DEVELOPMENT OF A LOW COST PERMANENT MAGNET BIASED BEARING

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ABSTRACT

The design of an active magnetic bearing (AMB) for industrial applications requires in addition to the technical characteristics the consideration of attributes like complexity, reliability, acquisition and running costs. Besides the AMB itself, the electronics, especially the power amplifiers have to be regarded.

In this paper a novel design of an AMB with low power consumption combined with an uncomplex mechanical construction is introduced. Rare earth permanent magnets are implemented to impress a constant bias flux whereas coils generate the control flux to stabilise the bearing. The flux of the permanent magnets and the flux of the coils lie in the same plane that is to say the introduced magnetic bearing is a heteropolar type.

Besides the mechanical construction and the functionality, the characteristic curves of the AMB determined by simulation and by measurements on a prototype, are presented.

INTRODUCTION

The economic efficiency of an AMB mainly depends on the manufacturing costs of the mechanical parts and the electronics as well as on the operating costs. The last two items are directly associated with the power consumption of the bearing. A high power consumption requires large power amplifiers with appropriate facilities to dissipate the heat produced in the power semiconductors. In applications with restrictions to the available space it is decisive to create a compact design of the system. This makes it difficult to integrate the power amplifiers in a convenient way.

On the basis of these facts one significant aspect for an efficient design of active magnetic bearings is to keep down the power consumption. An important contribution to achieve this aim is to establish the bias flux, which is impressed to provide the magnetic field for levitation and to linearise the control law, by the implementation of permanent magnets and not by means of a bias current. In such a configuration the coils only have to provide the control currents to stabilise the bearing. This results in smaller electromagnetic coils and in a reduced winding space. Therefor the load capacity of the AMB increases.

This is particularly advantageous in relation to AMBs with large air gaps where high currents would be necessary for premagnetisation.

In applications that allow to operate the rotor outside the centre position, active magnetic bearings biased with permanent magnets provide the opportunity to support static loads without the necessity of a direct current in the coils [1]. Because of the negative stiffness of the bearing, a rotor position of force-equilibrium can be found to support gravitational forces and static process forces to a certain extent. In this case currents, mostly with a low duty factor, are only required to stabilise the rotor and to support transient loads.

A very low current consumption of an active magnetic bearing biased with permanent magnets is possible, if the control flux produced by the coil-currents has not to be driven through the rare earth magnets with their very small relative permeability. In addition to the reduced requirements to the number of ampere turns, this configuration protects the permanent magnets against unintentional demagnetisation due to excessive control flux contrary to the direction of magnetisation. Different configurations and applications of AMBs showing this characteristics have been published [2], [3], [4]. These AMBs have in common that the bias flux and the control flux lie in different planes. They are referred to as homopolar types.

A not negligible disadvantage of magnetic bearings biased with permanent magnets compared to types with bias currents is the more complicated mechanical structure because the permanent magnets have to be inserted into the magnetic circuit. This results in divided stator respectively rotor configurations that have to be fitted together with the permanent magnets, which are relatively difficult to handle.

The AMB introduced in this paper attempts to combine the low power consumption of a homopolar bearing with the uncomplex mechanical design of a magnetic bearing biased with direct currents. Particular attention has been given to make a straightforward insertion of the permanent magnets possible. The shown AMB allows to insert the magnets at the end of the assembly process. The possibility to include the rotor before the insertion of the permanent magnets simplifies the mounting of the rotor.

CONFIGURATION

Figure 1 shows a drawing of the cross section of the proposed magnetic bearing with the principle arrangement of rotor, stator, coils and permanent magnets. A practical design can be seen in Figure 2. Figure 10 and Figure 11 illustrate realised fully operative prototypes of the bearing.

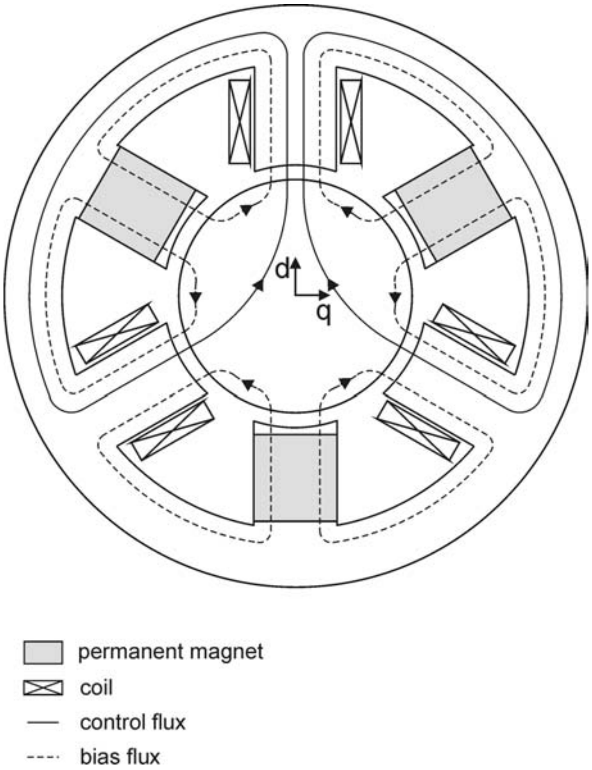

Figure 1: Principle arrangement of AMB with three concentrated coils

The laminated rotor core has a simple cylindrical shape. The stator has six salient poles, three permanent magnet poles and three iron poles. The three diametrical magnetised rare earth permanent magnets generate the pre- magnetisation of the magnetic bearing. The dashed lines in figure 1 indicate the bias flux impressed by each of the permanent magnets. The bias flux of one magnet divides in the rotor and flows across the air gaps, the iron poles and the stator yokes. Each of the three iron poles carries a concentrated coil to generate the control flux. By this means the flux density in the air gaps below the iron poles and thus the force to the rotor can be controlled. The control flux indicated by the solid lines in figure 1 characterises the situation where a force in the positive d-direction is generated. The magnetic flux produced by the upper coil increases the flux density in the air gap between the upper iron pole and the rotor whereas the magnetic flux density in the air gaps of the lower two iron poles is accordingly decreased. The magnetic fluxes generated by the lower two coils are directed to intensify this effect.

Three coils are sufficient to actively stabilise two degrees of freedom of the rotor [5]. The use of not more than three coils benefits from the possibility to utilise a conventional three phase amplifier.

Bias flux as well as control flux are split in the rotor and the stator yoke. For this reason the radial dimensions of the rotor and the stator yoke only need to be the half of the iron pole width as shown in figure 2. The control flux of the proposed magnetic bearing is restricted to the iron poles as indicated in figure 1. This

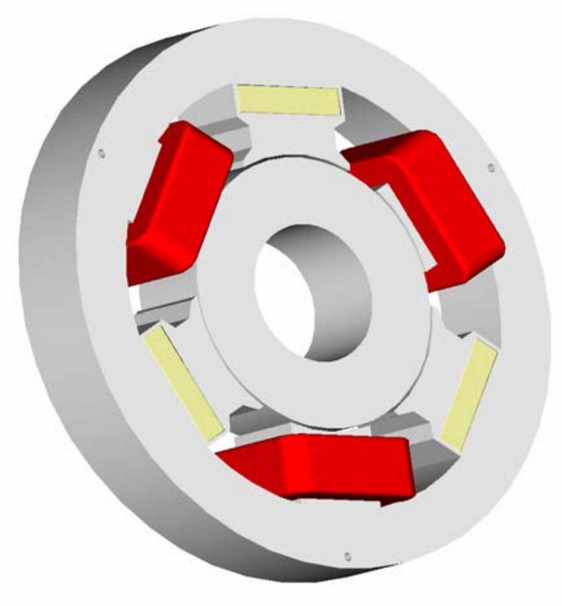

Figure 2: AMB with three permanent magnets and three concentrated coils

is due to the fact that the rare earth permanent magnets represent a high magnetic resistance compared to the iron poles because of the very small relative permeability of the permanent magnets. The magnetic resistance of the control circuits is mainly dependant on the air gap between the stator and the rotor. The characteristic that the control flux has not to be driven through the permanent magnets has, as earlier mentioned, the advantage of a reduction in the ampere turns requirement. The permanent magnets are protected against unintentional demagnetisation due to excessive control flux especially at elevated temperatures.

The constant bias flux and the control flux generated by the coils flow in the same plane. Together with the alternating polarity of the magnetic poles, forming a so called NSNSNS configuration, the introduced bearing can be classified as a heteropolar active magnetic bearing. Due to the fact that the control flux is not flowing through the permanent magnets, the flux density under these poles is uncontrolled. These poles do not actively contribute to the dynamic load capacity of the bearing. The permanent magnet poles only have an indirect influence on the dynamic behaviour because the gain of the iron poles is proportional to the generated bias flux. The lost dynamic load capacity can partly be compensated by expanded pole faces.

The absence of coils placed on the three permanent magnet poles provide the opportunity to design a bearing with very compact axial dimensions. The space in front of these poles which is, contrary to the iron poles, not filled with the winding overhang of coils, can be used to integrate the rotor position sensors. In this configuration the position sensors have only a small influence on the axial dimension of the bearing. A further advantage of this arrangement is the small distance between the location for measuring the rotor position and the point of application of force. The placement of the position sensors at the specified places also benefit from the characteristics of the magnetic field in these regions. Because of the distance to the coils and the distribution of the control flux, which is not flowing through the permanent magnet poles, the magnetic field in the regions of the sensors can be considered approximately constant. This can be recognised by the simulation result shown in Figure 3, where the flux density in the region of the permanent magnets is almost independent of the control flux impressed to generate a force in negative d-direction. The simulation result in figure 3 corresponds to the realised prototype shown in figure 10. Thus the influence of the time-variant control flux generated by the coils is low.

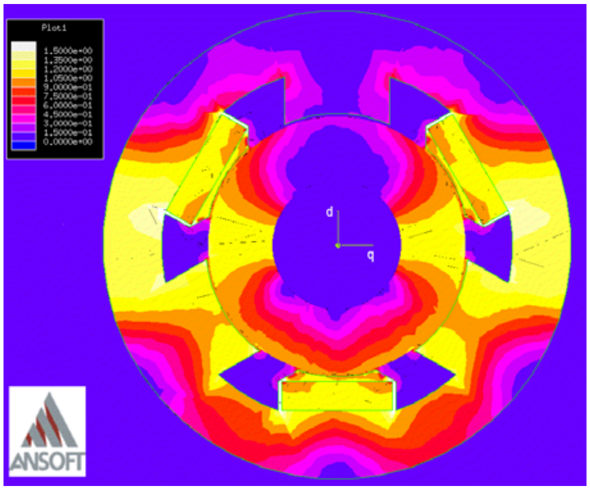

Figure 3: Distribution of the magnetic flux density

ARRANGEMENT OF THE PERMANENT MAGNETS

During the design process of the magnetic bearing great importance has been attached to the placement of the permanent magnets. The main objective is to form the seat of the permanent magnets in the laminated stator core in such a manner that a reliable linkage to the stator can be assured and the magnets can be

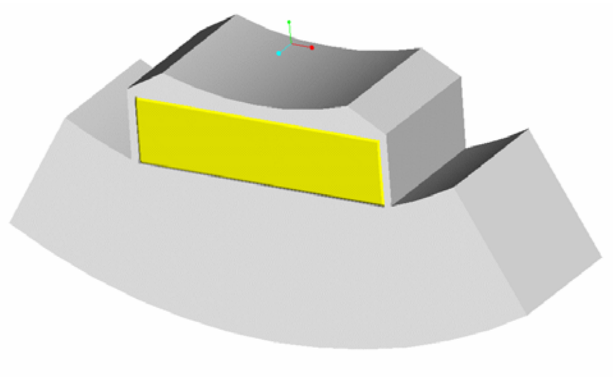

Figure 4: Permanent magnet pole with proposed pocket in stator core

mounted without difficulties. To meet these requirements, the proposed AMB has three pockets in the stator core, which accommodate the permanent magnets. Figures 4, 10 and 11 indicate this configuration. The pockets simplify the mounting of the magnets considerably. As a result of the magnetic forces the permanent magnets slide self-acting into the pockets. After insertion the magnets are reliably protected against mechanical damages and against unintentional separation from the stator core.

Besides the simplified assembly of the magnets, the presented configuration has the advantage of an undivided stator core. The pole shoes of the permanent magnet poles are an integral part of the stator. An adjustment and a mounting of the pole shoes on top of the permanent magnets is not necessary.

The wall thickness of the pockets is small in order to minimise the magnetic leakage flux through the iron webs parallel to the magnetisation direction of the permanent magnets that do not contribute to the premagnetisation of the bearing. The minimum thickness of the walls is determined such that a sufficient mechanical stability of the pockets is achieved. In addition the requirements for the punching process of the stator plates have to be considered.

Due to the small cross-sectional area of the iron webs the iron in this regions is saturated. The reduced magnetic relative permeability due to saturation together with the small cross sectional area results in a high magnetic resistance of the iron webs and therefore in a low leakage flux.

Figure 5 shows the distribution of the magnetic flux density of one permanent magnet pole. The result of this simulation points out the saturation level of the iron webs on either side of the permanent magnet. The loss in the load capacity due to the leakage flux through the iron webs is in the range of a few percent in comparison to a design without the introduced pockets in the stator core. Compared to the stated advantages this loss in load capacity is acceptable.

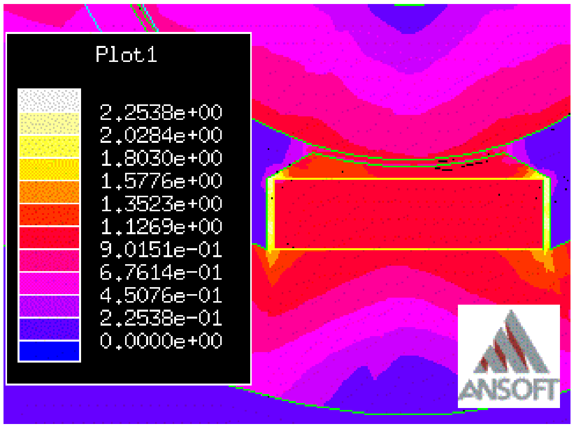

Figure 5: Distribution of the magnetic flux density of a permanent magnet pole

The pockets in the stator core allow the insertion of the permanent magnets after the mounting of the rotor. Thereby the mounting of the rotor can be performed without large expenditure of force. The same principle can be performed analogous for the removal of the rotor

EXPERIMENTAL RESULTS IN COMPARISON TO RESULTS FROM FINITE ELEMENT CALCULATION

Although the control flux generated by the coils and the bias flux of the permanent magnets lie in the same plane, i.e. they form a two dimensional problem, the simulations were carried out with a 3D finite element program. Thereby the end leakage is taken into consideration, which cannot be neglected because of the small axial dimension compared to the diameter of the bearing.

To confirm the results obtained by simulation, measurements have been carried out. For this purpose the prototype shown in figure 10 was mounted on a test bed equipped with a load cell and a cross table to allow measurements as a function of the rotor displacement from the centre of the bearing.

Figures 6 - 9 present the characteristic curves associated to this prototype. The load capacity as a function of current with the rotor in the centre of the bearing is shown in figures 6 and 7. Figures 8 and 9 indicate the force acting on the rotor as a function of the rotor displacement in relation to the centre. Figures 6 - 9 show the results determined by simulation and by

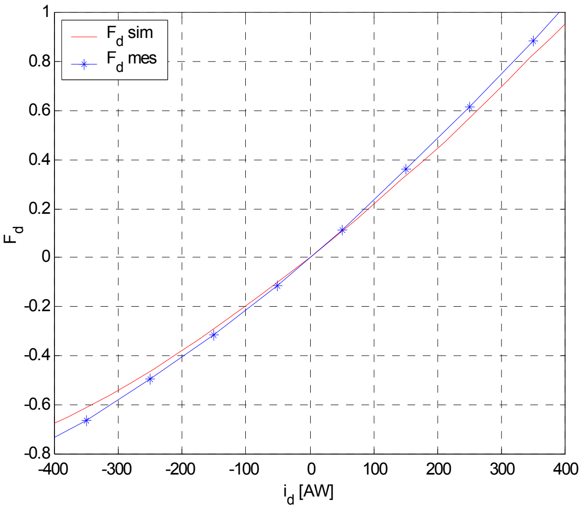

Figure 6: Radial load capacity as a function of i_d rotor centred

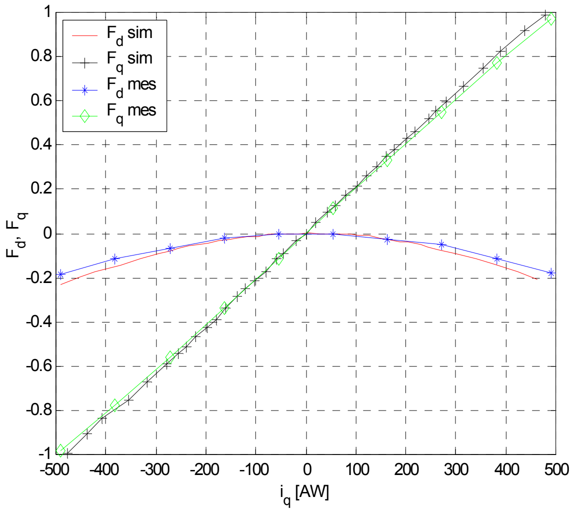

Figure 7: Radial load capacity as a function of i_q rotor centred

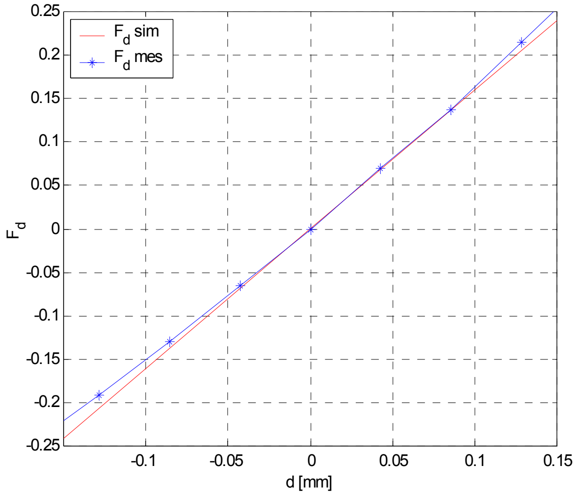

Figure 8: Radial force as a function of rotor displacement in d-direction; i_d=i_q=0

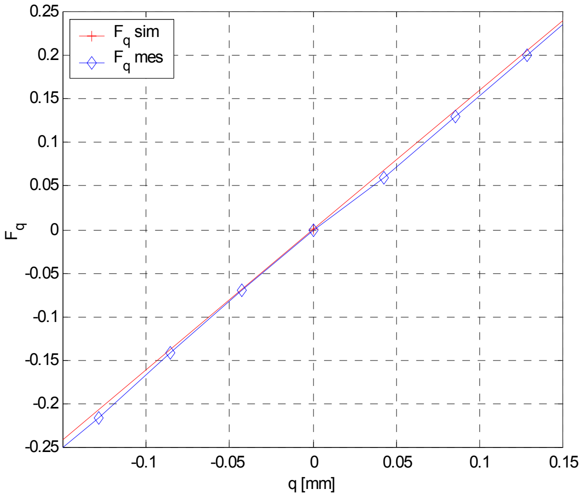

Figure 9: Radial force as a function of rotor displacement in q-direction, i_d=i_q=0

measurements. The difference between the measured and the simulated results is within 10 %.

The relationship between i_d and i_q shown in the diagrams and the three physical coil currents is given by transformation (1).

Figures 6 and 7 show a satisfying linearity of the characteristic curves at the operating point due to the premagnetisation of the bearing. Figure 7 also indicates the coupling between the d- and q directions which is characteristic of a configuration with three active poles. As expected figures 8 and 9 are almost coincident because of the geometry of the bearing.

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (1)$$

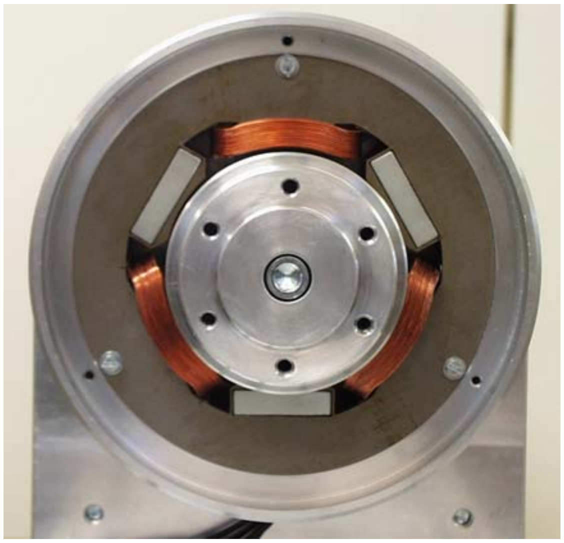

Figure 10: Prototype of three-phase radial magnetic bearing on a test bed

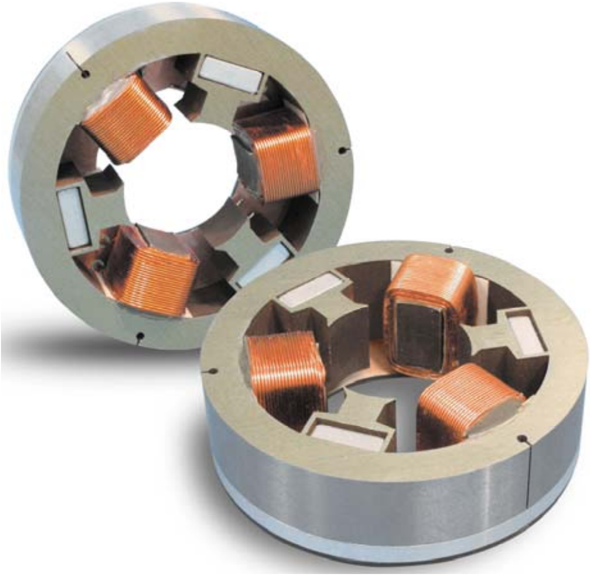

Figure 11: Functional prototypes of proposed magnetic bearing

CONCLUSION

This paper introduces a novel design of a magnetic bearing biased with permanent magnets. In addition to the description of the functionality some options are pointed out, concerning the insertion of the permanent magnets and the placement of the position sensors, that arise from the special construction of the bearing. In a final step the characteristic curves of a realised prototype, shown in figure 10, are presented.

ACKNOWLEDGEMENTS

The development of magnetic bearings is a project of the 'Linz Center of Competence in Mechatronics' as a part of the Kplus-program of the Austrian government. The project is kindly supported by Levitec GmbH, Lahnau, the Austrian and Upper Austrian government and the Johannes Kepler University of Linz. The authors thank all involved partners for their support.

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