Novel Linear Magnetic Bearings for Feed Axes with Direct Drives

A. Schmidt*, C. Brecher (2)*, F. Possel-Dölken*

*Laboratory of Machine Tools and Production Engineering, WZL, RWTH Aachen University, Aachen, Germany

Abstract

Contact- and frictionless magnetic bearings permit very high travel velocities and accelerations and provide excellent damping. Thus, they exceed the natural limitations of contact bearing systems. But they are also complex and voluminous and require an extensive electronic periphery. This paper introduces a novel linear bearing, which enables a complete suspension with a reduced number of magnets. The structure of these magnet modules and the ensuing feed axis is presented with special emphasis on their development, testing and characteristics. Furthermore, the paper details the achieved results regarding the stability of the bearing with different control structures and presents some planned control extensions.

Keywords:

Magnetic Bearing; Stiffness; State Control

1 INTRODUCTION

The technology of magnetic bearings is a constant topic of research and development in order to reduce their size, the number of electromagnets and the required electrical current. The continuing progress in computer technology and power electronics provides more use of its advantages than ever. The contactless and thus friction-free bearing permits very high speeds and accelerations with high damping and at the same time features no wear, no lubrication and a complete lack of abraded particles. This even allows its use in sensitive environments. And it also enables the possibility of influencing the bearing during operation, e.g. with position corrections in five degrees of freedom. On the other hand, it demands a highly dynamic, active control to achieve stable positioning and can only provide a limited dynamic stiffness.

Magnetic bearings are mostly used as rotating bearings for high speed shafts or as linear bearings in diverse transportation applications [1]. An application process for a machine tool which would profit from the very high feed speeds of a linear axis with magnetic bearings is pendular grinding. It is characterized by many repeated movements in one axis and exerts only moderate process forces on the moving slide.

The continuous advances in power electronics and data processing equipment as well as innovative core geometries promise a further improvement in the stiffness and the stability of magnetic bearings.

2 THE MAGNET MODULES

Newly designed magnet modules will reduce the required number of electromagnets for a novel linear magnetic bearing [2]. Instead of the 12 magnets, which are commonly used to control five degrees of freedom [3], only six modules are needed for a complete set of bearings. This reduction cuts the necessary number of inverters and current sensors in half and significantly lessens the wiring complexity of the system. In addition, the principle of the modules allows a favorable rearrangement of the needed space for the bearings.

The modules realize the permanent magnetic support of an electromagnet without creating the additional losses that are inherent to a classic hybrid magnet. I.e. they avoid the virtually enlarged air gap, which originates from the permeation of the permanent magnet material by the electromagnetic flux. Additionally a preload, which otherwise can only be created by two separate, facing electromagnets, is generated through the permanent magnetic force. These advantages allow the operation in a steeper section of the parabolic characteristic curve defining the relationship between the magnetic induction and the magnetic force without consuming additional electrical current. This increases the dynamics of the electromagnet and thus the dynamic stiffness of the complete bearing.

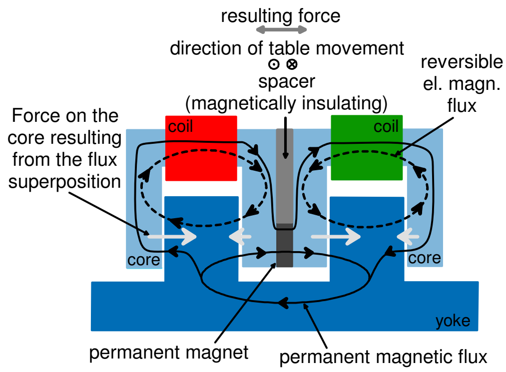

Figure 1: Functional principle of the magnet module.

The new magnet module consists of two U-shaped, laminated core halves with electric coils. Between these halves a layer of permanent magnets is embedded into the final core. The corresponding yoke has two teeth which fit into the openings of the U-shapes. Thus, the force generating pole areas are moved from the faces of the core arms to the inner side surfaces and the sides of the teeth, see Figure 1. The yoke and its teeth reach along the complete length of the track and demand a very high accuracy with regard to the straightness and the parallelism of the yoke. The air gaps between the core and the tooth sides are 0.5 mm wide in the nominal operating point.

The Neodymium-Iron-Boron (NdFeB) permanent magnets between the two halves of the core close their flux loops following two paths, which cross all four air gaps, also see Figure 1. As long as the core is in a central position above the yoke teeth, the created magnetic forces are equal in all four gaps and neutralize each other. The core rests in the position of an unstable equilibrium. As soon as the two coils are fed with an equal but differently signed amount of current, the superposition of the fluxes results in a usable force vector. If the position of the core above the yoke is measured and corrected with a sufficiently high frequency, a stable levitation state can be reached and controlled, including the compensation of additional disturbing forces.

In the first stage of the development, the geometry was analyzed and optimized with the help of FEM calculations to ascertain the strength of the magnetic flux in the core in relation to the generated force. Thus, the concept could be validated and the final dimensions of the magnet core were determined.

3 THE 1-DOF TEST BENCH

3.1 The set-up of the test bench

A prototype of the module and the control algorithms were tested on a single-degree-of-freedom (1-DOF) test bench, which fixates all degrees of freedom except the vertical movement. On this test bench the control and the stability of the levitation state can be optimized. In addition, it allows the measuring of the dynamic stiffness against disturbances and is also suitable for force measurements. The setting up operation of the single magnet module provided valuable experience for the construction of the feed axis and identified the potential difficulties.

In the test bench the module is clamped into an aluminum frame, which is connected to the structural elements by conventional roller bearings. This leaves only the degree of freedom which is orthogonal to the movement of the planned machine tool table and enables a vertical levitation but no rotations or feed movements. The control and supply of the module requires a number of peripheral components which are also tested on this test bench. The air gap of the magnet is measured with an inductive eddy current sensor, which uses the yoke surface as target. Separately, the coil current is measured with a contactless current transformer. The current is supplied from a Pulse-Width-Modulation (PWM) inverter which is controlled by the analog output voltage of the control loop. This inverter ascertains the maximum control frequency of 20 kHz. These components will also be used in the feed axis and hence are also tested in this preliminary set-up.

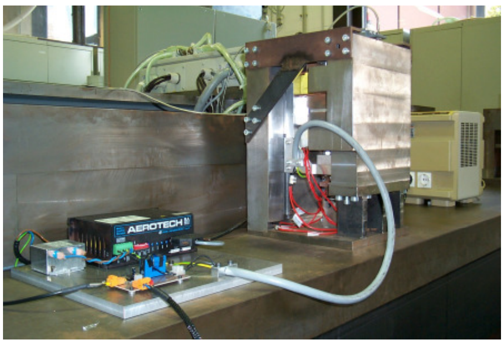

Figure 2: 1-DOF test bench.

3.2 Control characteristics and measurement results

The magnet module is controlled by a PI-state control algorithm [4], [5]. The closed feedback loop redirects the actual values of the air gap width, its differentiation and the current back to the control input as scaled state variables. In addition, the feed forward branch of the position error contains an integrator which nullifies static position offsets. This structure guarantees the fast compensation of disturbances and exact adherence to the target values.

Preliminary to the experimental validation of the module and control algorithm, its performance was tested in Matlab/Simulink simulations. These were used to model the control circuit as well as the characteristics of the magnet module and peripheral components and played a decisive role in the determination of the control parameters. The final dynamic stiffness of the bearing relies mainly on the optimal setting of these parameters.

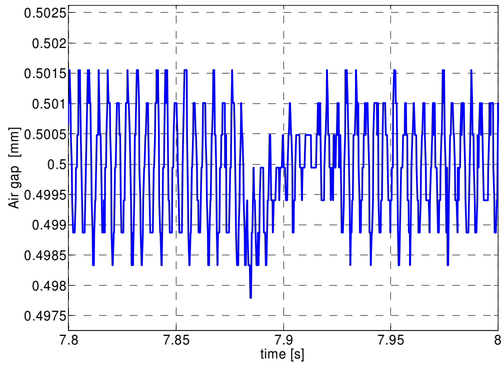

Figure 3: Air gap during a cut off experiment on the 1-DOF test bench.

For the operation of the 1-DOF test bench the control algorithms have been compiled into a digital signal processor, which receives the sensor signals, calculates control output and supplies it to the inverter. The control parameters remain accessible during operation and can be used to optimize the performance. Figure 3 displays an exemplary measurement result. Due to practical reasons the disturbance was limited to a 5 kg weight which was pulling the magnet module upwards using a pulley system and which was then cut off to create a repeatable force impulse. The slight noise disturbance of the air gap signal and an additional mechanical jitter are due to the tight parameter settings to achieve maximum stiffness.

The resulting disturbance can be seen clearly in the figure. The evaluation of several test series of cut-off experiments with varying control parameters proved a maximum stiffness of the single bearing of 23 N/µm. In the feed axis four vertical magnet modules will superpose their carrying power and thus their added stiffnesses will provide the slide's stability.

During steady state levitation in the 1-DOF test bench the module consumes about 0.6 A of current to carry its own weight and displays a jump of 0.15 A to compensate for the disturbance. The output voltage of the control, which could use a range of ±10 V, stays below 0.05 V to compensate for the force impulse.

Especially the parameter which scales the influence of the derived air gap width, was found to be very sensitive. The signal derivation strongly amplifies the remaining signal noise and degrades the quality of this state variable. Thus, there are ongoing tests to enhance the signal quality by using an additional acceleration sensor and integrating its signal. Preliminary results yielded an improved signal quality but not yet a utilizable increase in bearing stiffness. This is due to a significant phase lag in the signal, which originates from the necessary filtering. A promising approach seems to be the superposition of the derived position signal and the integrated acceleration signal in different frequency ranges. The limited frequency ranges would decrease the need for filtering, if they are chosen carefully.

4 THE FEED AXIS

The aim of the accompanying research project is the development of a prototype of a machine tool feed axis with magnetic bearings which consist of the described magnet modules. The axis is to reach a dynamical stiffness of at least 100 N/µm in the vertical direction, which would have to counter the majority of all process force related disturbances. With a projected feed speed of more than 3 m/s in the central segment of the track, the axis is supposed to sustain a highly dynamic pendular movement, thus providing a stable platform for e.g. a grinding application. In addition, the magnetic bearings can be influenced in various ways to offer supplementary possibilities, see chapter 4.2.

4.1 The structure of the feed axis

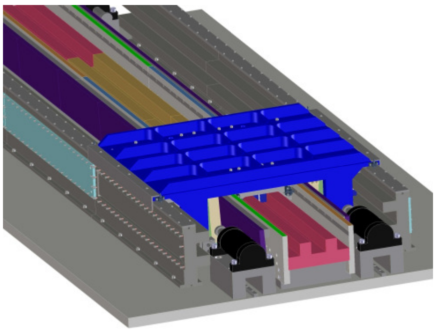

Figure 4: Construction model of the feed axis.

The feed axis features four vertical levitation magnets on the corners of a rectangular slide and one horizontally guiding module in the center of each face side. The structure of the slide was designed for maximum mechanical stiffness to ensure its stability against disturbing forces. Only thus is it able to guarantee the exact positioning of the magnet modules on their yokes. The levitation magnets provide the main carrying force and the rotatory stability against pitch and roll movements. And the remaining two modules control the horizontal alignment along the track and the yaw tendency of the table. They are designed equal to the vertical modules. Even though they do not carry any of the weight of the slide, they still have to deal with the normal forces of the feed drives.

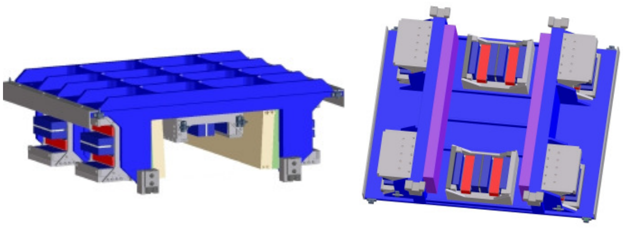

Figure 5: Details of the feed axis slide.

The feed drives are two linear motors, which are positioned to the left and the right of the table's long axis in parallel to the horizontal guiding modules. In these positions the combination of the motors forms a double-comb configuration, which balances the effect of the enormous attractive normal forces between the primary and secondary parts. Otherwise, the normal forces have to be absorbed by the bearings. The motors are slightly inclined to angle the force vector of the normal forces up and thus using it for the partial compensation of the slide's static weight. This eases the load of the bearings.

The slide is running in a 3 m track, that mainly consists of three yokes, which complete the magnetic circuits, and the secondary parts of the motors. Two yokes are set up vertically and each interacts with one pair of levitation magnets. The third, horizontally oriented yoke is integrated into a massive central beam and serves both guiding magnets. In addition, the secondary parts are mounted to the sides of this central beam.

Figure 6: The feed axis prototype.

4.2 Control principles and auxiliary control functions

The feed axis control principle is based on the same PI-state control algorithm as the 1-DOF test bench, only this time there are five degrees of freedom to monitor. The remaining sixth degree of freedom will be controlled by the linear motor through a separate control unit.

In this case all DOF will be controlled directly instead of controlling the single magnet modules. This requires an additional coordinate transformation, which transfers the actual movement at the position sensors and the air gaps of the individual magnet modules into the motion of the two translatory and three rotatory degrees of freedom. These transformed movements along the axes of the coordinate grid are processed through the state control loops and the outputs are transformed back into control signals for the six magnet modules and superposed, thus preventing them from working against each other.

It is a characteristic performance limitation of single magnet control principles, that two or more modules are bending the table structure while trying to adhere to their target values without regard to the mechanical coupling between them, which is due to their fixed position on the slide structure. The mechanic tolerances in the assembly of the slide and track prevent an ideal positioning. Thus, the four levitation magnets, which constitute an overdetermined system, never span one common, fully horizontal plane, as they theoretically should. The extent of the difference in performance of the two control approaches is a topic of the research project.

In addition to the DOF control the contactless bearing with its controllable air gaps and active control circuit offers several possibilities for supplementary control measures.

An auxiliary feed forward control for the compensation of the process forces is planned to increase the dynamic stiffness of the active bearing. The small reaction time to a disturbance normally is an inherent characteristic of every reactive, feedback control loop with unpredictable disturbances. It generally requires a deviation as control input before it can start to generate a compensation force. In a regular and repetitive process like pendular grinding, the expected and known process forces can be compensated very accurately. In every stroke the same force is projected at the same time as soon as the grinding wheel cuts into the material. The additional controller will adapt current and force in such a way that the complete compensation force is available at the right time. Thus the deviation of the vertical position of the table can presumably be avoided almost completely. At the beginning a teach-in of several strokes has to be observed, in which data about the timing and the amplitude of the disturbing force are collected. This will be averaged and transformed into the necessary compensation force. Besides, the algorithm has to calculate the timing when to start generating the force. The data collection will be continued after the activation of the controller to allow a continuous optimization of the compensation.

Furthermore, the accessibility of the air gaps opens the possibility to position the slide up to the accuracy of the air gap width sensors in several degrees of freedom. This possibility would extend to an adjustment of up to about ± 100 µm and could enhance the positioning accuracy of the slide greatly. However, the displacement would have to consider the effect on the bearing's stiffness since it would change the point of operation of the magnet module. Therefore the actual effectiveness of this function remains to be examined.

These auxiliary functions and additional tests with acceleration sensors as supplemental control input will be implemented in the course of 2007.

4.3 Current measurement results

In the current stage of the development the feed axis is set up completely with the exception of the linear drives. Thus, the current tests and optimizations are limited to stationary levitation and manual movement along the track.

The comparison of measurement results with a single magnet control and the first versions of the direct DOF control already show a definite enhancement of the control quality. The deviation and oscillation after a manual, vertical force impulse disturbance decrease notably, see Figure 7 and Figure 8. The figures can be considered exemplary for all modules. A further improvement of the levitation quality is to be expected with further optimization of the mechanical set-up and alignment on the one hand and the control parameters on the other hand.

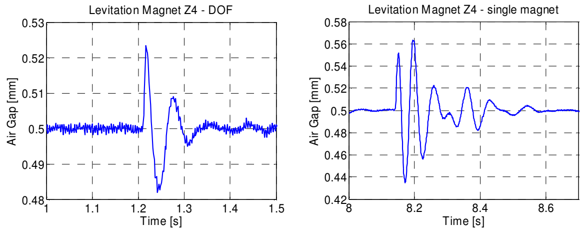

Figure 7: Air gaps of a vertical levitation magnet with DOF control (left) and single magnet control (right).

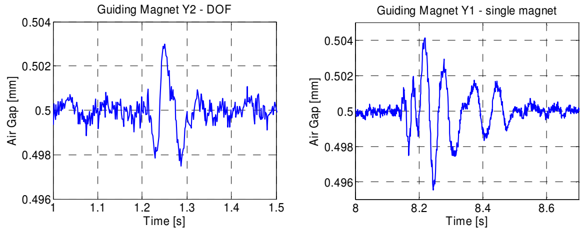

Figure 8: Air gaps of a horizontal guiding magnet with DOF control (left) and single magnet control (right).

To achieve the shown stable levitation state, each magnet module consumes about 3.5 A of current. Since the linear motors are not yet installed, they do not provide their weight compensation for the slide yet. The guiding magnets need almost no permanent current, since they are only stabilizing the table but do not carry any weight.

In the next step the stiffness of the bearing will have to be evaluated with measured, repeatable force impulses. The displayed preliminary experiments cannot be used for this, since neither the amplitude of the manually created disturbances is not yet reliably repeatable.

Special attention has to be given to the horizontally stabilizing modules. Since gravity does not exert a dampening influence on the operation of these modules, they are way more sensitive to disturbances. In addition, there are only two of them, in comparison to the four levitating modules, thus limiting the horizontal stability even further.

5 SUMMARY

This paper presents the development of a novel magnetic bearing for a feed axis with direct drives. The bearing mainly consists of magnet modules, which combine electro- and permanentmagnetic forces and can project a usable force in two directions along one axis, instead of one direction only. Thus the complete bearing uses considerably less actuators than comparable electromagnetic bearings. However, the innovative core geometry in combination with an optimized state control and several auxiliary control functions will result in a very stiff bearing, which can sustain very dynamic and stable movements along the track.

During the development the magnet module and its control underwent testing in simulations and a preliminary 1-DOF test bench for a single prototype without feed movement. Subsequently, the feed axis itself was constructed and is used to optimize all components of the bearing system. The final aim for the performance of the bearing is a pendular movement with a top speed of more than 3 m/s in the process area and vertical stiffness of at least 100 N/µm.

At the present stage of the development the feed axis can sustain a stationary levitation without feed. The ongoing measurements have so far yielded a significant difference between a single magnet control and direct control of the table's degrees of freedom. The DOF control enhances the quality of the levitation and adds stability.

6 ACKNOWLEDGMENTS

The research project, during which the presented results were achieved, is funded by the German Research Foundation (DFG).

7 REFERENCES

[1] Van Goethem, J., 2004, Verlustarme magnetische Lagerung für ein Förderfahrzeug mit normalkraftbehaftetem Linearantrieb, PhD Thesis, Aachen University

[2] Schmidt, A., Brecher, C., Weck, M., 2004, Schnell, dynamisch und trotzdem steif - Magnetlagerung für einen Werkzeugmaschinentisch, antriebstechnik 12, 56-59

[3] Wahner, U., 2002, Lineare Magnetführung für direktangetriebene Vorschubachsen, PhD Thesis, RWTH Aachen University

[4] Föllinger, O., 1994, Regelungstechnik - Einführung in die Methoden und ihre Anwendung, 8th revised edition, Heidelberg, Hüthig Buch Verlag

[5] Meyr, H., 1998, Regelungstechnik und Systemtheorie, Lecture notes, Institute for Integrated Signal Processing Systems, RWTH Aachen University, Wissenschaftsverlag Mainz