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Design and Optimisation of an Electromagnetic Linear Guide for Ultra-Precision High Performance Cutting

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Abstract

Ultra-precision machining is rarely used in the production industry due to high costs as a consequence of disproportionally long primary and secondary processing times. In this context, the implementation of innovative machine technologies presents a suitable approach to increase productivity and reduce manufacturing costs. This paper introduces the implementation of an electromagnetic linear guide within a two-axis positioning stage for ultra-precision and micro machining. Using analytical models and FEM simulations, an optimised design for the guide's structure and magnet configuration is developed with regard to the intended application in ultra-precision high performance cutting. The new guide system provides frictionless operation for rapid and precise feed movements. Stiffness and damping of the electromagnetic guide can be adjusted to current process requirements. Fine positioning of the levitating carriage within the air gap enables an increase of the overall position accuracy.

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Keywords: High performance cutting; Magnetic guide; Ultra-precision machining

1. Introduction

Ultra-precision machining acts as a key technology for the manufacture of optical components. Established production techniques for precision machining are suitable for the generation of micro-structured surfaces and freeform surfaces with optical properties. The area of application for precision machined parts covers astronomy, metrology, medical devices, automotive components and optical industries [1].

However, available ultra-precision machining processes are generally characterised by low productivity. On the one hand, limitations in productivity result from low applicable feed rates. An increase in feed velocity causes increased dynamic disturbances and deviations compromising the optical quality of the machined surface. On the other hand, time-consuming manual alignment of workpiece and cutting tool leads to long secondary processing times.

The implementation of innovative machine technologies presents a suitable approach to increase the productivity of ultra-precision machining. In this context, electromagnetic guides provide the necessary capabilities to improve the performance of ultra-precision machining processes. As mechatronic components, active magnetic guides function as a combined actuator and sensor system. Stiffness and damping can be adjusted to current process requirements within physical limits. The active damping of disturbance forces (such as process forces, breakdown torques or unbalances of rotating components) allows for an increased cutting performance without sacrificing surface quality or process stability. Positioning of the levitating carriage in 5 DOF enable the compensation of production and mounting tolerances in order to increase overall accuracy of the guide system. Furthermore, monitoring of the magnets' coil currents and air gaps enables identification of forces affecting the carriage. Thus, sensory properties of electromagnetic guides can be used for process monitoring and simplified workpiece and tool setup.

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Known implementations of electromagnetic levitation technology in machine tools focus on high performance cutting [2] [3] or workpiece positioning for non-mechanical processing [4]. Existing electromagnetic guides for high performance cutting operations show insufficient accuracy for ultra-precision machining; magnetic guides for precision application do not provide the necessary stiffness for machining processes. Thus, development of a novel electromagnetic guide is required in order to exploit the potential of electromagnetic levitation technology for high-precision application.

Nomenclature

A	magnet surface
B	flux density
F	magnet force
I	electric current
n	number of turns
δ	air gap
Φ	magnetic flux
μ_0	magnetic constant

2. Conceptual design of a prototypical electromagnetic linear guide for ultra-precision machining

Electromagnetic levitation guides distinguish themselves in several ways from conventional guide systems. The most noticeable difference is the reversed bearing force direction. Electromagnets generate only pulling forces; bidirectional force application requires a pair of two opposing electromagnets. Thus, simple substitution of guide components in conventional machine tools is usually not possible. Instead, integration of an electromagnetic guide within an existing machine structure requires a redesign of the surrounding modules.

2.1. Requirements specification

A fly-cutting process with increased cutting performance serves as the reference process for the novel guide system. High performance machining of the planar reference surface with optical quality presents the main objective. Table 1 shows the technical specification for the magnetic guide.

Table 1. Requirements specification for the prototypical guide system

Specification	Value
Feed rate [mm/min]	3000
Acceleration [m/s²]	9.81
Travel range [mm]	100
Straightness (over travel range) [µm]	0.16
Position accuracy [µm]	< 1
Resolution of air gap measurement system [nm]	1
Position noise [nm]	< 10
Bearing stiffness [N/µm]	200
Load capacity [kg]	50

2.2. Design considerations

The novel electromagnetic guide requires a design approach which incorporates two fundamental aspects: First, functional requirements of magnetic guides have to be considered; second, principles of precision machine design have to be taken into account. Imperative design points are the magnet arrangement, magnet design and placement of the feed drive system. The previous design points affect the structural design of the guide. Furthermore, the choice of construction material determines thermal and mechanical properties of the guide's carriage and frame.

A methodology for the conceptual design of an electromagnetic guide for use in ultra-precision machining is presented in [5]. Using the proposed approach, a concept for a novel electromagnetic ultra-precision linear guide was developed (Fig. 1). Key considerations revolve around functional independence and a minimum error budget. Accordingly, the design features a differential magnet arrangement for independent horizontal and vertical positioning. If possible, active components are mounted on the guide's frame to reduce cable drag as a source of non-linear friction. A recessed mounting position of the feed drive achieves minimal breakdown torques. High resolution measuring systems are integrated to monitor the carriage's six DOF. Granite as the main construction material for the guide's carriage and frame provides thermal stability and high damping.

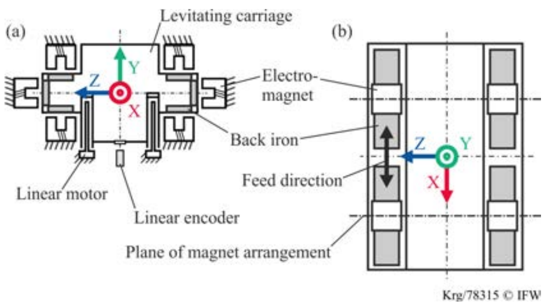

Fig. 1: Concept for an electromagnetic ultra-precision linear guide: (a) Front view; (b) Top view

3. Electromagnet design and optimisation

The magnetic guide's overall properties mainly result from the mechanical and electrical configuration of the electromagnets. Framework conditions for electromagnet design are predominantly set by the requirements regarding the magnet forces. Calculation of magnet forces necessitates detailed knowledge of the electromagnet's geometry and the non-linear properties of the core material. For the application at hand, an analytical model of the magnetic circuit provided an approximation of magnet forces for an initial design. Finally, accurate results were obtained using the finite element method. Optimisation of magnet parameters was achieved using parametric finite element simulation in conjunction with a multi-objective genetic algorithm.

3.1. Analytical calculation

An approximation of magnet forces for the initial design was made by analytical calculation in consideration of feasible simplifications. The required magnet surface was estimated using Maxwell's pulling force formula for the iron-air transition

$$F = \frac{B^2 A}{2\mu_0}. \quad (1)$$

An E-shaped core with three poles was chosen to realise a compact design. Laminated steel as the material for the magnet's core and back iron reduces eddy currents for increased force dynamics.

The electromagnet works with a nominal flux density of up to B = 1.0 T; therefore, magnetic saturation of the core material does not occur at rated operation. Without saturation the iron core can be neglected in the magnetic circuit. Therefore, a closed solution for the magnetic flux can be obtained as deduced in [6]:

$$\Phi = \frac{A\mu_0 nI}{4\delta}. \quad (2)$$

Further, the magnetic flux can be calculated with the generally valid expression for symmetrical magnets

$$\Phi = \int_{A/2} BdA \approx \frac{BA}{2}. \quad (3)$$

Thus, equations (2) and (3) yield a correlation between electrical excitation and force generating induction which is valid for B ≤ 1.0 T:

$$B = \frac{\mu_0 nI}{2\delta}. \quad (4)$$

Accordingly, the pulling force formula (1) can be modified with equation (4) to determine the coil parameters for the initial design:

$$F = \frac{A\mu_0 (nI)^2}{8\delta^2}. \quad (5)$$

3.2. FEM simulation

The analytical results were verified by numeric calculation using the finite element method. The initial magnet design delivered a FEM model for magnetostatic simulation in ANSYS Workbench (Fig. 2). The model exploits the magnet's two symmetry planes to enable a fast and effective calculation; rounded corners and mounting bores were neglected for an efficient surface mesh generation. The finite elements analysis provided accurate results on the magnetic circuit's flux density, the resulting magnet forces and the inductivity of the coil.

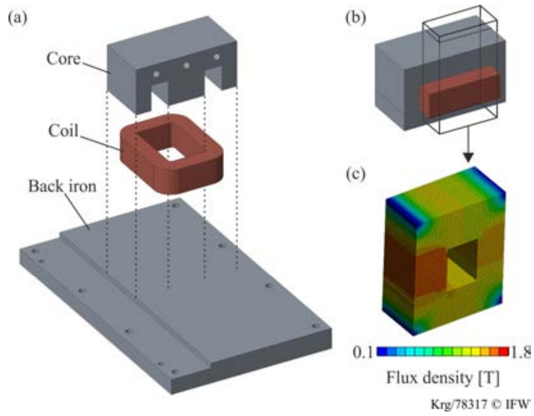

Fig. 2: Initial magnet design: (a) Exploded view; (b) Simplified model for finite element analysis; (c) Simulated flux density distribution

3.3. Parameter optimisation

The electromagnet design presents a highly complex task due to interdependencies of magnet parameters. The design process can be described as a multi-objective optimisation problem. Optimisation was performed at two stages for a practical magnet design approach. First, the magnet's geometry was optimised using parametric simulation in ANSYS Workbench. The geometry of the inner and outer poles was altered for an even flux density in the magnet core. At the second stage, optimal electrical parameters were identified to achieve the required force dynamics.

Force dynamics are primarily limited by the coil's inductivity as well as the performance of the used current amplifier. Current amplification is achieved with a digital servo drive with output control by pulse width modulation (PWM). In comparison to analogue amplifiers digital drives offer lower power dissipation and dynamic parametrisation options. The possibility of dynamic parametrisation is especially helpful for applications with alternating load conditions. Then again, pulse width modulation of the output signal leads to a current ripple which results in unintentional magnet force deviations. Consequently a jitter is induced at standstill.

The digital current amplifier's DC link voltage determines current injection in the coil depending on the coil's momentary inductivity. A low coil inductivity is required to achieve sufficient magnet forces for a wide frequency range. At the same time, coil inductivity and DC link voltage significantly affect the current ripple. High inductivity in combination with low DC link voltage are preferable for minimum current ripple. However, this condition is not compatible with dynamic force requirements.

In order to find a solution for the conflicting objectives a multi-objective genetic algorithm [7] was applied. The optimisation goal for the genetic algorithm was the minimisation of the field coil's inductivity for a set magnet force at nominal flux density. Secondary objectives include minimum resistance of the field coil which minimizes the electrical losses. Coil parameters (such as number of turns and coil current) and nominal air gap were varied to produce populations. Individuals were evaluated with regard to force dynamics and electrical losses.

3.4. Final electromagnet design

For set magnet core and coil dimensions, the magnet's electrical time constant and electrical losses correlate with the magnet force. The optimisation results demonstrate that magnet configurations with low coil inductivity feature a low current sensitivity. Hence, only minor differences in force deviations due to current ripple were identified regardless of the coil's inductivity. Thus, coil parameters like the number of turns and the nominal coil current were adjusted to achieve minimum coil inductivity and maximum force dynamics.

Table 2 presents the technical specification of the final magnet design. Fig. 3 shows the assembly of the final magnet design.

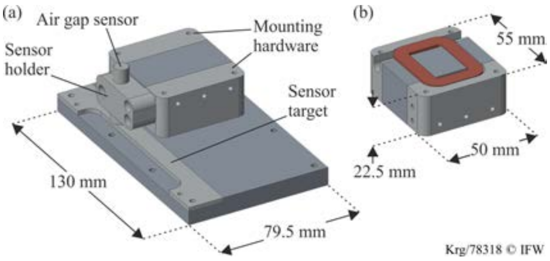

Fig. 3: (a) Final electromagnet assembly; (b) Bottom view of the core unit

Table 2. Technical specification of the optimised magnet design

Specification	Value
Pole surface [cm²]	8.25
Air gap [mm]	0.2
Number of turns	50
Coil inductivity (@ 1.0 T) [mH]	3.95
Coil resistance [Ω]	0.084
Coil current (nominal/maximum) [A]	6.2/12
Flux density (nominal/maximum) [T]	1.0/1.6
Magnet force (nominal/maximum) [N]	300/700
Dynamic magnet force (@ 1000 Hz) [N]	100

4. Ultra-precision two-axis positioning stage

The new design was incorporated within a two-axis positioning stage for ultra-precision machining (Fig. 4). The development of the positioning stage focused on a minimum error budget. A box-in-a-box design minimises cumulative errors. Granite is used as the main construction material for the positioning stage to lessen the effects of thermal expansion.

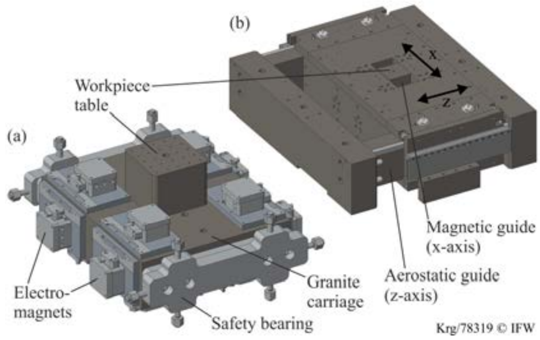

Fig. 4: (a) Carriage of the electromagnetic guide; (b) Two-axis position stage

5. Summary and conclusion

This work focuses on the design and optimisation of electromagnetic actuators as the core components of active magnet guides. An initial magnet design was developed based on an analytical model of the iron circuit. Analytical results were verified by finite element analysis. A parametric FEM simulation was set up and coupled with a multi-objective genetic algorithm in order to optimise magnet geometry and electrical parameters. The final magnet design was evaluated with regard to current amplification and force dynamics.

The optimised magnet design was incorporated in a novel electromagnet guide system. Implementation of the new guide within a two-axis-positioning system for ultra-precision machining was considered.

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