ELECTRODYNAMIC PASSIVE MAGNETIC BEARING WITH PLANAR HALBACH ARRAYS

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ABSTRACT

Active magnetic bearings are finding an increasing number of practical applications. However, system costs are still high. Passive contact free magnetic bearings need no sensors and no electronic control, such systems could therefore open up new application fields such as e.g. flywheels. Furthermore, today's active magnetic bearings have small air gaps between stator and rotor (some few tenths of millimeters) and therefore do not allow for large rotor deviations from the nominal position. The presented passive magnetic bearing uses permanent magnet rings as radial bearings and an electrodynamic system as the axial bearing. The latter is composed of two planar Halbach arrays and of two sets of short-circuited coils. The total rotor weight is magnetically compensated. For axial stabilization at the rest or at low speeds two mechanical touch-down bearings are provided. If a certain moderate rotational speed is exceeded then the complete rotor levitation will be achieved. The clearance of air gaps is so ample that the rotor can spin about its principal axis of inertia without touching the stator. For rotor stabilization no electronics is needed.

INTRODUCTION

We have developed new concepts for passive magnetic bearings which are simpler and less expensive than the servo-controlled bearings now in use. Furthermore, they can operate with air gaps of the order of some few millimeters. Such bearings have lower stiffness than the active ones. Nevertheless, even lower bearing stiffness may be sufficient for a stable levitation if an appropriate damping is provided. The admissible rotor excursions will be larger than for active bearings. If the rotor speed exceeds the critical speed, then it is possible to let the rotor spin about its principal axis of inertia within the air gap and without touching the stator. In spite of the fact that no careful balancing has been carried out, the rotor is free of unbalance forces.

SIMULATION METHOD

Simulations of different magnetic field configurations, acting forces and evaluation of stiffnesses have been performed with an excellent and simply utilizable finite elements packet FEMM [1]. In spite of its limitation to 2D simulations, axisymmetric problems can also be resolved, which is especially important for the conception of our bearings.

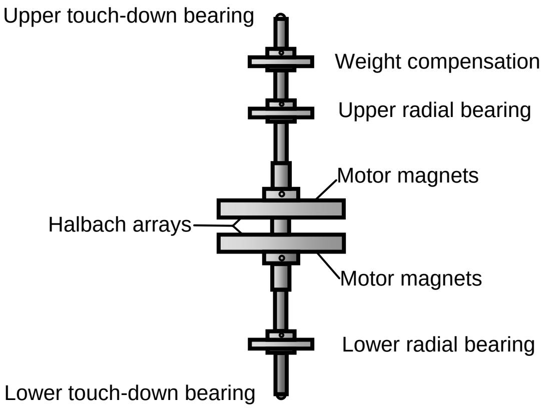

Fig. 1: Rotor assembly

DESCRIPTION

An experimental test rig with a vertical axis is presented consisting of the following parts:

Permanent magnet radial bearings, electrodynamic thrust bearing, rotor weight compensation, eddy current damping, ironless permanent magnet synchronous motor and touch-down bearings.

We have chosen a vertical axis configuration, because of its symmetrical geometry in comparison with a horizontal axis system.

Furthermore, we prefer a combination of electrodynamic axial bearing and permanent magnet radial bearings. A radial electrodynamic bearing is in principle possible as well. This combination, i.e. permanent magnet axial bearing and electrodynamic radial bearings has already been described in a dissertation [2]. However, the former solution offers a better efficacy than the latter one because in that case not all bearing's coils work at the same time, i.e. the copper volume is not optimally used.

The height of the rotor is 293mm and it is depicted on the Fig. 1. The cross-section of the whole system (as seen from above) is triangular with triangle side lengths of 190mm. The total height of the system is 330mm.

RADIAL BEARING

Each radial bearing uses two identical NdFeB permanent magnet rings (OD 40mm / ID 23mm x 6mm) in an attractive mode, one stationary and the other fixed to the shaft and rotating. The clearance between the axle and stator rings is about 3mm; the axial air gap between rotating and stationary rings is about 8mm. Therefore it is possible to let the rotor spin about its principal axis of inertia within the clearance and without touching the stator. Thus the rotor is free of unbalance forces. The bearing stiffness can easily be adjusted by changing the axial distance between the stationary and rotating magnets. The upper bearing may be advantageously combined with the weight compensating system by using one magnet ring for both functions.

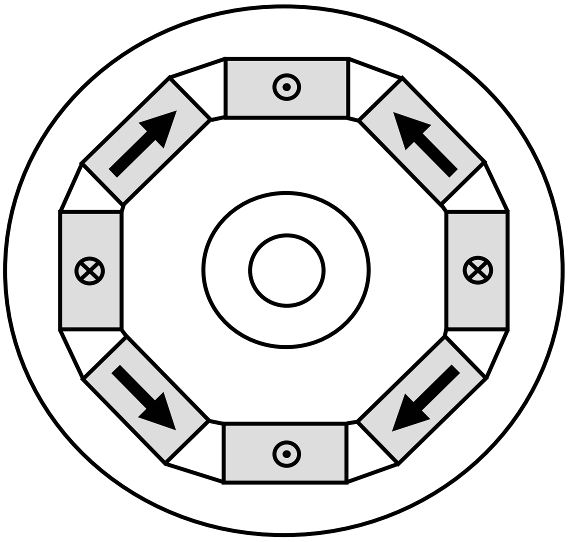

Fig. 2: Planar Halbach array

AXIAL ELECTRODYNAMIC BEARING

The axial electrodynamic bearing consists of two multipolar planar Halbach arrays in a repulsive mode. The housing of the arrays has a diameter of about 90mm and axial thickness of 12mm. We use four poles in our case, i.e. an array is composed of eight circumferentially located magnets (Fig. 2). Ideally, permanent magnets of a circle sector shape should be used, but for the sake of simplicity rectangular permanent magnets (20mm x 12mm x 8mm) have been chosen. Four of them are polarized along the 8mm direction, the other four along 20mm. Due to its rectangular shape, the azimuthal magnetic path is not completely closed, and nevertheless the magnetic induction within the axial air gap between arrays attains values of about 0.3T. Two such Halbach arrays are fixed on the shaft with an axial air gap of 26mm and operate in the repulsive mode. They are rotating with the rotor (Fig. 1).

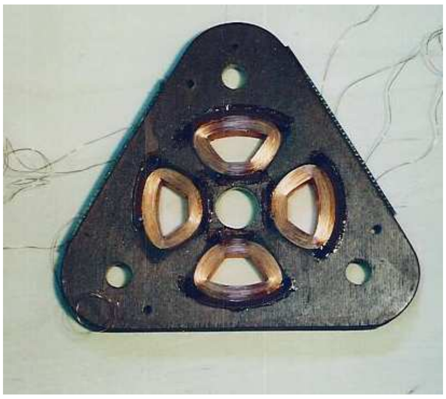

Fig. 3: Coils of the electrodynamic bearing

A stationary set of four short-circuited coils is located at the middle of the air gap between the arrays. We use two coil plates; the thickness of the plates is 10mm each, therefore the axial clearance at the both sides is 3mm. The axially neighboring coils are connected in series and short-circuited.

Ideally, each coil should occupy full 90 degrees of the circumference, but from construction reasons they are a little smaller in the azimuthal direction (Fig. 3). The main advantage of the axial electrodynamic bearing in comparison with a radial electrodynamic one is that all coils work simultaneously while in the latter case only two diametrally opposite coils are in operation.

As the coils are located in a relatively strong alternating magnetic field, eddy currents within the copper bulk volume may arise. In order to eliminate this problem, thin copper wire or HF-litz should be used. In our case, the coils are wound of 0.3mm diameter copper wire, each coil having 670 turns. We have proved that the influence of eddy currents for this wire diameter is negligible. The coil resistance is 15 ohms and its inductance 11.3mH.

Provided the rotor remains at the axially nominal position, a half of the magnetic flux issuing from the Halbach arrays and interacting with the coils goes upwards and the other half downwards (Fig. 4). Therefore, no current is induced in the coils, no force arises and no losses are present. However, if

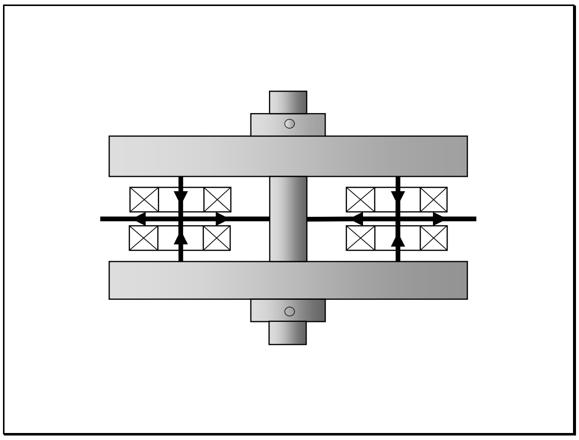

Fig. 4: Flux within the coils at the axially centered position

the rotor is displaced from this nominal position, a voltage is induced within the coils (Fig. 5). Consequently, currents flow through each coil and as a result an axial restoring force is created. At first the magnitude of this force increases with the rotational speed and then, at high speeds, asymptotically reaches a maximum. If a certain moderate speed is attained, the force becomes sufficient to axially stabilize the rotor. The shape of this dependence is given by the ratio between the coil reactance and its ohmic resistance, i.e. by its time constant (0.75ms for one coil in our case).

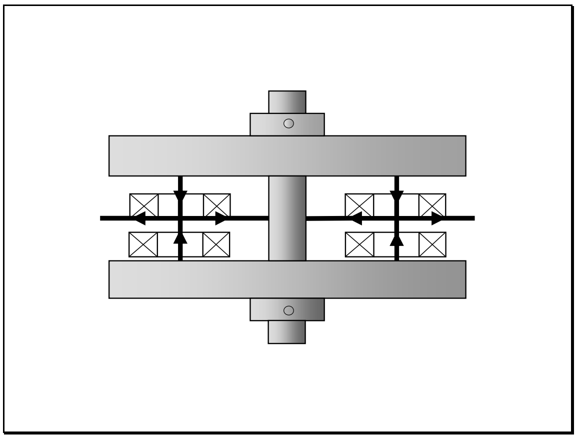

Fig. 5: Flux within the coils at the axially displaced position

Provided that the weight compensation is appropriately adjusted, the thrust bearing need not support any load. As the current only flows when a restoring force is required, no losses are present unless the rotor is deviated from the axially nominal position.

ROTOR WEIGHT COMPENSATION

The weight compensating system consists of three coaxial identical permanent magnetic rings (OD 40mm / ID 23mm x 6mm again) arranged in a compound attractive/repulsive mode. Two of them are stationary and the third one is rotating. The rotating magnet is fixed to the shaft and located approximately at the middle between the stationary magnets. The upper half of the system operates in an attractive mode, the lower half in the repulsive one [3]. Therefore, a strong force upwards in the vertical direction will be created and so the weight of the rotor (about 1.3kg) will be completely supported. The rotor weight can be exactly compensated by adjusting the distance between the stationary and rotating magnets. Axial air gaps are about 18mm. The outstanding property of the applied configuration is that the system does not introduce any disturbing forces or stiffnesses, provided the rotor remains in the nominal position. This continues to be valid even for small excursions from this position. The system just delivers the axial force needed to compensate the rotor weight. Note, that even a significant rotor weight can be supported by relatively small magnets.

DAMPING

The stationary magnet rings are elastically embedded in a plastics foam rim (Fig. 6). They are therefore allowed to displace slightly in the radial direction, but not in the axial one. Thus a certain kind of mechanical damping is achieved.

Otherwise, the eddy current damping systems in our bearing consist of stationary conductive surfaces in relative motion to magnetic fields produced by permanent magnets. Aluminum discs (dia. 85mm, thickness 8–12mm) in association with already present magnets are used. When the rotor remains at the radially centered position, the discs experience constant magnetic fields, even during the rotor’s rotation. Thus no eddy currents are induced and no losses arise. In case of radial or axial excursions, however, an electrodynamic damping will follow. These stator discs also serve as rudimentary touch-down radial bearings.

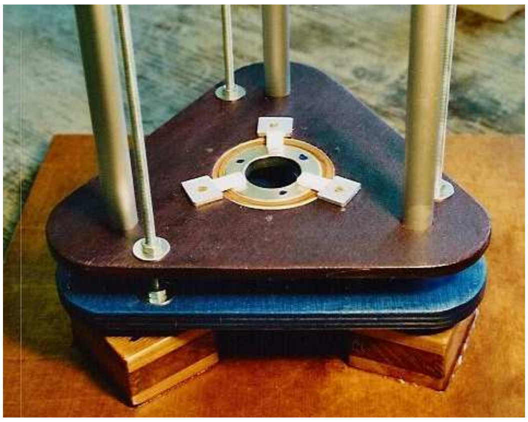

Fig. 6: Elastically embedded permanent magnet ring

MOTOR

The rear sides of the Halbach arrays are advantageously used as a rotor for an ironless four-pole synchronous permanent magnet motor. Such an ironless motor does not introduce any disturbing forces both in radial and axial directions, because it uses Lorentz forces only. Four magnets (dia. 20mm x 5mm) are fixed to each side at 90 degrees azimuthal interval with alternating polarity without back iron (Fig. 7). Appropriate Halbach arrays may be used as well, but for the sake of simplicity we have chosen this way.

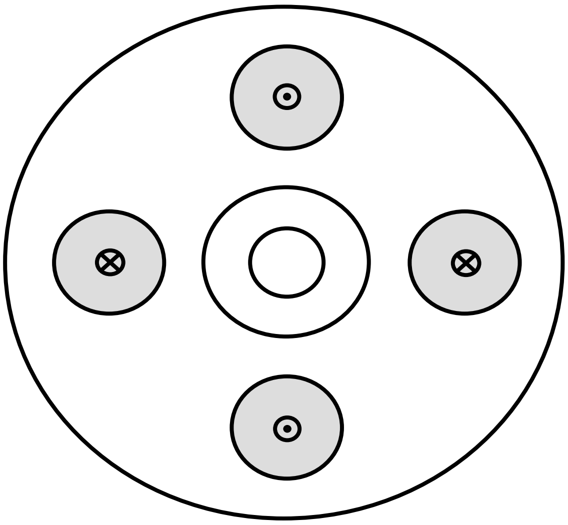

Fig. 7: Synchronous motor magnets

The stator is composed of two 5mm thick plates each containing six coils at 60 degrees interval (Fig. 8). The coils are wound of 0.3mm diameter wire, each coil having 245 turns. The coil resistance is 6.3 ohms and its inductance 1.8mH.

Fig. 8: Coils of the synchronous motor

The opposite coil-pairs of one plate are connected in series and then the three pairs in star, while both plate coil sets are connected in parallel. As a motor power supply the three phase programmable frequency inverter OMRON Sysdrive 3G3JV with maximum frequency of 400 Hz is used and with output voltage set to about 30-35 volts.

TOUCH-DOWN BEARINGS

As the electrodynamic bearing does not work at rest or at low speeds some axial touch-down bearings are needed. The touch-down bearings are simply composed of two steel balls (dia. 4mm, see Fig. 1) fixed to the both ends of the shaft and rotated with it; and two stationary steel plates (knife blades). The friction losses of such bearings are negligible. Note that the bearings operate at low speeds only, before the rotor begins to levitate or in case of emergency.

STABILITY

The stability in the radial direction is achieved by the radial magnetic bearings and in the axial direction by the electrodynamic thrust bearing. In our case the upper bearing is partially combined with the weight compensation rings (Fig. 9). The radial bearings have a positive stiffness in the radial direction but a stronger negative stiffness in the axial direction. In order to acquire a complete levitation the following condition has to be fulfilled: The positive axial thrust bearing stiffness has to be greater than the negative radial bearing stiffness in the same direction. Note that the electrodynamic thrust bearing does not introduce any disturbing negative stiffness in the radial direction. The axial stiffness of the electrodynamic bearing can be arbitrary increased by stacking several thrust bearings along the axial direction. However, in our case one bearing turns out to be sufficient.

In order to better demonstrate the axial bearing operation, the bearing coils are not short-circuited individually, as described above, but they are connected with an appropriate polarity in series. Therefore the total resistance and inductance of all eight coils in series is 115 ohms and 106mH, respectively (i.e., the time constant is 0.92ms).

Then by means of a switch they can be either short-circuited as a whole or let open. Therefore, in the latter case the thrust bearing operation is disabled, the rotor hits one of the touch-down bearings and ceases to levitate. When the short-circuit is established again, the rotor - after small

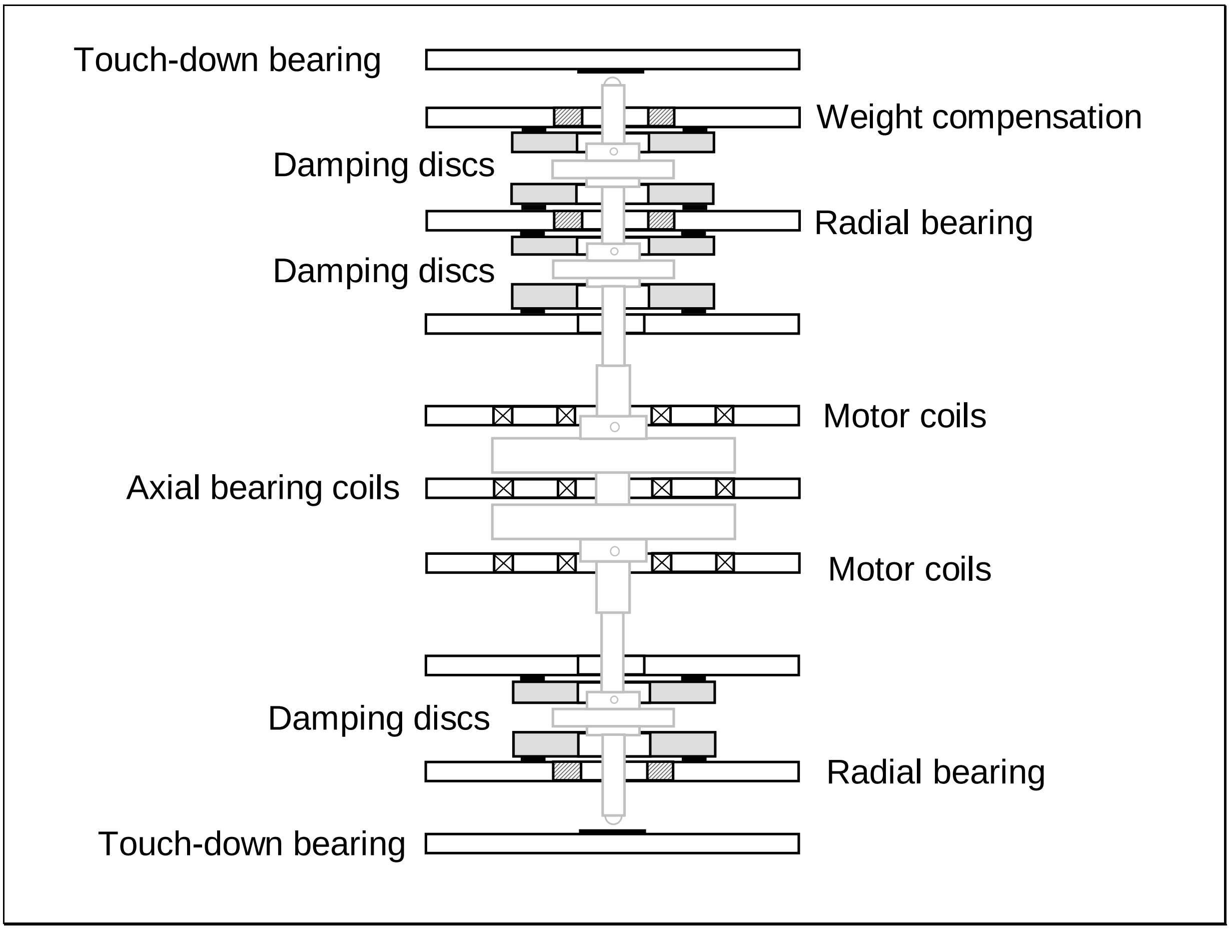

Fig. 9: **Stator assembly**

damped oscillations - returns promptly into its stable levitated position.

RESULTS

The overall view on the magnetic bearing test rig is shown in the Fig. 10. As the motor torque is rather low (otherwise the motor coils get too hot), it takes about 2 minutes to reach a speed of 6’000 rpm (this corresponds to the frequency of 200Hz, considering our four-pole motor). The rotor begins to levitate at about 4’800 rpm. The axial clearing from the touch-down bearings attains about 2mm, which can be easily recognized. The induced voltage in the axial bearing four coils is about 95 volts at the speed of 6’000 rpm. As the both coil sets are connected in series with opposite polarity, the resulting voltage at the axially nominal position is zero. The controlling current during excursions from the nominal position does not exceed 80mA, thus the power needed to levitate the rotor is lower than 0.8W.

Due to system construction limits we have purposely resisted to the temptation to achieve higher speeds, in spite of the sufficient power supply capabilities (up to 400 Hz, which would correspond to 12’000 rpm). The rotor’s behaviour is very conform and stable. Even after some light lateral or axial shocks the rotor returns quickly to the nominal position.

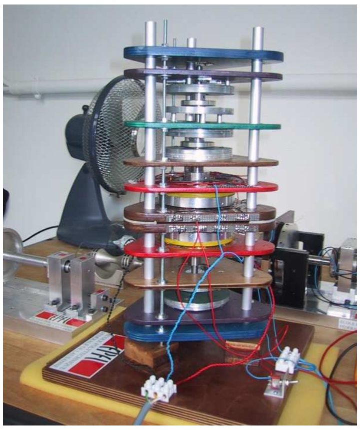

Fig. 10: Magnetic bearing test rig assembly

FUTURE DEVELOPMENTS

The stiffness of the presented passive magnetic bearing is rather moderate, but for the given configuration sufficient to attain a stable levitation. For a better performance bearing air gaps can be reduced or larger permanent magnets may be used.

This results in an increased radial bearing stiffness, which consequently calls for a stiffer electrodynamic axial bearing. The stronger stiffness can be accomplished either by using a compound planar Halbach array, where the magnetic path is closed both in the azimuthal and radial directions or stacking several thrust bearings along the axial direction. Thus, in the latter case, an arbitrary stiffness may be attained.

Other geometries and configurations, such as cylindrical Halbach arrays, radial bearings in a repulsive mode or weight compensation for horizontal rotors are possible.

CONCLUSION

This new passive magnetic bearing system has been especially developed for applications, where large air gaps and rather high compliance of the rotational axis position can be tolerated. To our best knowledge, there is nothing in the literature equivalent

Potential application could be e.g. flywheels (as electromechanical energy storage) or momentum wheels for stabilization of satellites (without the necessity for weight compensation, of course). Other practicable uses can be in centrifuges, textile spindles, rotating mirrors or beam choppers. However, it is not applicable e.g. for machine tools, where the position of the rotational axis has to be guaranteed with a (sub) micrometer accuracy even for different loads.

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