 4 shows the generalised coordinates of the slide for a step response in y-direction. The measurement results indicate a satisfactory decoupling of the five DOFs with only minor interdependencies for the rotational DOFs. Once more, the derivative term of the control algorithm compromises the noise level leading to a position noise of approximately 450 nm and 4 µrad respectively.

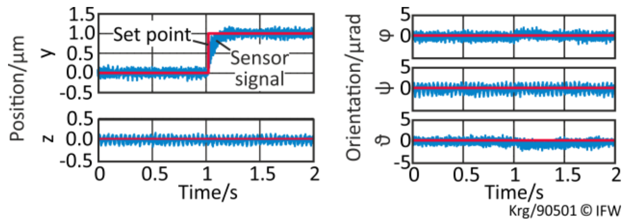

Figure 4. Control of the slide's five DOFs

5. Conclusion

This contribution outlines the commissioning process of a novel electromagnetic linear guide for ultra-precision high performance machining. The prototypical guiding system was integrated in a high-precision cross table at the IFW. A suitable control environment was created to drive all electromechanical systems of the cross table. Finally, decoupled control of the levitating slide's five DOFs was realised with independent PID feedback mechanisms for an initial proof of functionality.

The original experimental results confirm the submicrometre positioning capability of the new active magnetic guide despite the use of a rather simple control layout. Existing limitations are mainly the result of an inaccurate system model and the derivative terms of the PID controllers. Following a full plant identification, the implementation of the previously developed state space controller based on Kalman filtering presents a promising approach to improve position noise and accuracy of the guiding system.

Future work includes a repeated precision alignment of the guiding system's components and a metrological investigation of the assembly in order to supply an accurate state space representation of the plant.

Acknowledgement

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