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Compact Passive Electrodynamic Thrust Bearing

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ABSTRACT

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. Passive electrodynamic bearings are usually composed of permanent magnets and coil systems or conductive surfaces. However, both configurations have some drawbacks. Bearings with conductive surfaces produce a considerable braking torque at low speeds, which has to be overridden before the nominal speed is attained and even then, at the bearing's nominal position, some losses always remain. In bearings with coil systems such as the one presented four years ago, the coils cannot occupy the whole space available. Furthermore, the discrete coils lead to pulsating restoring forces which is not optimal.

A new compact configuration of a passive thrust bearings especially useful for open core flywheels with vertical axis is presented here. This passive magnetic bearing uses permanent magnet rings as radial bearings and an electrodynamic system as the axial bearing. Instead of discrete coils, this thrust bearing consists of a special conductive structure composed of interconnected copper wire segments, which we call "distributed coils". With this new desing, no braking torque at low speeds, no force ripple is created and no losses are present at nominal position. The total rotor weight is magnetically compensated. Provided that the compensation is appropriately adjusted, the thrust bearing needs not to support any load, it serves only to stabilize the rotor. Above a given rather moderate rotational speed, complete thrust stabilization is achieved.

Keywords

Electrodynamic bearing, open core flywheel, low loss bearing, high speed bearing, distributed coils.

INTRODUCTION

Four years ago at the ISMB9 conference we presented a passive magnetic thrust bearing consisting of two stationary sets of discrete coils located between two rotating planar repulsive Halbach arrays [1]. During the last ISMB10 conference two years ago a model of such bearing was successfully demonstrated. We will present here a modification of this bearing by changing the disc shape into a compact cylindrical one and by replacing the discrete coils by a structure which can be described as "distributed coils", similar to a squirrel cage induction motor. This modification is particularly suitable for open core flywheel applications.

A simple bulk copper cylinder can lead to excessive eddy currents. Though such a bearing will work (in accordance with maglev principles), a braking torque at low rotating speeds will prevail over restoring forces and losses will be present even in the bearing's centered position. In order to overcome these drawbacks another conductive structure has be chosen.

DESCRIPTION

We will describe design and operation of the thrust bearing only; the rest of the system, i.e. radial bearings, touch-down bearings, weight compensation, etc., will be not mentioned here.

The new conductive structure is made of many thin insulated copper wire segments. The segments are oriented in axial direction with several layers in radial direction; thus a cylindrical shape is formed. The segment ends are interconnected on the face ends of the cylinder in such a way that induced currents are forced to flow in rectangular loops covering the full length of the segments.

Using discrete coils in the previous electrodynamic system causes pulsating restoring forces. In contrast, with the distributed coils described above, the restoring forces act steadily, because the available volume is now optimally filled with copper. This was not the case with the previously demonstrated model.

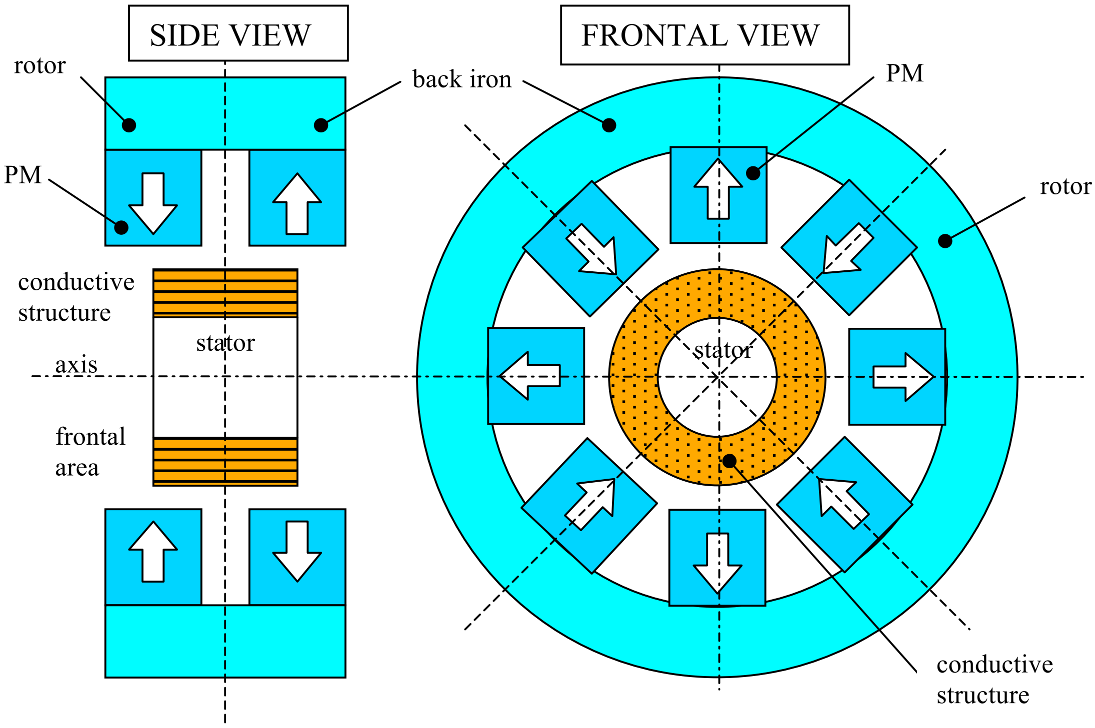

FIGURE 1: Schematic sketch of a compact thrust bearing with four pole-pair outer rotor.

Instead of a Halbach array, a simple alternating permanent magnet configuration with back iron is used. (Obviously, Halbach arrays may also be used, but their implementation is more laborious). The magnets are located on a cylindrical mandrel or inside an open cylindrical core, depending on the desired orientation of the magnetic field. The magnetic field can emanate either outward or inward; both possibilities are feasible. From the rotating machinery stability point of view, a rotating magnet array and stationary conductive structure is preferred in order to avoid the well known destabilizing effect of damping on the rotating body. Therefore, in Fig. 1, the inward field version is shown.

Manufacturing and design

The conductive structure could be produced as follows: First a structure is wound with a continuous uninterrupted wire on a cylindrical mandrel, closing in loops above and below the cylinder either along the whole perimeter or in sectors. The choice of the wire diameter depends on the nominal rotational speed and on the number of poles. The wires are then glued together (e.g. melting the thermoplastic wire insulation).

The loops at the face ends are then cut away and the mandrel is removed; thus a hollow cylindrical shape is created. The resulting frontal areas are then polished and finally a thin copper layer is electroplated over the wire segment ends. Thus continuous layers of individual conductive loops are created.

Note that during operation this copper structure is located in a strong radial alternating magnetic field. As it consists of thin wire segments, only very weak eddy currents will be induced and the losses are then minimized as compared to a bulk copper sleeve where eddy currents are possible anywhere. Only in axially decentered position will significant eddy currents be induced in the loops, thus producing the restoring forces. The thinner the wires the better. For speeds up to 100’000 rpm (about electrical 10 kHz, depending on the number of poles) a wire diameter of 0.3 mm works well. Instead of wire, an interwoven HF-litz can be used (e.g. 120 x 0.07mm braid), which is especially recommended for higher frequencies.

The choice of the radial thickness of the cylindrical copper wire structure is a compromise between the volume available and the bearing's efficiency. Note that wire layers in immediate vicinity of the air gap produce strong restoring forces, but layers far away from the air gap will lead to rather weak restoring forces simply because they are located in a zone of weaker field strength. Of course, overall restoring force depends strongly on rotational speed, it increases with higher speed which is a desirable property e.g. for a flywheel.

BEARING OPERATION

The configuration of the current loops is approximately given by number of rotor poles. The exact shape of the loops strongly depends on the distribution of the magnetic field. In principle, for proper operation of electrodynamic bearings some phase shift between the induced voltage and current is required. This is inherently realized owing to the structure's inductance and resistance.

The ohmic resistance of individual closed rectangular loops can be evaluated analytically in a quite straight forward manner. Estimating the loop inductance will be more arduous. Although it can be computed by known approximate formulae, it should be taken into consideration that there also is some inductive coupling among adjacent loops, which tend to decrease the previously calculated inductance. As coupling factors are difficult to estimate, only a coarse approximation of inductance is possible at the present time.

More precise evaluation of the copper structure's time constant and consequently of the bearing operation can be obtained by finite element simulations, especially by including the influence of eddy currents. In such simulations the steady fields of permanent magnets should be replaced by alternating fields with a frequency corresponding to the rotating speed and the number of poles.

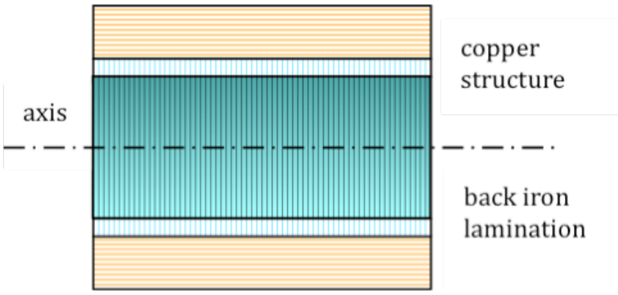

FIGURE 2: *Copper structure with back iron lamination added*

Provided the rotor remains at the axially nominal position, one half of the magnetic flux issuing from rotor permanent magnets and interacting with the copper structure goes upwards and the other half downwards (Fig. 1). Therefore, no current is induced in the copper structure, no force arises and the system operates without losses.

However, if the rotor is displaced from the nominal position, a voltage is induced within the copper structure. Consequently, currents will flow and as a result an axial restoring force arises. At a given moderate speed, the force becomes sufficient to axially stabilize the rotor. At first the magnitude of this force increases with the rotational speed and then, at high speeds, it is expected to asymptotically reach a maximum.

The restoring force as function of rotational depends on the ratio between the coil inductance and its ohmic resistance, i.e. on its time constant.

As is depicted in the Fig. 1, the conductive structure axial length does not occupy the whole axial length of permanent magnets. The structure length is approximately half of this, depending on the axial air gap between magnets. In centered position exactly one half of the magnetic flux penetrates inward in and the other half outward of the structure, therefore no current is induced in the loops. In order to obtain axial restoring forces during axial excursions, it is necessary that the ends of the structure still remain in a region where the magnetic lines follow the radial direction.

The eddy currents created within the copper structure rotate synchronously with the rotor. For a given speed and position their intensity remains steady; they are not pulsating as it was the case with discrete coils. Therefore, for a given bearing space, the restoring forces are reaching an optimum with the new configuration proposed here.

Addition of an iron core

There is a possibility to slightly increase the inductance to resistance ratio of the copper structure (i.e. its time constant) by adding a back iron core at its inner surface (Fig. 2). As a result, the shape of the magnetic field within the structure will be changed; it will be more constrained into the radial direction. It means that the bearing's electrodynamic action begins at lower speeds than without the core. Due to a stronger magnetic field within the copper structure stronger currents will be induced and correspondingly a stronger restoring force will be created.

In order to suppress eddy currents within the ferromagnetic core, the core should be laminated in axial (thrust) direction; e.g. it may be composed of thin iron rings. Another possibility is to use a bulk ferrite cylinder, especially for high rotation speeds, i.e. higher electric frequencies; then the eddy currents in the core can be almost completely eliminated.

It is worth mentioning that introducing a ferromagnetic material in the vicinity of permanent magnets changes the bearing's properties in two ways: the axial stiffness for low rotational speeds will be increased (which is desired), but simultaneously the radial stiffness of permanent magnet radial bearings will be decreased (which is not desirable). By adjusting the radial thickness of this ferromagnetic structure an optimal compromise can be found.

However, at higher rotational speeds the bearing's operation will not change, because the magnetic field does not penetrate deep enough into the structure and the back iron becomes in this case "invisible".

In axially centered position no voltage is induced within the structure, thus no losses are present in this case. Only during axial excursions restoring forces are created. Owing to maglev principles, these forces act not only in the axial direction, but in the radial one too; i.e. a thrust and simultaneously a radial operation will ensue.

CONCLUSION

The newly developed passive thrust bearing presented here for the first time may be used either for large or small systems. Bearing parameters such as size of magnets, number of poles, dimensions of the conductive structure, wire diameter, etc., can be tuned optimally according the the principles outlined. As the current only flows when a restoring force is required, no losses are present at nominal position, making this an ideal bearing e.g. for flywheels.

In principle, a similar conductive structure is also conceivable for a disc shaped bearing, but the configuration of such a copper structure may prove more difficult to realize.

References

[1] J. Sandtner, H. Bleuler: "Electrodynamic Passive Magnetic Bearing with Planar Halbach Arrays", *Proc. of 9th International Symposium on Magnetic Bearings ISMB9*, Lexington, Kentucky, USA, Aug. 3-6, (2004), Paper #5
(also available at www.silphenix.ch/lexington.pdf)