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Enabling electromagnetic levitation technology for ultra-precision high performance machining

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Abstract
Currently, the feed axes of ultra-precision machine tools are limited to low feed rates and accelerations in order to achieve a position accuracy in the nanometre range. In this context, the use of electromagnetic guides presents a promising approach to remedy current productivity restriction in ultra-precision machining. However, transfering electromagnetic levitation technology to ultra-precision high performance cutting requires a diligent revision of the guiding system's integral components.
This contribution expands on the capacitive air gap measurement system of an electromagnetic linear guide prototype for use in ultra-precision machining. Starting with an analysis and evaluation of existing disturbance variables, applicable measures were derived to reduce the signal noise due to interference of the electromagnets with the capacitive probes. Further on, the thermal behaviour of the optimised actuator design was investigated to determine the coil temperature increase and the thermal deflection at the air gap sensor. Consequently, a thermal steady state was identified and the signal noise was reduced by 44%.

Active magnetic guide, capacitive measurement system, ultra-precision machining

1. Introduction

The increasing use of components with functional micro-structures and optical surfaces consolidates the role of ultra-precision machining as a key technology of the 21st century [1]. However, the productivity of ultra-precision machine tools still suffers from considerable limitations of the applicable feed rate and acceleration during the machining process. In particular, the feed axes of ultra-precision machine tools contribute to existing restrictions since they are designed to operate at low feed rates in order to ensure the highest level of position accuracy [2].

Against this background, feed axes based on electromagnetic levitation technology present a promising approach to remedy current productivity restrictions. The development of electromagnetic guides with sufficient position accuracy and dynamic stiffness for use in ultra-precision machining requires a careful reconsideration of the guiding system's integral components, i.e. sensor system, control algorithm, power electronics and actuators. Accordingly, an electromagnetic guide prototype for ultra-precision machining was developed at the IFW.

Previously, the results from the prototype's commissioning process demonstrated a decoupled control of the guide's five degrees of freedom as well as a submicron positioning accuracy of the levitating slide [3]. At the same time, the initial operation revealed the need for further optimisation regarding safety bearings, precision alignment of the functional surfaces and integration of the capacitive measurement system. Most notably, a significant increase of the capacitive probes' signal noise by a factor of 6 to 12 was observed as soon as the power electronics supplied a current to the actuators. Additionally, a long term drift of the sensor signal was detected which indicates thermal effects or the accumulation of electrical charges on the measurement surface. Since the signal quality of the capactive probes particularly determines the positioning accuracy and standstill jitter of the active guiding system, this paper expands on the implemented capacitive air gap measurement system.

2. Experimental setup

The test bench for the electromagnetic guide prototype and its commissioning results were previously presented in [3] and [4]. Figure 1a points out the core components of the guiding system. Figure 1b shows the original design of the electro-magnetic actuators which are individually powered by digital servo amplifiers (Copley Controls Junus JSP-180-20).

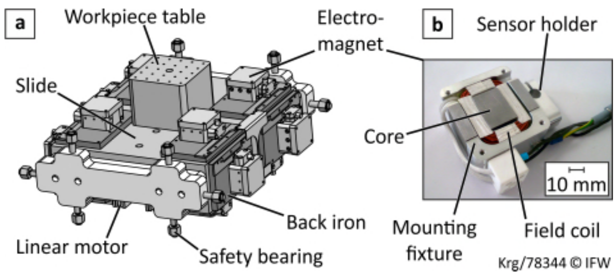

Figure 1. Setup of the electromagnetic guide and initial actuator design

Each electromagnet is equipped with a capacitive probe (Physik Instrumente PISeca D-510.050 probe and E-852.10 signal conditioner) for air gap measurement with the back iron acting as a grounded measurement target. Figure 2 shows the signal chain of the capacitive measurement system. For the considered investigations, the measurement range was set to 125 µm and the bandwith to 10 kHz. Except for the 80 kHz anti-aliasing filter of the analog-to-digital converter (ADC), no other filters were used in the course of the experiments to avoid distorted measurement results.

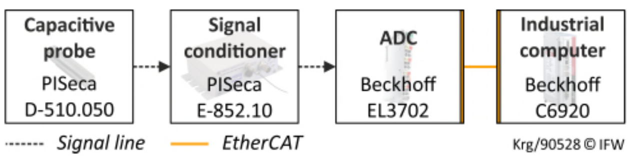

Figure 2. Signal chain of the capacitive measurement system

After the commissioning, resistance temperature detectors (RTDs) were subsequently attached to the magnets' field coils to monitor thermal effects. The PT100 type RTDs were directly wired to appropriate ADCs (Beckhoff EL3204).

3. Methodology

In order to evaluate the disturbances of the capacitive measurement system, the impact of the coil current and the temperature on the air gap signal was analysed. First, the performance of a capacitive probe was assessed on a separate test rig to obtain an undistorted reference. Then, the capacitive probe was attached to an electromagnet and the sensor noise was measured for practical current settings of the corresponding field coil ranging from 0 to 8 A. The position controller was deactivated to rule out an unintentional amplification of existing noise. The measurement was repeated with a glass ceramic sensor holder to determine the influence of the electrical insulation between the electromagnet and the sensor housing (Figure 3a). Further on, the measurement surface was separated from the iron circuit by introducing a diamagnetic high-grade steel plate which provided a dedicated measurement target (Figure 3b). Finally, long-term temperature measurements were conducted to identify the steady state temperature and thermal deflection for the considered current settings.

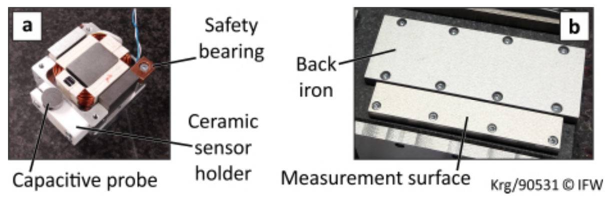

Figure 3. Revised electromagnetic actuator design

4. Results

4.1. Sensor noise

The initial reference measurement with inactive power electronics shows a sensor noise of $\sigma_x = 5$ nm (standard deviation) and $x_{pp} = 40$ nm (peak-to-peak) respectively. Figure 4 summarises the results regarding the sensor noise. The error bars indicate minimum and maximum values for repeated measurements.

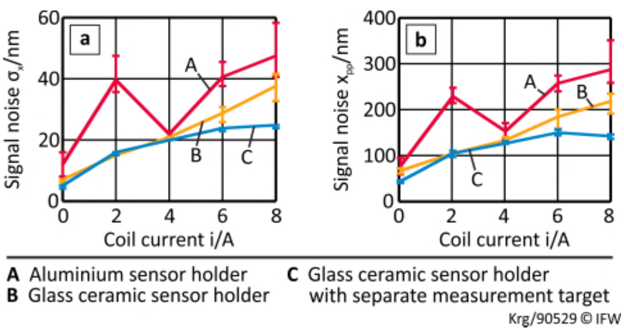

Figure 4. Standard deviation (a) and peak-to-peak (b) noise levels of the air gap measurement system

The original actuator design with an aluminium sensor holder (A) shows an increase of the sensor noise of up to $\sigma_x = 59$ nm and $x_{pp} = 355$ nm. The increased noise levels presumably occur due the operating principle of the probe and the signal conditioner. The measurement system is susceptible to fluctuations of the electrical charge on the sensor housing which result from the pulse width modulation of the coil current. Thus, an electrical insulation between the magnet core and the probe presents an apparent solution. For this purpose, different sensor holder materials were considered. Since the application requires a material with a high dielectric strength and a low thermal expansion coefficient, the revised sensor holder was made of a machinable glass ceramic (B). It effectively reduces the sensor noise by an average of 32% for the investigated coil current range. With the use of an insulated measurement target (C) the sensor noise was further reduced to 44% on average.

4.2. Thermal deflection

Due to the ohmic losses in the coil windings, a temperature increase at the electromagnets is inevitable while the guiding system is active. Figure 5 displays the first 60 minutes of the coil temperature and thermal deflection measurement for the actuator setup with a ceramic sensor holder and a separate measurement target. The recorded data indicates two mechanisms affecting the sensor position (Figure 5b). First, the power dissipation at the coils leads to a heat build-up at the magnet core's centre pole. Hence, the centre pole expands and pushes the mounting fixtures and the sensor holder out- and upwards resulting in an increase of the measured air gap. After approximately 5 minutes this mechanism is superimposed by a downward motion of the sensor due to overall expansion of the mounting fixtures and the sensor holder. With a maximum current of 8 A, the steady state temperature of 51 °C was reached after nearly 3 hours. The maximum overall position error amounts to approximately 1 µm.

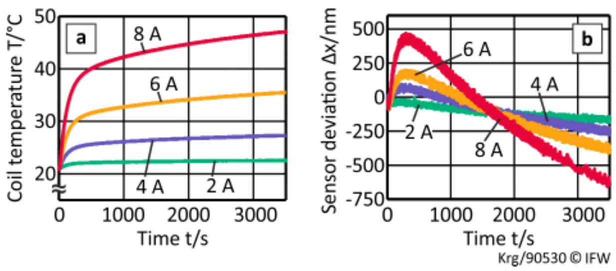

Figure 5. Thermal effects at the revised electromagnetic actuator

5. Summary and outlook

This work focuses on the capacitive air gap measurement system of an electromagnetic guide for ultra-precision machining. The initial operation of the active magnetic guide revealed a significant impairment of the capacitive probes' position signals by the energised electromagnets. By means of a systematic fault effect analysis, appropriate measure were derived to optimise the actuator design. Consequently, the signal noise was reduced by an average of 44% with the use of glass ceramic sensor holders and insulated measurement targets which allows for improved position accuracy and standstill jitter of the guiding system. In addition, the thermal behaviour of the electromagnets and thermal deflection at the air gap sensor were characterised to determine the steady state condition.

Current work includes the reassembly of the test bench after precision alignment of its individual components followed by recommissioning of the electromagnetic guide with an updated modell-based controller.

Acknowledgement

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