A Novel Design of a Five Axes Active Magnetic Bearing System

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Abstract: In prospective applications for active magnetic bearings, apart from performance and reliability, system costs are a major concern. The design of the proposed five axes active magnetic bearing system allows low manufacturing and assembly costs. Based on a simple modification, a radial bearing of heteropolar or homopolar type can produce radial as well as axial forces. Radial and axial forces are generated by the same set of permanent magnets and coils. This simplifies power electronics design considerably. Simulation and experimental results demonstrate the characteristics of the proposed design.

Keywords: Active Magnetic Bearing, Permanent Magnet Biased Bearing, Heteropolar Bearing, Homopolar Bearing, Multi-axis Magnetic Bearing

Introduction

During the last two decades, lots of research work has been done to improve properties like power consumption, dynamic behaviour and reliability of active magnetic bearings (AMBs). However, the relatively high system costs limit the introduction to high volume products and cost sensitive markets so far. For this reason, [1] introduced a low cost radial magnetic bearing, combining the low power consumption of a permanent magnet biased bearing with the basic mechanical structure of a DC-current biased bearing. Three phases permit the use of standard motor control electronic components in the power converter. Magnetically levitated systems normally require a minimum of two radial AMBs with the associated three phase converters. An additional thrust bearing is necessary if the magnetic reluctance forces are not sufficient to stabilize the axial position. A significant increase in system complexity and costs is inevitable. In a first step this paper presents a simple modification of the heteropolar radial AMB introduced in [1] creating a combined radial and thrust bearing. Two of the proposed bearings can actively stabilise all five degrees of freedom [2]. In a second step, modifications of a radial homopolar magnetic bearing as proposed in [3], [4] and [5] are presented to allow the additional generation of axial forces. This configuration benefits from lower coupling and lower losses at higher rotational speeds.

Five axes active magnetic bearing system based on a heteropolar radial bearing

The basic configuration is shown in Fig. 1. The radial bearing consists of the stator- and rotor iron, three coils and three permanent magnets. Both, control flux introduced by the coils in order to regulate the radial position and bias flux due to the magnets are coplanar. If this configuration is extended by a back iron on one side, the permanent magnet bias flux will not only be established in radial direction through the rotor but also via the axial air gap and the attached back iron as shown in Fig. 2. This creates a force on the rotor in axial direction. The axial force can be modulated by in-phase coil currents i_{az} with equal amplitudes, superimposed on the coil currents for radial force generation. The flux generated by these currents flows three-dimensionally via the axial air gap and the back iron. The radial bearing and the thrust bearing are biased by the same set of permanent magnets and controlled via the same set of coils. Two of the proposed bearings when inversely mounted onto the rotor shaft allow the active stabilisation of five degrees of freedom. With reference to Fig. 3 and Fig. 4, the relationship between the currents for force generation in x, y and z direction and the three physical coil currents are given by the transformation

$$\begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 1 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} & 1 \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & 1 \end{bmatrix} \begin{bmatrix} i_{rx} \\ i_{ry} \\ i_{az} \end{bmatrix}. \qquad (1)$$

In-phase thrust bearing currents can be easily provided by independently controlled coils. A star connection of the coils is preferable in order to benefit from the good availability and cost advantages of three-phase motor control converters. This option is only available if both bearings are star connected and star points are interconnected as shown in Fig. 4. In this way, thrust bearing currents with the same amplitude but opposite signs in both of the three phase systems can be generated. The bias flux will be amplified on one side and attenuated at the other side which results in an axial force.

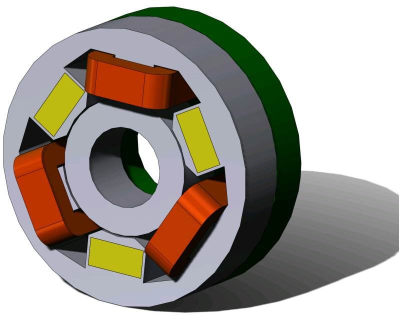

Fig. 1 Basic arrangement

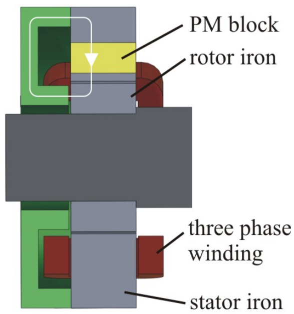

Fig. 2 Permanent magnet bias flux

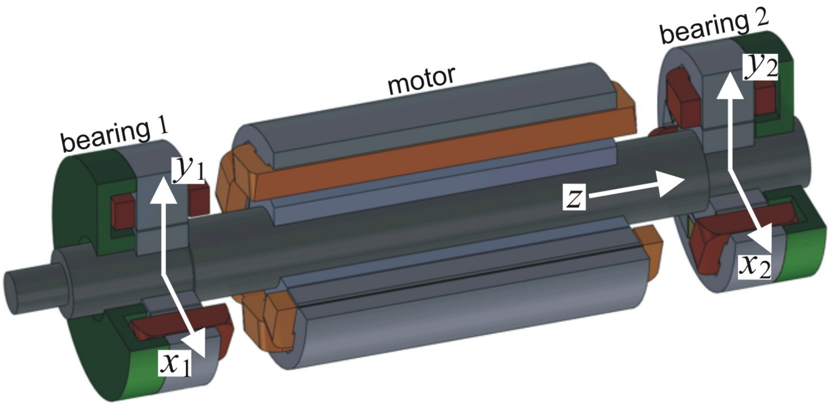

Fig. 3 Arrangement with two bearings for stabilisation of five DOF

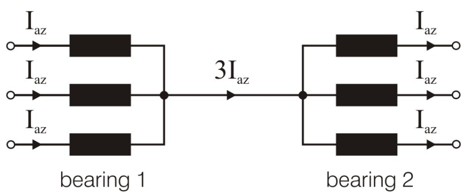

Fig. 4 Star connected bearings with common star point

Fig. 5 – 8 show the normalised characteristic curves of the arrangement given in Fig. 3. The results were obtained by simulation. The nominal axial to radial load capacity ratio of the designed system is 2:1. Axial force generation due to the coil current component i_{az} is shown in Fig. 5. The bias and control flux of the thrust bearing also cross the air gap of the radial bearing section. Therefore, there is a coupling between axial and radial forces. The degree of coupling depends on the axial to radial load capacity ratio. The operating point and negative stiffness of the radial bearing is dependent on the actual load of the thrust bearing because the magnetic flux created by the current i_{az} alters the pre-magnetisation of the radial bearing. Fig. 6 and 7 indicate the correspondent variations of the characteristic curves. In addition, there is an influence on the radial bearing dependent on the axial position of the rotor. This relation is shown in Fig. 8. Decreasing the axial air gap results in lower pre-magnetisation of the radial bearing and higher pre-magnetisation of the thrust bearing and vice versa.

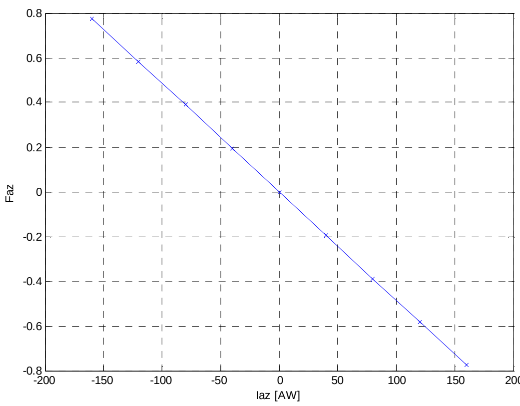

Fig. 5 Total axial force, rotor centred

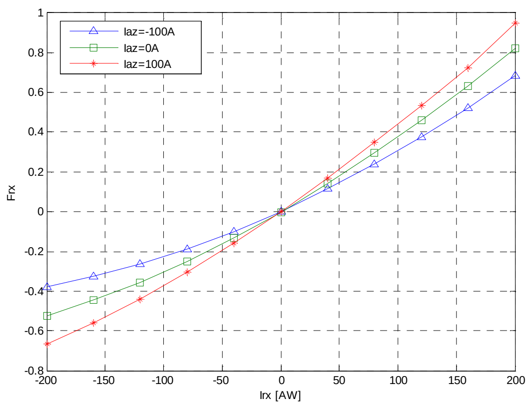

Fig. 6 Radial force – current relationship at different axial load currents

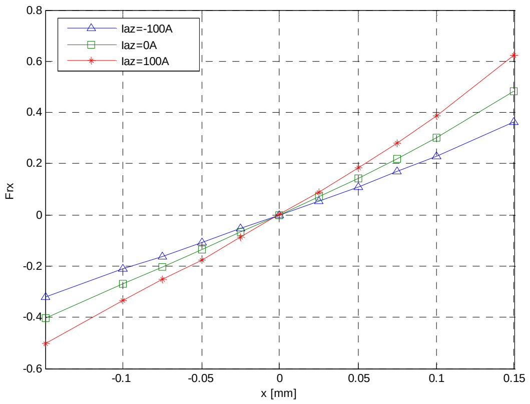

Fig. 7 Radial force – radial displacement relationship at different axial load currents

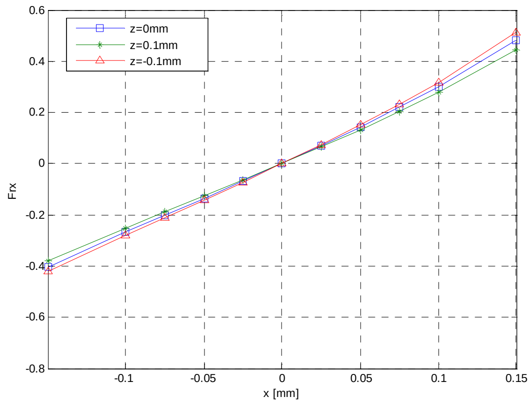

Fig. 8 Radial force – radial displacement relationship at different axial positions

Iron losses of a radial heteropolar bearing configuration at elevated rotational speeds are high because of the alternating polarity of the flux. The proposed configuration will intensify these losses due to the additional flux required by the thrust bearing which adds to the amplitude of the alternating flux in the air gap of the radial bearing. The contribution to the losses of the thrust bearing itself is small due to the uniform flux distribution in the axial air gap. The main fields of application for this type of bearing are therefore systems with high radial and low axial loads, operating at low rotational speeds. In applications with high demands for axial loads or high rotational speeds, a bearing system based on a homopolar radial bearing is favourable.

Five axes active magnetic bearing system based on a homopolar radial bearing

The basic configuration of the proposed combined radial / thrust bearing is shown in Fig. 9 and Fig. 10. As previously discussed, the thrust bearing is formed only by an additional back iron segment and is controlled by the three phases of the radial homopolar bearing. Each of the three phases shown in Fig. 9 consists of two adjacent, series connected coils to allow for a simple winding technique. The basic arrangement and the interconnection of the phases indicated in Fig. 3 and Fig. 4 are applicable for the homopolar bearing as well. Pre-magnetization of the radial and the axial air gap is achieved by a single radially magnetised permanent magnet ring (Fig. 10). In contrast to the configuration shown in Fig. 1 and Fig. 2,

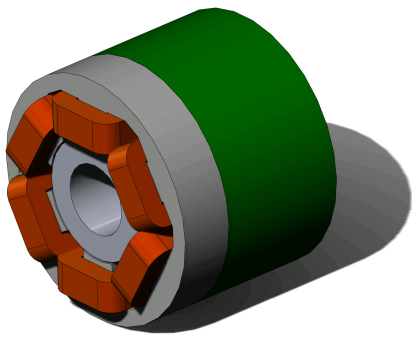

Fig. 9 Basic arrangement

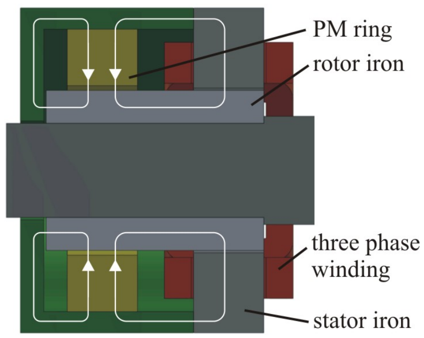

Fig. 10 Permanent magnet bias flux

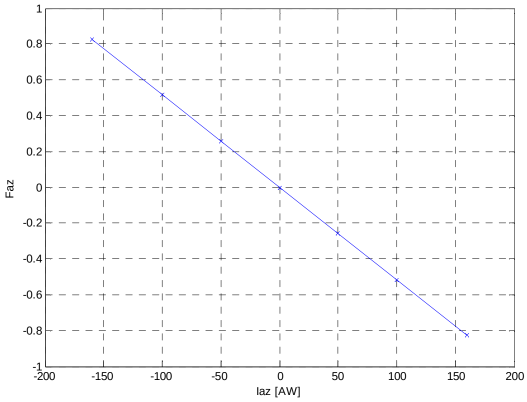

Fig. 11 Total axial force, rotor centred

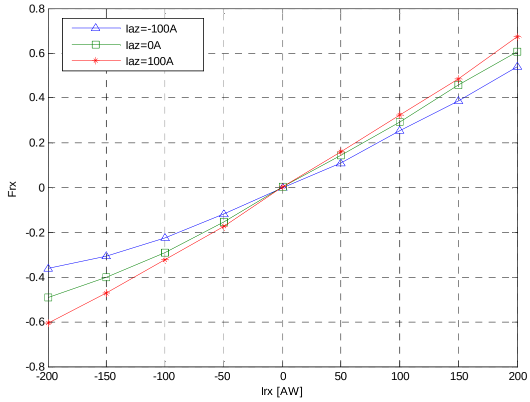

Fig. 12 Radial force – current relationship at different axial load currents

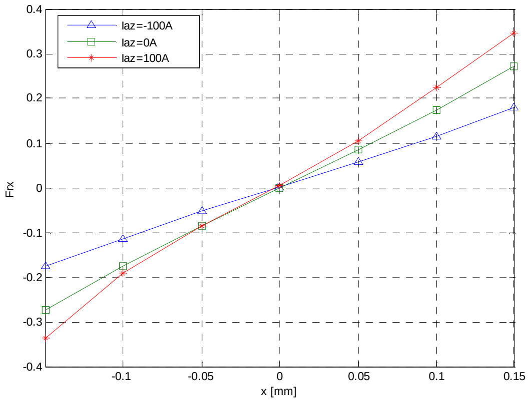

Fig. 13 Radial force – radial displacement relationship at different axial load currents

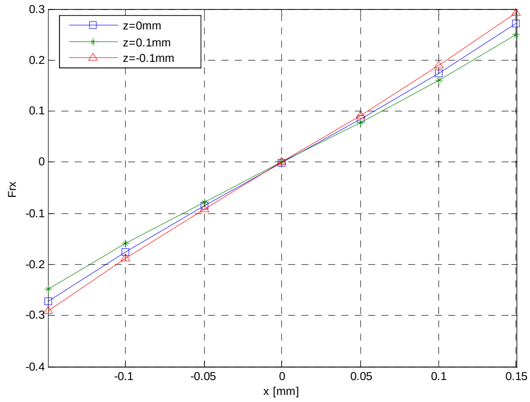

Fig. 14 Radial force – radial displacement relationship at different axial positions

the permanent magnet bias flux of the thrust bearing does not pass the radial bearing air gap. This results in a reduced negative stiffness for the radial direction. The flux distribution due to the permanent magnet and the current component i_{az} is uniform in the air gaps. Only the coil current components for radial force generation add a variable magnetic flux component to the radial air gap. These physical characteristics qualify this configuration for high rotational speeds and high axial to radial force ratios.

Fig. 11 – 14 show the normalised characteristic curves of a system designed for a nominal axial to radial load capacity ratio of 2:1. Nominal load capacity and outer diameter of the simulated bearing are equal to the configuration of Fig. 1, i.e. the results can be directly compared to the characteristic curves of Fig. 5 – 8. A comparison of Fig. 7 and Fig. 13 indicates that the negative stiffness of the radial bearing is reduced almost by half.

Experimental results

The realized prototype is shown in Fig. 15. The nominal axial bearing force of the system is 50N. The nominal radial load per bearing is 25N. Measurements with a load cell, carried out on a test rig, showed a good correlation to the simulation results of Fig. 11 - 14. To verify the controller algorithm, an assembly with two of the prototypes shown in Fig. 15 and a motor was constructed. The mathematical model, controller implementation and system behaviour at rotational speeds up to 20.000rpm are described in [6].

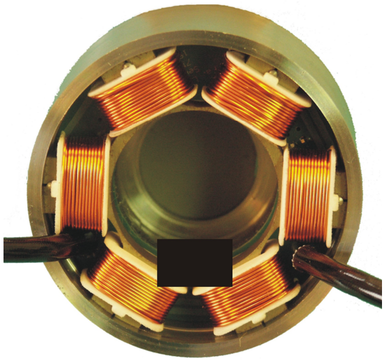

Fig. 15 Prototype of three phase radial / thrust bearing
based on radial homopolar bearing

Summary

This paper introduces a novel design of a combined radial / thrust bearing to realize a five axes active magnetic bearing system. A rather simple modification of a heteropolar or homopolar radial bearing allows the additional generation of axial forces. Radial and axial pre-magnetisation and force generation is accomplished by the same set of permanent magnets and coils. The possible application of three phase systems in star connection reduces power electronics complexity. The specified characteristic curves illustrate the existing coupling between radial and thrust bearing which have to be dealt with in controller implementation.

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