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Electromagnetic Levitation Guide for Use in Ultra-Precision Milling Centres

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Abstract

Today's machine tools for ultra-precision machining are generally characterised by low productivity. Above all, practical cutting parameters are limited due to uncontrollable disturbance forces. Therefore, it is necessary to pursue the qualification of new technologies to overcome current limitations in productivity. In this paper, an approach for the design of a novel electromagnetic levitation guide for use in ultra-precision milling centres is presented. Design and arrangement of the magnetic guide's components are considered with regard to requirements and design principles of precision machines. Deterministic methods are utilised throughout the engineering process to ensure high stiffness and high dynamics. As a result, a concept for the electromagnetic ultra-precision linear guide is derived.

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1. Introduction

1.1. Ultra-precision machining

Ultra-precision machining provides production techniques for generating complex micro-structured surfaces and high precision freeform surfaces with optical properties [1]. It is considered as a key technology for the processing of optical components. The area of application covers astronomy, automotive and medical devices as well as metrology and optical industries.

Over the last decades research and development predominantly focused on measures for a further increase in accuracy [2]. However, the overall performance of ultra-precision machine tools is still limited by low feed rates along with time-consuming manual workpiece and tool alignment. Restrictions of cutting parameters in particular result from rigorous workpiece tolerances of optical elements. An increase in cutting performance inevitably leads to increased dynamic disturbances caused by process forces, drive torques and unbalances of rotating components. Consequently, a growing

influence of these disturbance forces may compromise surface quality and process stability.

In order to overcome current limitations it is necessary to pursue the qualification of new machine concepts and technologies [3]. In this context, active magnetic bearings and guides offer considerable potential to improve the productivity of ultra-precision machining processes.

1.2. Potential of active magnetic guides in machine tools

The guide system in a machine tool has a significant impact on its overall performance. Active magnetic guides offer considerable advantages in comparison to conventional systems such as friction guides, roller guides, hydrostatic or aerostatic guides. Providing friction free operation, electromagnetic levitation technology enables fast and precise motion. The absence of fluid media and wear makes the system basically maintenance-free.

In contrast to established concepts, which utilise repelling forces, the working principle of magnetic guides is based on inherently unstable pulling forces of electromagnets. Thus, an

active control system is required to ensure dependable operation at all times. Accordingly, an active control of the electromagnetic actuators allows for an adaptive adjustment of the guide's properties, resulting in high damping and an infinite static stiffness. Furthermore, the guide functions as sensor and actuator, allowing identification of process forces and precision positioning operations.

Contemporary machine tool prototypes with magnetic guides demonstrate the potential of this technology [4, 5] (Figure 1). Experimental evaluation of electromagnetically guided spindle slides confirms improved chatter stability compared to operation with conventional ball guides [5]. In addition, an in-process force estimation and fine-positioning in 5 degrees of freedom can be accomplished [6].

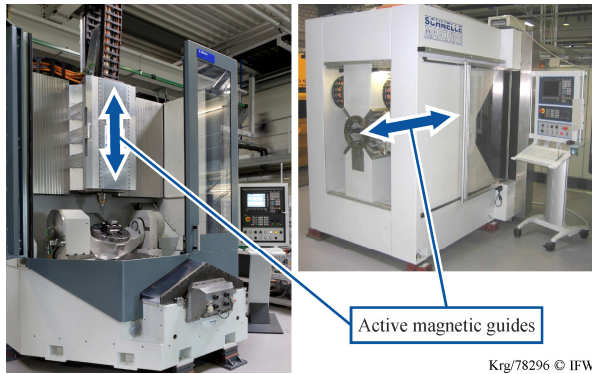


Fig. 1. Machine tool prototypes with active magnetic guides

Ultra-precision machine tools are sure to benefit from the before mentioned features of active magnetic guides. A process-oriented adaption of the guide's stiffness and damping creates ideal conditions for improved cutting performance without compromising quality or stability. Implemented within a workpiece-sided biaxial positioning system, fine-positioning operations allow for compensation of static and dynamic deviations, e.g. manufacturing and assembly errors, mechanically and thermally induced deformations of the machine frame or position errors of subordinated axes. Moreover, the mechanism can be used for accurate alignment of workpiece and tool.

1.3. Objective

Despite the general benefits of electromagnetic levitation technology, existing magnetic guides for use in machining centres do not achieve the accuracy needed for ultra-precision machining. Known precision applications are limited to transport and positioning [7], e.g. in lithographical processing. An active magnetic guide for actual use in ultra-precision machining has not yet been published.

This paper presents a design approach for an electromagnetic levitation guide for use in ultra-precision milling centres. First, a methodology for the design of electromagnetic ultra-precision linear guides is proposed. It is then exemplarily applied to derive a suitable magnet arrangement. Also, choice of construction materials and integration of functionally relevant components are

considered. Finally, a concept for the novel electromagnetic guide is presented.

2. Design approach for electromagnetic levitation guides

To begin with, design of precision machinery is guided by specific concepts and principles (Figure 2). Methods, techniques and tools are provided to ensure a high working precision of the constructed machine [8, 9]. For the application of magnetic bearings and guides in machine tools, basic functional requirements of electromagnetic levitation technology have to be considered. Distinctive feature of active magnetic guides is a reversed direction of bearing forces. Thus, simple substitution of existing guide elements is not possible. Implementation of this technology requires a redesign of the guide's components and surrounding modules in consideration of the designated application.

Hence, a holistic design approach for the novel magnetic guide is required. In order to structure the development process, it can be divided into several work steps. Throughout the distinct work steps special attention is paid to fundamental principles of precision machine design. Deterministic methods and tools are applied throughout the engineering process.

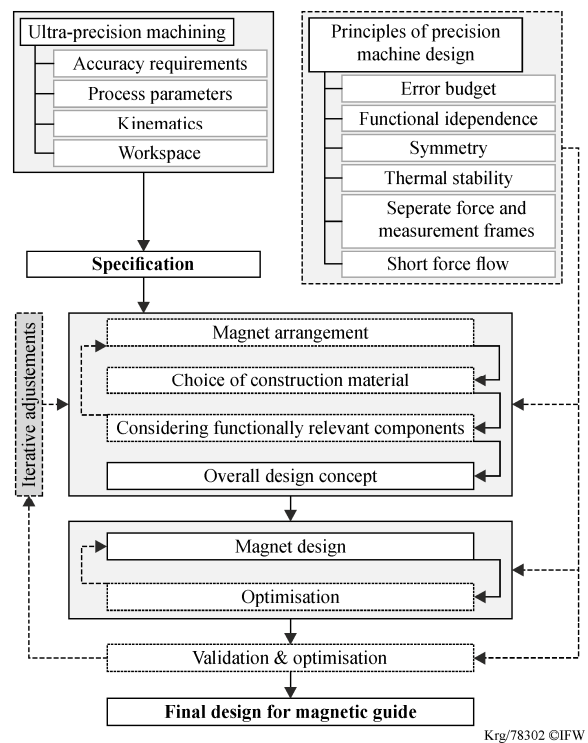


Fig. 2. Design approach for an electromagnetic ultra-precision linear guide

Initially, the area of application and its specific requirements are defined. On this basis, the arrangement of the electromagnets is derived, followed by selection of construction materials and essential components. Then, integration of relevant components is considered. The prior work steps determine the overall appearance of the magnetic

guide and set boundary conditions for the consecutive design of the electromagnetic actuators. At last, validation and optimisation lead to the final design. Figure 2 outlines the proposed design methodology in detail.

3. Exemplary application of proposed design methodology

In the following, the major steps of the methodology are applied exemplarily for the design of an electromagnetic ultra-precision linear guide.

3.1. Requirements definition

Objectives and technical specifications are mainly derived from the envisioned application in ultra-precision machine tools. Fly cutting with enhanced cutting performance is chosen as a reference process. The process data is displayed in table 1.

Table 1. Reference process

Parameter	Value
Feed rate [mm/min]	500 ... 3000
Cutting speed [m/min]	7500
Depth of cut [μm]	5
Kinematic surface roughness [nm]	< 10

Machining of a workpiece's complete surface requires the use of a second feed axis. Therefore, integration of the newly developed guide within a two-axis positioning stage is considered (Figure 3). A box-in-box-arrangement is chosen to realise a compact design. Accessibility of workpiece and cutting tool has to be ensured.

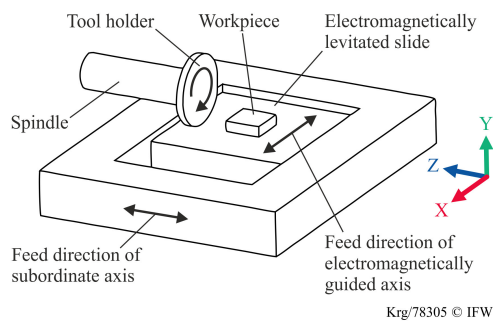


Fig. 3. Machining kinematics for reference process

Likewise, the novel guide has to be able to meet the performance requirements of established systems. Technical specifications for the electromagnetic ultra-precision linear guide are illustrated in table 2.

Table 2. Technical specification of the active magnetic guide

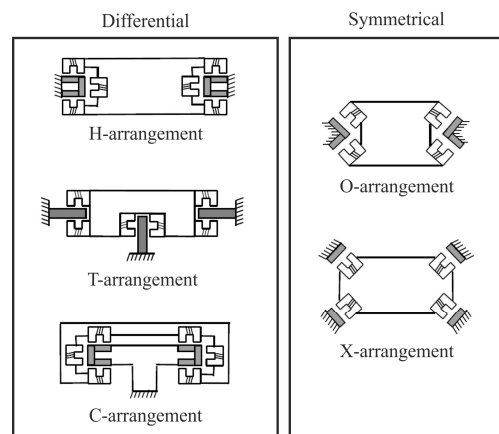
Specification	Value
Feed rate [mm/min]	3000
Acceleration [m/s^2]	9,81
Travel range [mm]	100
Straightness (over travel range) [μm]	0,16
Resolution of air gap measurement system [nm]	1
Position noise [nm]	< 10
Bearing stiffness [$\text{N}/\mu\text{m}$]	200

3.2. Arrangement of electromagnetic actuators

The arrangement of the electromagnetic actuators determines the design of the guide's slide and frame. Also, it defines the boundary conditions for the integration of other functionally relevant components. Criteria for the selection of a suitable layout are compact design, high stiffness of the resulting slide construction, high actuation torque and minimal error budget.

With respect to a relatively short travel range, stationary magnets are implemented. Therefore, the electromagnets, as the actuating system's active components, are mounted on the guide's frame. This reduces the amount of necessary supply lines and cable drag as a source of non-linear friction forces on the slide. At the same time, variable magnet forces are considered in order to ensure levitation in every position along the travel.

As for the layout, differential and symmetrical arrangements are considered (Figure 4). Differential arrangements utilise actuators consisting of opposing electromagnets to apply bidirectional forces. This allows for an independent control of individual degrees of freedom. Symmetric arrangements, on the other hand, reduce the number of necessary magnets at the expense of functional independence. This is achieved through inclined positions of single magnets, which leads to increased complexity due to linked degrees of freedom.



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Fig. 4. Differential and symmetrical magnet arrangements

Despite the reduced number of magnets, symmetrical arrangements may require more space within the machine structure. This is due to the relationship between active magnet surface and magnet force expressed by Maxwell's pulling force formula:

$$F = \frac{B^2 A}{2\mu_0}$$

where F describes the magnet force, B the flux density, A the magnet surface and μ_0 the magnetic constant.

Since fewer magnets have to absorb occurring loads, magnet surface and overall magnet dimensions respectively have to be increased for symmetrical arrangements. An exemplary calculation was performed in order to determine the minimum pole surface per magnet for differential and symmetrical configurations. The minimum magnet surface is defined by the minimum magnet force, which is required to enable a dependable levitation of the slide across the full travel range. The maximum flux density was assumed to be 1.6 T. For symmetrical arrangements the inclination angle of the electromagnets was set to 45°.

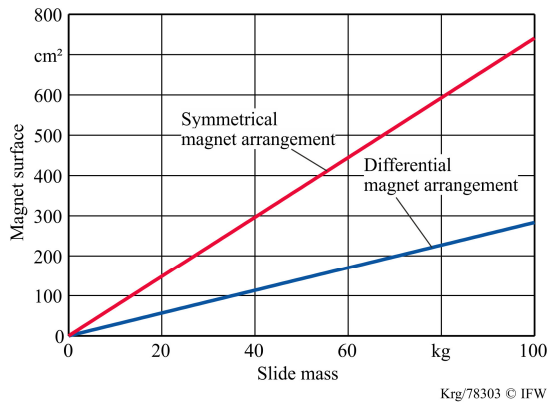


Fig. 5. Minimal magnet surface for differential and symmetrical arrangements

Calculation results show a significantly higher minimum magnet surface for symmetrical arrangements (Figure 5). Thus, differential arrangements are an appropriate choice to realise a compact design. Also, uncoupled actuation of individual degrees of freedom provides functional independence and simplifies initial operation.

Table 3. Evaluation of magnet arrangements

Evaluation criteria	H	T	C	O	X
Number of magnets	-	-	-	+	+
Magnet dimensions	+	+	+	-	-
Actuation torques	+	+	+	++	-
Error budget	++	-	++	-	-
Slide's structural stiffness	+	-	--	++	++
Functional independence	++	++	++	--	--

Comparison of proposed variations reveals a differential H-arrangement to be most suitable for the intended application (Table 3). A differential C-arrangement results in a very compliant structure of the slide and is eliminated as an option. In case of a T-arrangement recessed installation of the actuators for horizontal positioning decreases the slide's stiffness. Hence, it is excluded as well.

The initial H-arrangement from figure 4 is adapted to a stationary magnet configuration and slightly altered to provide an easy access to the workpiece mounting area. Figure 6 shows the resulting setup.

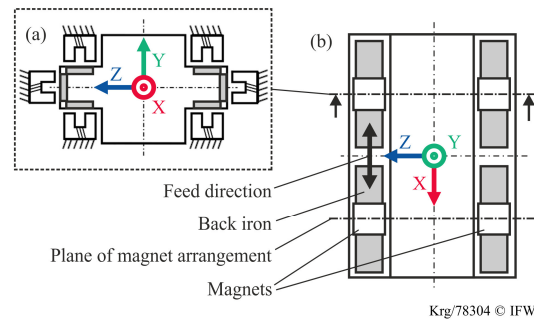


Fig. 6. Magnet arrangement for electromagnetic ultra-precision linear guide

3.3. Material selection

Steel is the common choice for the construction of machine tools. High stability and durability make it a perfect material for mechanically stressed structures. In ultra-precision machining, process forces typically lie below 10 N. Therefore, mechanical stress is primarily induced by the drive system and other potential actuators. Alongside mechanical characteristics, thermal properties are decisive for a reasonable choice of material. A selection of construction materials most commonly used for precision machines as well as the respective material properties are listed in table 4.

Table 4. Properties of common construction materials

Properties	Steel	Aluminium	Invar	Granite
Modulus of elasticity [GPa]	210	71	148	76
Density [kg/m³]	7,800	2,710	8,030	2,600
Material damping loss factor [%]	<0.0003	<0.00001	<0.0003	0.005
Thermal expansion coefficient [10 ⁻⁶ /K]	12	23	1.2	6
Thermal conduction coefficient [W/(m*K)]	54	177	11	1.6

In order to evaluate the impact of mechanical and thermal properties on attainable accuracy, an investigation of different materials is conducted using FEM analysis. For this, a FE-model of the slide derived in chapter 3.2 is build (Figure 7). Mechanical properties are examined by applying a downward force of 10 N at the workpiece position. Thermal effects are investigated by an increase in surrounding temperature of

0.1 K. The absolute deflection in y-direction at the workpiece position is calculated. Simulation results for regarded materials are shown in figure 7.

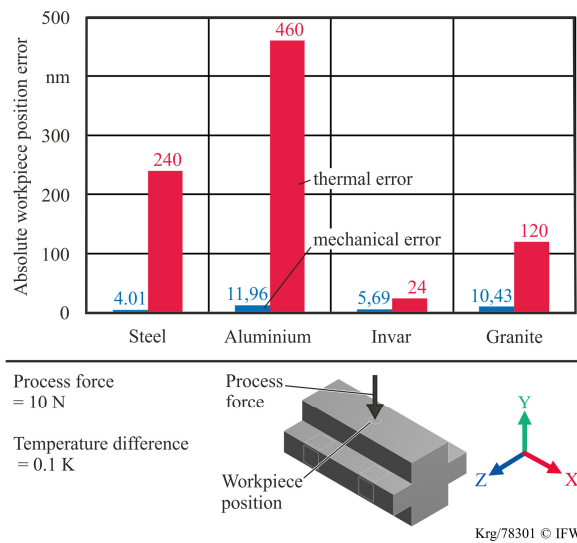


Fig. 7. Mechanically and thermally induced deflections at workpiece position

In consideration of low estimated process forces of ultra-precision machining, it stands to reason that position errors due to thermally induced material expansion are more eminent. Extensive use of steel and aluminium in precision machines is limited due to relatively high coefficients of thermal expansion. Invar, a nickel-iron alloy, proves to have both ideal mechanical and thermal properties. However, high costs for raw material and difficult machining conditions make a wide-ranging application of Invar uneconomic. Granite provides thermal stability as well as high material damping. Density and rigidity are similar to those of aluminium while material damping is significantly higher. For these reasons, granite is commonly used for the manufacture of precision machine components.

Consequently, granite is chosen for the construction of the guide's slide and rack. Other materials are purposefully used according to their specific properties. Steel is used to reinforce mechanically stressed regions. Aluminium is employed for selective heat dissipation. Invar is utilised for components with extraordinary precision requirements, e.g. target surfaces for position measurement.

3.4. Integration of functionally relevant components

Due to the unstable character of magnetic forces, an electromagnetic guide requires continuous measurement of magnetic air gaps along with an active control of respective actuator currents. Capacitive sensors are used to monitor the air gap of each magnet. For this, a stationary magnet and sensor configuration is beneficial to the overall precision because of a constant distance between measurement system and tool centre point. Furthermore, accelerometers are attached to the slide to gain additional information on its state

of movement. Primarily, this information is used to increase the resolution and bandwidth of position measurement by means of sensor fusion [10]. Moreover, the data can be used to obtain information on the slide's structural mechanics.

In order to function as a complete feed axis for use in precision machine tools, a feed drive system has to be integrated. Ironless linear direct drives are chosen as they deliver high precision and motion dynamics. Most importantly, attractive forces and cogging between the coil unit and the magnet track are eliminated because of the absence of an iron core within the coil unit. Ironless direct drives are often installed in a space-saving horizontal position (Figure 8(a)). Because of the eccentric point of force application, undesirable breakdown torques and position errors are the consequence. Also, this configuration results in an asymmetrical heat input into the guide's slide and rack. A more sensible type of installation is a recessed vertical position as illustrated in figure 8(b). Moving the point of applied force closer to the slide's centre of mass significantly reduces the impact of drive torque on the error budget. Further on, this configuration permits an even heat influx and efficient dissipation at the coil unit.

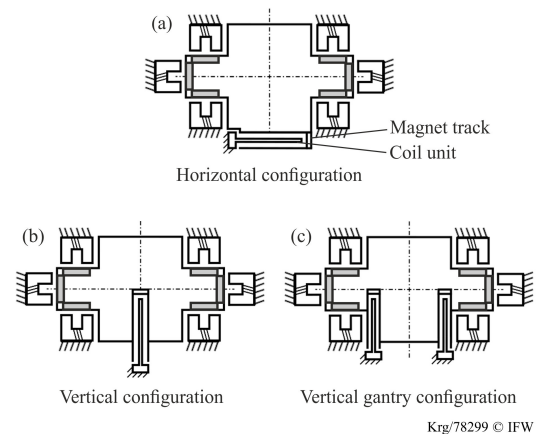


Fig. 8. Placement of feed drive system

In accordance with the magnet arrangement, the coil unit is immovably mounted to the guide's frame whereas the slide accommodates the magnet track. Thus, the slide's dimensions restrict the overall length of the magnet track. At the same time, the coil unit's size is proportional to the attainable feed force. Given the technical specification of available ironless direct drives, required feed force and travel cannot be realised with a single drive for a set magnet track length. Hence, a gantry configuration of two downsized linear direct drives is chosen (Figure 8 (c)).

An exposed linear encoder provides the position data for the drive control. Thereby, one linear encoder is used to control both drives. Parallax errors are taken into account for the selection of encoder placement. Measurements errors result from the slide's rotation about its y- and z-axis. Based on the definition of the setup's fine-positioning range, the maximal angle of inclination is estimated with 0.25 mrad for

both axes. Different positions for the linear encoder are considered with regard to the total error budget (Figure 9).

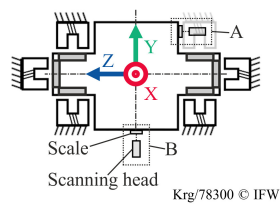


Fig. 9. Placement of linear encoder

In combination with a gantry system for the feed drive, a central placement of the linear encoder seems suitable (Position B in figure 9). Installation in position A marginally reduces the position error in feed direction from $27.50 \mu\text{m}$ (Position B) to $23.75 \mu\text{m}$. However, this configuration places the scanning head on the force frame in between the electromagnetic actuators, which results in an increased error budget. Thus position B is chosen.

With magnet arrangement and integration of functionally relevant components considered so far, figure 10 illustrates the current concept for the novel electromagnetic ultra-precision linear guide. Evaluation of the error budget over the course of development reveals a decrease of the estimated overall error at the workpiece position of approximately 51 % when compared to a non-optimised design.

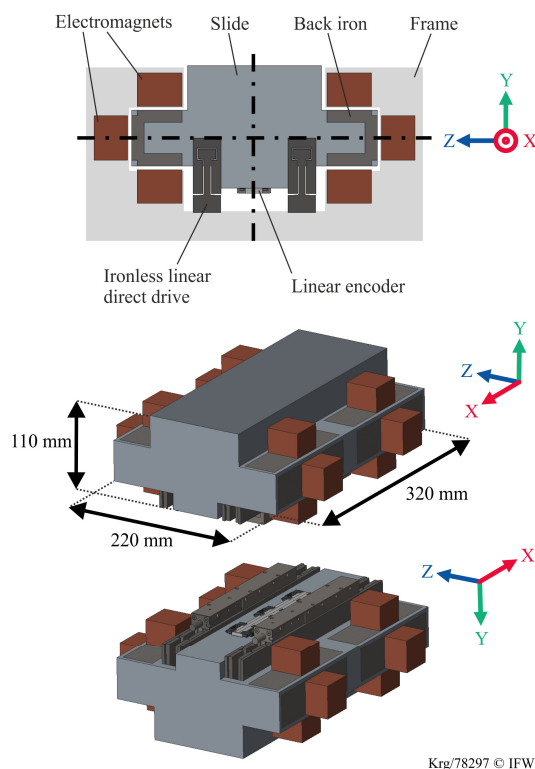


Fig. 10. Concept for novel electromagnetic levitation guide

4. Conclusion

Despite the technical capability, machine tools for ultra-precision manufacturing are characterised by low productivity due to disproportionately long primary and secondary process times. Qualification of new machine concepts and technologies is a suitable strategy to remedy the situation. In this context, the potential of active magnetic guides for use in ultra-precision machining is discussed. Benefits and prototypical implementations of electromagnetic levitation technology in machine tools are outlined.

Furthermore, a design methodology for a novel electromagnetic ultra-precision linear guide is proposed. It provides a systematic approach, which allows to break down the complex development process into several work steps. Also, it implements deterministic concepts, joining together methodical procedures for the construction of magnetic guides and principles of precision machine design. Deterministic tools make it possible to consider the impact of specific design features on the construction's overall properties, which enables a purposeful and efficient design process when compared to approaches based on empirical knowledge. The proposed design methodology is exemplified by deriving a concept for the novel electromagnetic guide. Analysis of the error budget confirms a decrease of the estimated error at the workpiece position by means of ideal arrangement of actuators, sensors and drives, specific material selection as well as optimisation of the slide's topology.

Acknowledgements

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