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Conceptual design for electromagnetic guided rotary table in machine tools

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Abstract

Difficult-to-machine materials are still challenging the production industry. Examples are highly complex components of aircraft engines. Alongside innovative processes, also improved machine tool components are helping to comply with the demands of this task. This paper presents a design approach of a rotary table with an active magnetic bearing. Opportunities in machining through employing magnetic guides are presented and discussed in the beginning. In the following, a workflow for the magnetic bearing design in swivel rotary tables is proposed. The mentioned steps are executed based on a presently under design rotary table.

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Keywords: active magnetic bearing (AMB); swivel rotary table; machine tool

1. Introduction

Aircraft engine components stand for complex 5-axis machining tasks. Some reasons are the high demands on form, on surface accuracy and the challenging material properties. Repairing these parts extends the mentioned challenges due to unique part characteristics. New machining strategies, cutting tools but also machine tools or components have to be developed to successfully overcome the difficulties [1, 2].

One promising approach is the use of electromagnetic guides in machine tools. Magnetic guides can be used as sensor and actor, which significantly eases the implementation of adaptive machining strategies.

So far, there exist implementations of magnetic guides in the linear z-axis of machine tools [3, 4]. A workpiece-sided use of this technology is realized in stand-alone rotary tables [5, 6]. A (swivel) rotary table in machine tools is not yet accomplished.

This paper aims for presenting a sensible design approach for magnetic guided machine tool tables. It is organized as follows: General benefits and limitations of electromagnetic guides in machine tools are outlined and discussed in chapter 2. In chapter 3 a methodology for the magnetic bearing design in swivel rotary tables is proposed. This methodology is applied in the following chapter. Conclusions are drawn in chapter 5.

Nomenclature

P_s	mean position scatter
A	magnet surface
B	magnetic flux density
F	magnet force
μ_0	magnetic constant
R_m	magnetic resistance of the core
R_b	magnetic resistance of the back iron
R_δ	magnetic resistance of the air gap
Θ	magnetomotive force
Φ	magnetic flux

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2. Active magnetic guides in machine tools

Magnetic guides offer significant benefits. High damping, an infinite static stiffness of the guide and the system inherent capabilities to work as a sensor and actuator are the most obvious ones. The here presented characteristics are derived from a linear electromagnetically guided z-axes in a machine tool [3, 4].

2.1. Structural behavior

The structural dynamics exhibits the specific properties of active systems. The low frequency range is determined by the controller settings of the system while the high frequency range shows the structural behavior of the actively guided component.

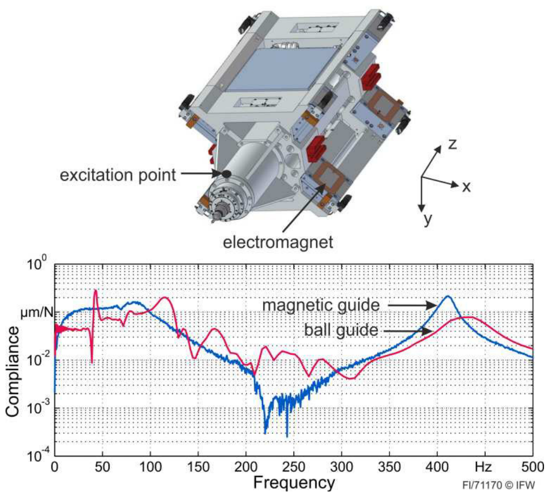

Fig. 1. Compliance of an electromagnetically guided spindle slide

In Figure 1, a magnetically guided spindle slide of a machine tool z-axis is shown. For comparisons, it is also possible to use the slide with conventional ball guides. The lower figure shows a drive point frequency response function (FRF) in y-direction. Implementing electromagnetic guides, an increase of stiffness in the low frequency range is obvious. This is because of an integrator in the position control loop. Only the maximum force of the electromagnet limits the static stiffness. The most compliant frequency range of the controlled slide is around 70 Hz. This is equivalent to the bandwidth of the position control. There is no overshoot because of maximized damping. The first bending mode of the slide is at 420 Hz. Using conventional guide systems the rigid body mode of the guide is at 40 Hz. This mode is poorly damped and results in a significant overshoot in the FRF.

2.2. The guide as sensor and actuator

The slide can be positioned in its five degrees of freedom (DOF) within the air gap of the electromagnets (approximately 400 μm). The dynamic and accuracy of this positioning movement considerably exceeds the possibilities of conventional feed drive systems in machine tools. The positioning bandwidth is listed in Table 1.

Table 1. Positioning bandwidth (-3dB boarder)

x	y	φ	ψ	θ
51 Hz	51 Hz	59 Hz	46 Hz	72 Hz

Positioning accuracy of the magnetic guide in y-direction was measured with a Renishaw ML10 laser interferometer. Due to the friction free operation, the random error in positioning is about five times smaller than in the conventional feed drive system. The mean position scatter is $\mathbf{P_s}$ = 0.36 μm (magnetic guide) and $\mathbf{P_s}$ = 1.81 μm (conventional y-axis), respectively.

The sensory capabilities allow estimating process forces without additional instruments. Disturbance forces have to be compensated by the guide's control system and can thus be identified. This is realized with a disturbance force observer. The algorithm is outlined in [7]. Figure 2 presents the force estimation. A bandwidth of around 50 Hz is reached. Here, the disturbance force was applied by a shaker close to the TCP of the linear axis.

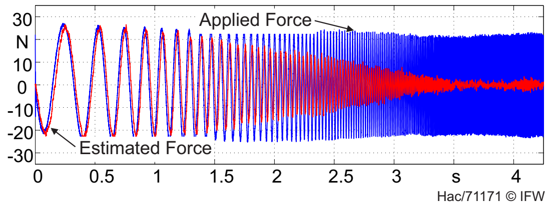

Fig. 2. Force estimation with magnetic guide.

2.3. Outlook: rotary tables

Friction free operation set the conventional speed limits of roller bearings aside. Loads are solely limited by the chosen magnetic setup. Structural behavior significantly benefits of a compact and stiff design in rotary tables. By avoiding low frequency eigenmodes control performance can be raised. In turning operations fine-positioning can be used for alignment or out-of-center turning.

3. Design methodology for a magnetic guided rotary table

The development process of an electromagnetic guided rotary table is divided into multiple steps. The here presented design methodology proposes a sequence of necessary work steps and its results as shown in Figure 3.

In the beginning of the design process the specific area of application and its requirements have to be defined. Detailed specifications are the result. Hereby the magnet design is limited by given geometries. Typical limiting components in rotary tables are the direct drive, the media transfer unit and the clamping mechanism of the axis. Based on the specifications and the usable free geometry within the rotary table, the needed magnet forces can be calculated. A first guess of magnet type and its number of poles is the needed input for an optimization process. The optimization goal is either determined by the limiting geometries or by individual factors. Design conflicts can thus be identified.

If a geometry conflict occurs, an iterative cycle is triggered as a result to the interlocking of the magnet design, its placing and the overall requirements. Adjustments or a compromise have to be made depending on the individual development goal. For example a minimal size and a maximum loading capacity is causing a conflict.

Finally, the resulting magnet configuration has to be validated whereas small adjustments are made to fine-tune the design. Subsequently a detailed construction of the entire swiveling axis can be made.

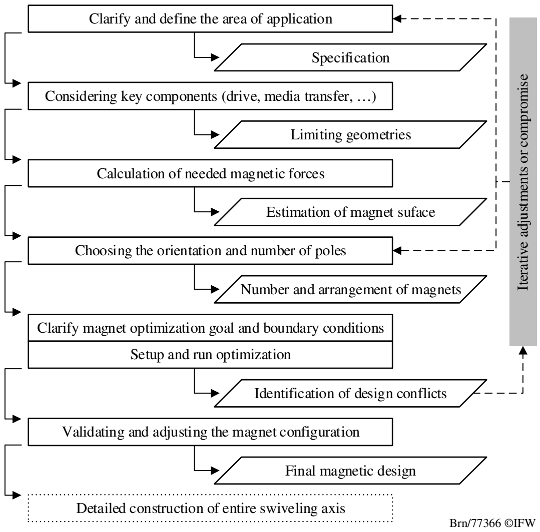

Fig. 3. Design methodology for an electromagnetic guided rotary table.

4. Exemplary application of the methodology

4.1. Defining the requirements and the limiting geometries

Here, the shown design methodology is applied to develop a specific rotary table in cooperation with MAG and Siemens. Therefore, the technical requirements result from a standard rotary table in machine tools. Table 2 illustrates an excerpt. Standard industrial components are used.

Table 2. Technical requirements of the rotary table

Requirement	Unit	Description
Table diameter	mm	450
Loading capacity	kg	350
Max. rotation speed	1/min	1500
Torque of direct drive	Nm	S6 = 1420
Repeatability in clamping	arcsec	5
True-running	mm	0,01
Max. torque clamped	Nm	1500

A key to acceptance of magnetic guides is to achieve comparable performance to regular bearings at higher functionality. For example rolling contact bearings in rotary tables are mostly limited in a range of 100 rpm to 1000 rpm. Using a friction less bearing this limitation is excluded. Hence, the here intended direct drive 1FW6150 by Siemens – allowing up to 1500 rpm – becomes one of the speed limiting components. Additionally, it consequently limits the utilizable space by its geometry, too. The transfer of media from the stator to the rotating table further reduces the available space. As in conventional designs it is arranged in the rotational axis. Because of the still unknown dimensions a rough estimation has to be made.

In this conceptual design the direct drive and the media transfer are fixed geometries. Therefore, the magnet design has to be adjusted to their dimensions.

4.2. Calculation of magnetic forces

The calculation of forces implies choosing a magnet arrangement. Here, three conventional arrangements are proposed. The differential arrangement uses opposing magnets to control the five DOF separately as seen in Figure 4(a). In contrast, the symmetrical arrangement reduces the number of magnets but raises the complexity due to linked DOF. The latter arrangement can be further divided into an O-arrangement (Figure 4(b)) and an X-arrangement (Figure 4(c)).

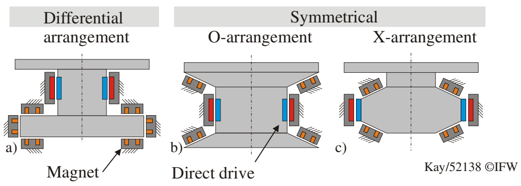

Fig. 4. Three possible magnet arrangements

Here, all three arrangements were considered. The calculation of the needed magnet forces has to be done for each possible swiveling angle. Due to the weight shift while swiveling, the forces will rise to a maximum at a certain swiveling angle. In Figure 5 a radially positioned magnet is exemplarily plotted.

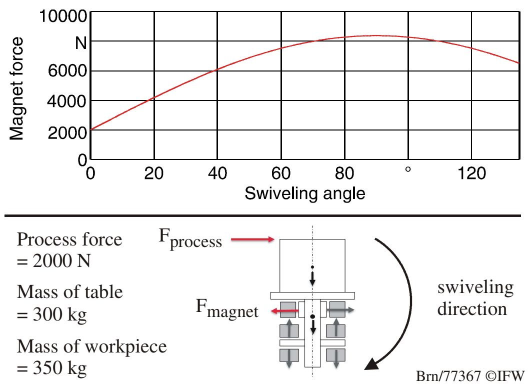

Fig. 5. Exemplary radial magnet forces.

Obviously the maximum load occurs at 90° because the magnet has to bear the downward pointing mass and the process force. At 0° only the process force is compensated by the magnet. Other magnets and arrangements will have their maximum at differing angles.

Maxwell's pulling force formula is used to roughly calculate the magnet force **F**:

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

where **B** describes the flux density, **A** the magnet surface and μ_0 the magnetic constant. By solving the equation for **A** an estimation of the necessary magnetic surface is obtained. B=1.6 tesla can be considered as a maximum flux density. For the most laminated magnetic materials the magnetic saturation will already be exceeded. Reducing the maximum flux density will increase linearity of force and current in a conventional opposing magnet configuration but increases the required magnet surface and volume.

As a result, the symmetrical arrangement requires significant higher forces due to the angled and curved magnets. Therefore a larger surface and larger magnets are necessary. Hence, the differential arrangement was chosen to achieve a more compact design in this specific example. On the downside two different magnet types – an axial and a radial magnet – have to be designed.

Other arrangements may have to be chosen depending on the boundary conditions.

4.3. Choosing the orientation and number of poles

The orientation of the magnetic poles defines the path of the magnetic flux and influences the losses. Depending on the maximum occurring rotation speed, available materials and the producibility, two different orientations can be selected. Either a heteropolar (Figure 6(a)) or a homopolar (Figure 6(b)) magnet can be realized.

For example, in small active magnetic bearings (AMB) it is difficult to reduce eddy-current losses by lamination due to their size. Therefore a homopolar orientation is preferred using a solid core and rotor as presented in [8].

In larger systems – as the magnetic guided rotary table – with static or dynamic loads the induced field variation needs a laminated rotor [9]. Because a homopolar orientation cannot be reasonably laminated, a heteropolar orientation is dictated.

When choosing the number of poles it has to be kept in mind that fewer poles reduce hysteresis losses and eddy-currents within the rotating back iron at higher rotating speeds. This is caused by the changing magnetic field. Paired poles (N-N-S-S) in heteropolar bearings are beneficial to further reduce losses as shown in [10]. Though, the maximum magnet dimensions determine the minimum number of poles. For example a larger cross section within the yoke can reduce the number of poles because more flux can flow through one single pole. Therefore an iterative process is needed to find the suitable number of poles.

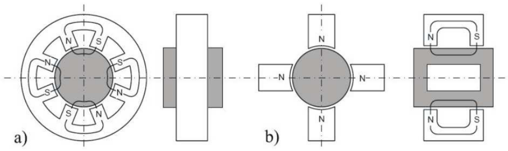

Fig. 6. (a) Heteropolar; (b) Homopolar (from [9]).

In theory, a minimum of three poles is possible but results in a strongly nonlinear system due to the magnetic coupling and the coupled axes. The most common configuration without major coupling is the 8-pole design as in Figure 6(a). Eight poles can be realized by four U-core magnets. The next higher number of poles would be a 12-pole design consisting of four E-core magnets. To further reduce the core size, a multiple of either one of them is used (for example: two E-cores are combined).

Here, U-cores were initially intended. Due to the results of the magnet optimization in the next step, a higher pole number had to be chosen.

4.4. Magnet design optimization

For optimization, a genetic algorithm (GA) is used. Due to the frequent function calls of the GA, a fast and efficient magnet calculation is needed. Therefore, each individual magnet is computed via equivalent magnetic networks. This speeds up the algorithm immensely compared to multiple FEM. As an example the equivalent magnetic network for a radial E-core is shown in Figure 7. A single coil generates the magnetomotive force **Θ**. Hence, the magnetic flux **ϕ** divides into the left and right leg of the yoke.

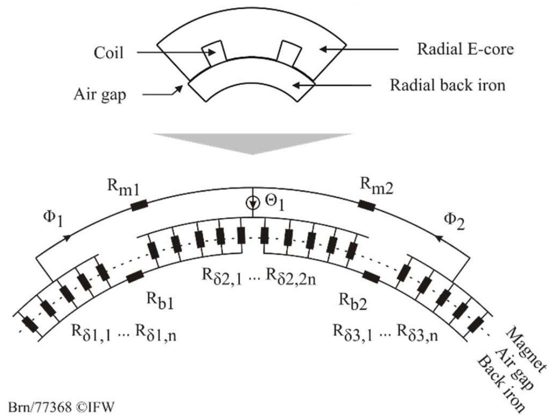

Fig. 7. Equivalent radial E-core magnetic network.

The air gap is split into an adjustable number of slices. Each slice's magnetic resistance $\mathbf{R}_\delta$ is determined by the position of the circular back iron. Thus, the influence of locally unconstant air gaps – e.g. while fine-positioning – can be analyzed. The nonlinear material permeability is approximated by a third-order polynomial and linked to the magnetic resistance $\mathbf{R_m}$ and $\mathbf{R_b}$ of the material.

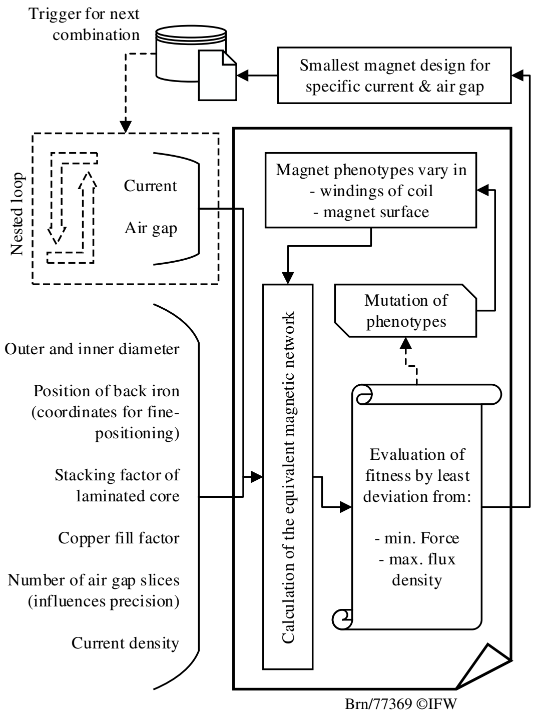

Fig. 8. Genetic algorithm for magnet optimization.

The genetic algorithm set-up is illustrated in Figure 8. Design possibilities were identified by running the GA within a nested loop to vary current and air gap. As a result an E-core was chosen for the radial magnets and two E-cores were chosen for each axial magnet to comply with the maximum height.

4.5. Validating and adjusting the magnet design

Finally, a validation and small adjustments have to be made to the magnet design. For this purpose a FEM analysis is performed. It is the aim to utilize all cross sections within the magnet core evenly. Areas with lower flux density (e.g. by flux leakage) are identified and the pole cross section is altered. These small changes do not require a rerun of the GA. Furthermore, areas with lower flux density are used to insert bores for assembly.

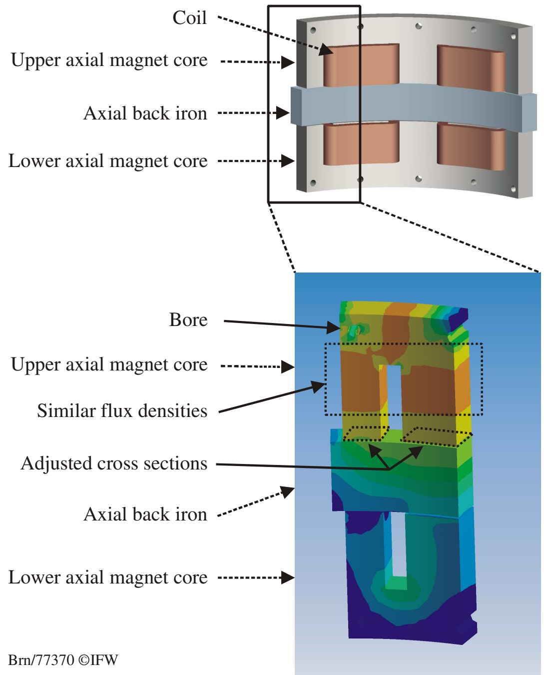

Fig. 9. Flux density in axial magnets at maximum force.

In Figure 9 a quarter of the axial double E-core is shown. The upper and the lower core as well as the circular back iron can be seen. The cross sections of the legs of the yoke differ slightly to achieve similar flux densities. As a result of the differential arrangement a minor current flows through the lower coil at maximum force in centered position. Neighboring magnets are separated from each other to further decouple the magnetic flux. A simulation confirms the benefit. Figure 10 and Figure 11 show the final axial and radial magnets.

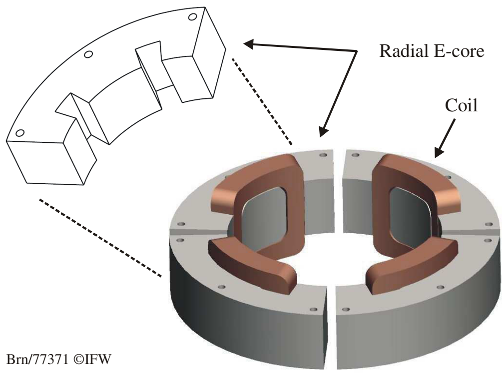

Fig. 10. Radial magnets.

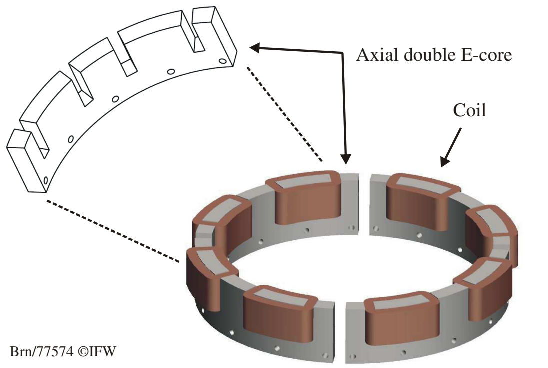

Fig. 11. Axial magnets.

A layered cut of the complete magnet arrangement can be seen in Figure 12. The lower axial magnets are positioned around the direct drive. Between the axial magnets the shared back iron is placed. In front of the radial magnets the radial back iron is positioned. In the center the space is reserved for the media transfer unit. Both back irons will be connected to the rotating shaft of the media transfer unit.

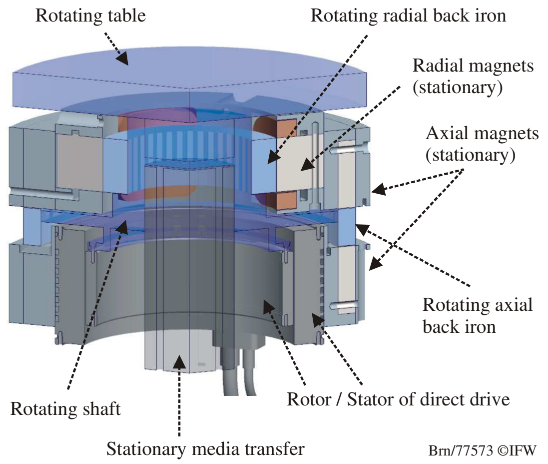

Fig. 12. Complete magnet arrangement.

5. Summary

Innovative machine tool components are demanded to solve challenges in manufacturing complex parts, e.g. aircraft engine components. Electromagnetic guides represent one suitable approach to enhance machine tool performance. The benefits of high damping, infinite static stiffness and sensory and actuator capabilities are outlined. The workpiece-sided application in rotary swivel tables enables further benefits.

Hence, a new design methodology for electromagnetically guided rotary tables for the use in swiveling axis is presented. It divides the complex design process into a step by step guideline. Each step is exemplified by a rotary table which is currently under design. The magnet design process is illustrated in detail by choosing the arrangement, geometry and shape. The usage of a genetic algorithm to find the best possible geometry is discussed. Finally the overall arrangement is shown.

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