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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.

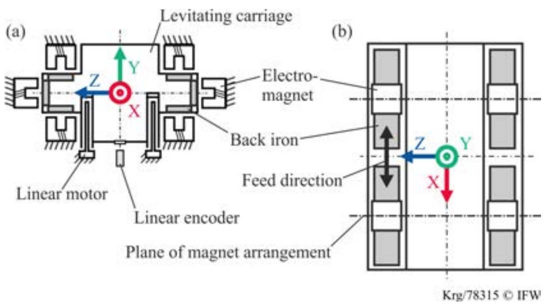

Fig. 1: Concept for an electromagnetic ultra-precision linear guide: (a) Front view; (b) Top view

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.

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