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Control system for an ultra-precision electromagnetic linear guide

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Abstract
Up to the present, ultra-precision machining is characterised by low productivity caused by limited feed rates and time-consuming tool and workpiece setup. In order to improve the productivity of precision machining operations, a novel electromagnetic linear guide is developed. This paper presents the control structure for the newly developed electromagnetic guide for use in ultra-precision machining. A state space controller based on Kalman filtering is implemented to achieve a decoupled control of the magnetically levitated slide's five degrees of freedom. Simulation of the feedback control system is performed to verify the function of the state space controller and determine the stiffness of the guide system.

Keywords: Active magnetic guide, state space control, ultra-precision machining

1. Introduction

Ultra-precision machining acts as a key technology for the production of optical components. Primarily, established production techniques are applied to generate micro-structured surfaces and complex freeform surfaces with optical properties. However, long machining times due to limited feed rates and time-consuming tool and workpiece setup present a substantial disadvantage of ultra-precision machining.

In this context, active magnetic guides provide the necessary capability to improve the productivity of ultra-precision machining processes. The use of electromagnetic levitation technology provides friction-free movement and adaptive control of the guide's properties such as stiffness and damping. This allows for high feed rates and cutting speeds without sacrificing position accuracy or process stability. Moreover, the guide system's functionality as a combined sensor and actuator offers additional benefits for an efficient process setup.

Known applications of active magnetic guides focus on high performance cutting [1] or high precision workpiece positioning for non-mechanical production processes and measurement tasks [2, 3]. However, electromagnetic guides for mechanical processing are currently unable to achieve the accuracy required for ultra-precision machining; magnetic guides for high precision positioning lack the necessary stiffness for machining operations. Therefore, a novel electromagnetic linear guide for ultra-precision high performance cutting is developed [4].

Stable operation of the active magnetic guide requires the use of a control system consisting of a sensor system, a suitable control algorithm and power electronics. Design and setup of the control system determine the guide's overall characteristics including stiffness, damping and achievable accuracy. This paper presents the control system for the newly developed electro-magnetic guide. The guide's structure and control setup are introduced in section two. Section three discusses the results of the control system's closed loop feedback simulation.

2. Electromagnetic ultra-precision linear guide

2.1. Design of the electromagnetic guide

The newly developed guide features a differential magnet arrangement with twelve stationary electromagnets (Figure 1). The magnet layout provides functionally independent horizontal and vertical positioning capability. Two ironless linear motors act as a feed drive system. Electromagnets and linear motors are arranged for an effective force application with minimum breakdown torques. An exposed linear encoder is used for position feedback in x-direction. Position feedback for the other five degrees of freedom (DOFs) is realised via capacitive probes at each magnet. Furthermore, four three-axis-accelerometers provide additional information on the slide's state of movement. Table 1 displays the key specifications of the ultra-precision electromagnetic linear guide. Further details on the design of the guide system are presented in [4].

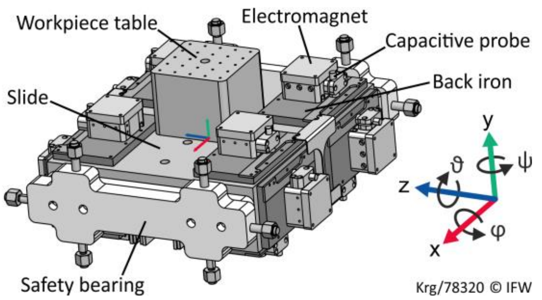

Figure 1. Electromagnetic linear guide for ultra-precision application.

Table 1. Requirement specifications for the new electromagnetic guide.

Travel range (x-direction)	100 mm
Straigtness (over travel range)	0.16 µm
Fine positioning range (y- and z-direction)	± 25 µm
Resolution of the feedback systems	1 nm
Position noise	10 nm

2.2 Control structure

The general structure of the control system is depicted in figure 2. Electromagnetic levitation is realised via state space control in five generalised coordinates which represent the slide's five DOFs ($y\ z\ \varphi\ \psi\ \vartheta$) (Figure 1). For this purpose, the measured air gaps are transformed into generalised coordinates. The sixth DOF (x-direction) is controlled by the two linear motors with the servo drives' inherent cascade loop control. The state space control's algorithm calculates corrective forces in the generalised coordinate system. Generalised forces are then allocated to individual magnet forces depending on the slide's current position. The electromagnets' characteristics – that is the nonlinear relation between the magnet's air gap, coil current and pulling force – are provided by look-up tables. Current amplification is achieved with digital servo amplifiers (MOSFET H-bridge) with a current ripple frequency of 40 kHz. A superimposed PI controller compensates permanent control deviations. The slide's velocity is estimated using Kalman filtering in order to reduce position noise. Additionally, the accelerometers' measurement data is used to improve the velocity signal. The control loop runs at 20 kHz.

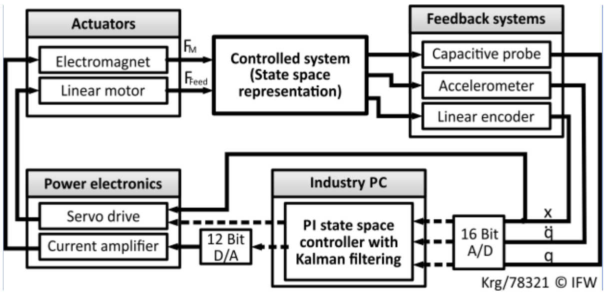

Figure 2. Control structure of the electromagnetic guide.

The state space control was realised in a MATLAB/Simulink environment. The controlled system was modelled using a state space representation based on the slide's equation of motion. Full state feedback was investigated to estimate the attainable stiffness. In order to demonstrate positioning performance and control accuracy, step response of each individual axis is investigated. Furthermore, the impact of Kalman filtering and fusion of position and acceleration sensor data on signal quality and position noise is examined.

3. Simulation results

In theory, active magnetic guides can achieve an infinite static stiffness due to the integrator in the position control loop. Actual restrictions result from the maximum achievable magnet forces and the frame's stiffness. The dynamic stiffness mainly depends on the levitating mass and the control system's configuration. Normally, effective variation of the slide's mass is not possible since it is given by choice of design and material. Thus, pole placement presents a suitable method to adjust the dynamic properties of electromagnetic guides. An increase of the pole radius p_r, that is the complex pole's Euclidian norm, results in improved stiffness and bandwidth (Figure 3). However, high gain factors increase signal noise and induce vibrations in the mechanical structure. Based on previous research [1] a pole radius of at least $p_r = -1000$ can be assumed for the newly developed guide. The phase angle of the complex poles determines the damping behaviour ξ. Conventional roller bearings usually display a damping of $\xi < 0.1$ whereas active magnetic guides achieve a maximised damping of $\xi = 1$. A damping behaviour of $\xi = 0.6$ presents a practical choice since further increase delivers only marginal benefit.

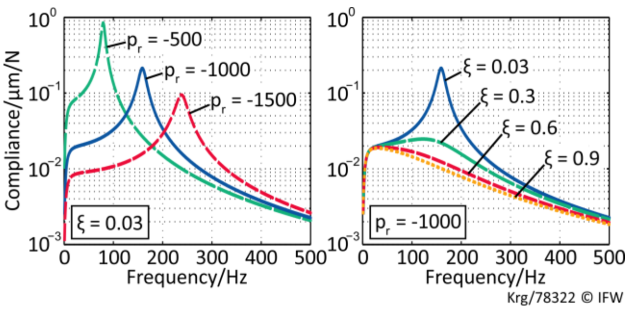

Figure 3. Frequency response function of the closed loop system.

With this configuration, a minimum dynamic stiffness of approximately 52 N/µm at 41 Hz can be expected for the new electromagnetic guide.

Figure 4 demonstrates the fine positioning capability of the electromagnetic guide. The simulation data shows the slide performing 25 nm steps. Deviations occur mainly due to sensor noise (white noise with a standard deviation of 10 nm for the capacitive probes and 0.002 m/s² for the accelerometers), system-specific dead time (approximately 150 µs) and magnet force fluctuations (of 0.2 N per magnet) which were considered in the state space model. By implementing Kalman filtering and sensor data fusion the position noise was reduced to approximately 15 nm for the y- and z-axis.

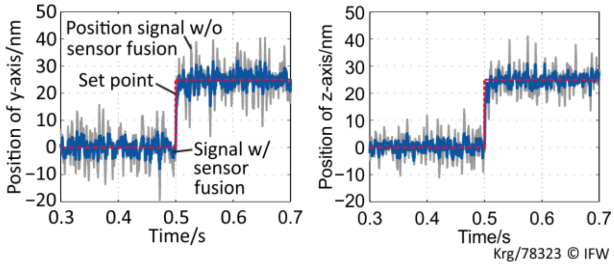

Figure 4. Step function response and position noise.

The stationary magnet configuration leads to changing force requirements along the x-axis travel. The implemented PI controller is not capable of compensation the resulting position deviations because of the limited dynamics of the integrator. Hence, an algorithm was implemented for calculation of the optimal magnet force allocation along the travel.

4. Summary and conclusion

This work introduces the control structure for an ultra-precision electromagnetic linear guide. A PI-state space controller based on Kalman filtering was developed and realised in MATLAB/Simulink. Simulation of the closed loop control system was carried out to verify the controller's functionality.

A practical choice of pole radius and damping indicates a minimum dynamic stiffness of 52 N/µm at 41 Hz. The guide system's theoretically infinite static stiffness is only limited by maximum magnet forces and frame stiffness. The step response function displays a remaining position noise of 15 nm.

In conclusion, the simulation results indicate a satisfactory performance of the control system for precision applications. The acquired data is used to define suitable control parameters for initial operation of the electromagnetic guide. Further optimisation of the control parameters is required to reduce position noise below 10 nm which is a critical prerequisite for ultra-precision machining. Future research will focus on experimental investigation of the control structure.

Acknowledgement

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