Electrodynamic passive magnetic bearing using reluctance forces

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10.1 Passive Magnetic Bearings

Keywords

Halbach array, Inductrack, null-flux,, passive magnetic bearings, reluctance force.

Abstract

Electrodynamic passive magnetic bearings with Halbach arrays and air coils produce only moderate Lorentz restoring forces. These bearings are especially conceived for high speed applications. In order to obtain weaker drag forces and properly directed restoring forces additional inductances in series with the stationary coils are required. These inductances comprise ferromagnetic cores, which are located outside the bearing magnetic field. Therefore no radial instability occurs. In the here presented bearing version, instead of Lorentz forces, much stronger reluctance forces are used, but the laminated ferromagnetic core has to be located inside the bearing magnetic field. This introduces a very strong radial instability. Therefore, the instability has to be compensated by permanent magnet rings, usually in a repulsive mode. The axial stability is achieved by axially splitting the Halbach array. Bearings using reluctance forces operate even for relatively low speeds without the necessity for additional inductances.

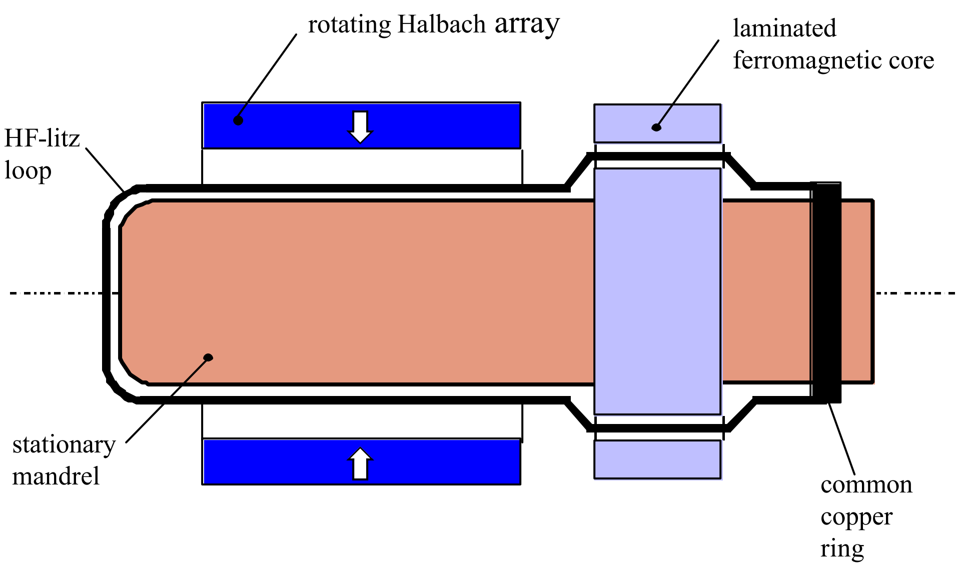


Fig. 1: Air-coil bearing with diametrally connected wires and additional inductances.

1 Introduction

1.1 Air-coil magnetic bearings

Electrodynamic passive magnetic bearings (PMB) using rotating Halbach arrays together with stationary air coils or conductor loops [1 – 3] produce only moderate Lorentz restoring forces. The air-coil version of PMB is especially conceived for high speed applications. In order to obtain larger and properly directed restoring forces and at the same time weaker drag forces even for relatively low rotational speeds, an additional inductance in series with each air coil has to be used. These inductances are located outside the Halbach magnetic field.

1.2 Magnetic bearings with ferromagnetic core

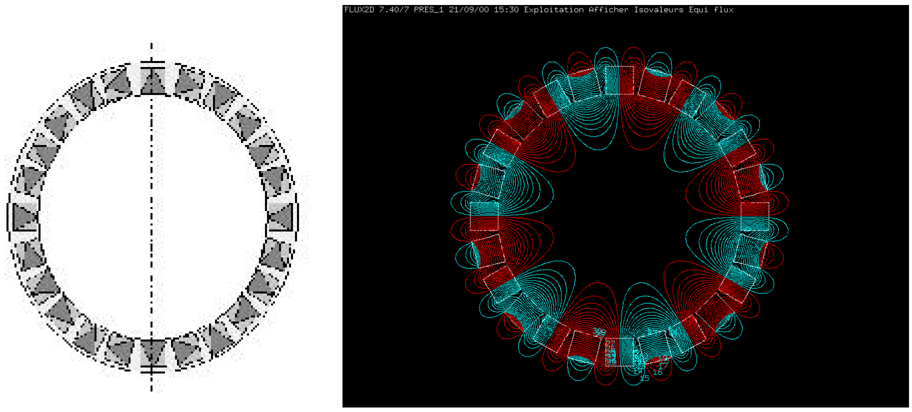
PMBs making use of reluctance forces necessarily comprise a ferromagnetic core located inside the Halbach magnetic field. The stationary coils are embedded within the core in a way similar to the rotor cage of an induction motor. Thereby much stronger restoring forces are achieved for the same coil currents in comparison with air-coil bearings. However, such a design leads to a strong radial instability. This instability has to be compensated by coaxial permanent magnet rings, usually operating in a repulsive mode (not shown in Figures).

2 Prototype of an air-coil bearing

In our laboratory we have developed and constructed a passive magnetic bearing system using Lorentz forces. The bearing is composed of an outer rotor and an inner stator (Fig. 1).

2.1 Halbach array

The rotating Halbach array contains 24 magnets (5 x 5 x 40 mm), located along the perimeter in a six pole-pairs distribution (Fig. 2). The inner diameter of the array is 44 mm, its axial length 40 mm. High performance NdFeB magnets are used for the Halbach array. The magnets used have typically a remanence of about 1.2 T.



Halbach array   Halbach array magnetic field

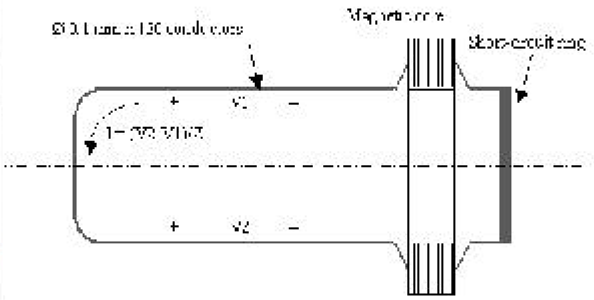
Fig. 2: Halbach array with 24 magnets and its magnetic field.

The multipolar arrays produce a very strong radial field gradient. Its strength depends on the number of pole-pairs; the more pole-pairs, the stronger the gradient. Generally, the field is exponentially decreasing in the direction towards the axis of the system, being exactly zero at the axis. Therefore, the required variation of the repulsive force with radial displacement can be made to be correspondingly steep.

The Halbach array is fixed to the rotor and thus, when it is rotating, it creates a periodic magnetic field inside the rotor opening. The maximum flux density at the active diameter (ca. 42 mm) attains about 0.35 T. The magnetic field rotates at the rotor speed and the field frequency is the rotor speed multiplied by the number of magnetic pole-pairs. That is, for the six pole-pairs array, the field speed is six times the mechanical one.

2.2 Air coils

The short-circuited conductors fixed to the inner stator mandrel interact with the Halbach magnetic field. Each conductor goes all along the innermost axial coil support and returns at the diametrally opposite side. Therefore, when the rotor is exactly centered, a voltage of the same magnitude, but with opposite polarity is induced at both sides of each conductor (Fig. 3) and no current results (a null-flux system). This means, no drag forces and no electric losses are present in the centered nominal position of the rotor (and also no restoring forces).



Cross-section with only one diametrally connected loop shown

Fig. 3: Air-coil bearing with 72 wires (36 diametrally connected loops).

The additional inductance consists of an laminated ferromagnetic core with radial slots (Fig. 1). The core is located on the stationary part of the system outside the reach of the Halbach magnetic field, thus not influencing the radial stability of the system.

The HF-litz wires are passed through the slots parallel to the system axis in the following way (Fig. 1). The wire beginning is connected to a copper ring, which is fixed on the stator. Then the wire is passed through one core slot, conveyed along the inside of the Halbach array opening to the diametrally opposite location. Then the wire goes back to the core, is passed through the diametrally opposite slot, but this time in the opposite axial direction. Finally it is soldered to the same copper ring again. Thus many short-circuited loops are created (Fig. 5).

The value of the additional inductance can be modified by changing the axial length of the lamination stack (in our case, we have used a 10 mm stack). Thereby the minimal operating speed can be adjusted. Furthermore, the slots may be let open or they may be magnetically closed from outside, in order to further increase the additional inductance.

For a radially displaced rotor, the induced voltages at each diametrally opposite side are different in magnitude and a finite current flows within the loop (Fig. 3). The value of this current depends on the circuit impedance. Thus the Lorentz restoring force (and also some drag) is produced. Note that the wires are located within a very strong magnetic field. Therefore, in order to eliminate parasitic eddy currents within the wire cross-sections, the 36 conductors connected diametrally have been realized with HF-litz wire (dia. 0.1 mm x 120 conductors).

It should be noted that the structure described above only ensures the radial stability of the rotor. Both the axial and angular stability must be provided by another non-contact system. On the other hand, this air-coil version does not introduce any radial instability.

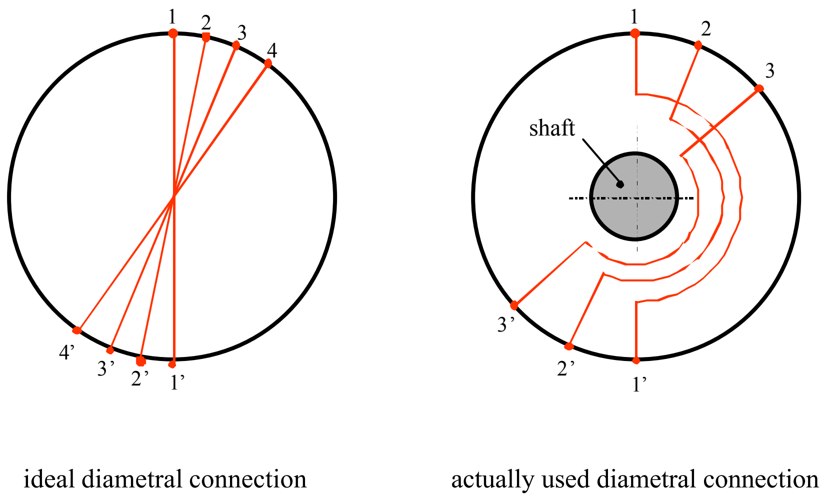


Fig. 4: Ideal (difficult to realize) and actually used diametral connection

2.3 Estimation of the inductance value

The lift-to-drag ratio at the displaced position is given by the ratio reactance-to-resistance of the loop at an actual rotational speed. Therefore, the bearing performs better at higher speeds and the importance of the loop inductance becomes obvious. However, this inductance should not be too large, because the loop current depends on the total loop impedance. As a rule of thumb, the loop reactance at the minimal operational speed is chosen to be about three times its ohmic resistance. It should be emphasized that for this estimation the influence of the mutual inductance due to neighboring short-circuited loops has to be taken into consideration.

Consequently, the phase angle between the induced voltage and current approaches 90 degrees (in fact 72 degrees). For higher speeds, the loop current for a given radial displacement remains quasi constant, because both the loop induced voltage and reactance increases with the speed.

2.4 Coil construction

From the construction point of view, it is not so easy to accomplish the diametral connection of the opposite located wires, because of obstructing wire-crossings near to the axis (Fig. 4). To facilitate the design of practical system, we have developed another connecting procedure (Fig. 6).

At one axial side of the bearing, all the wires are soldered to one common copper ring again. Generally, there is a greater number of wires than the number of pole-pairs in a given Halbach array. This means, that those wires, which are located at the same azimuth within one Halbach period, are linked with the same magnitude of the magnetic field, independently of their azimuthal position with respect to the Halbach array. Consequently, at the radially centered position, the induced voltage in these wires has the same magnitude and polarity. Therefore, those wires can be connected to another collecting copper ring at the other axial side of the bearing and still no current will be flowing. This is valid for all the wires within the Halbach period.

There has to be the same number of collecting rings as is the number of wires within one Halbach period. During radial excursions, the operation of the bearing will be identical to that with diametrally connected wires.

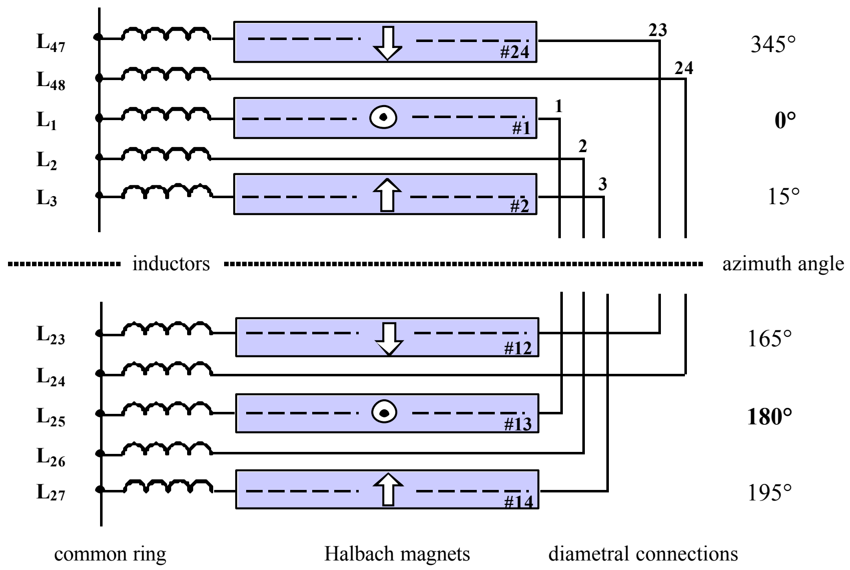


Fig. 5: Air-coil version with 24 diametral connections and 48 inductors

The induced voltage due to the alternating flux produces a current within the loops. In order to achieve minimum of drag and maximum of restoring force during radial excursions, this current has to be shifted by nearly 90 degrees relative to the induced voltage. If the coils' impedance is rather resistive, the phase angle between induced voltage and current is close to zero. However, if the coils' impedance is mainly inductive, this angle approaches 90 degrees. As the reactance grows with the rotational speed, drag and lift forces also vary with speed (during deviations from the radially centered position).

3 Bearing using reluctance forces

Using the ferromagnetic core now inside the Halbach array opening has the following advantages: much stronger reluctance forces are produced and for the proper operation required additional inductance may become smaller. In cases, when the nominal rotational speed is fairly high, the additional inductance can be omitted completely.

The new system is composed of several identical Halbach arrays (Fig. 7) having a very small axial length (e.g. 5 mm). These individual Halbach arrays are axially separated by non-magnetic and non-conductive rings (e.g. by plastic rings, also 5 mm thick). Accordingly, the stationary ferromagnetic core is composed of the same number of axially laminated discs with the same axial length as the Halbach arrays and also separated by plastic discs. Thus magnetic "teeth" linking with the corresponding Halbach arrays are created. The reluctance between stator and rotor attains minimum at the axially centered position. When the rotor is axially displaced, the reluctance increases and axial restoring forces are produced. Therefore, this passive reluctance bearing is axially stable.

However, in contrast with the precedent system without ferromagnetic core, this system is strongly unstable in the radial direction. This radial instability has to be counterbalanced by some number of coaxial permanent magnetic rings polarized in a repulsive mode.

3.1 System stability

It should be emphasized that achieving the overall stability is a quantitative matter. The whole system has to be dimensioned in such a way that for the non-rotating system the axial stiffness will be

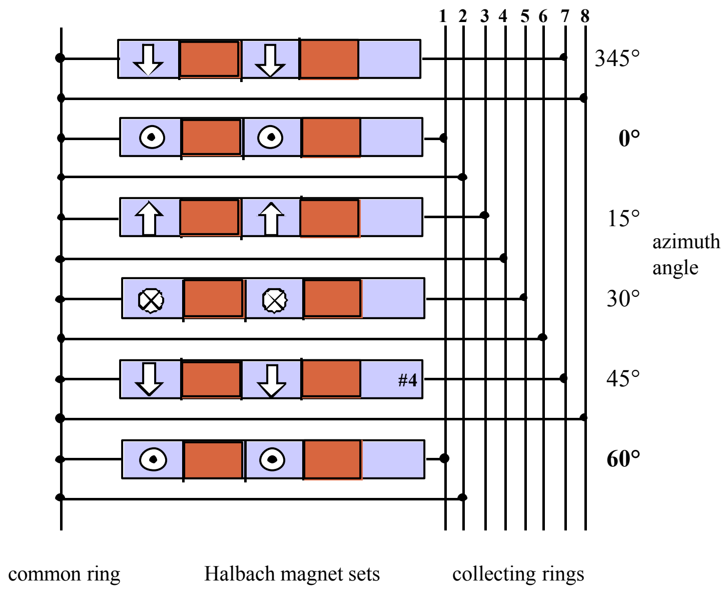


Fig. 6: Reluctance version with 48 wires and 8 collecting rings

prevailing. This means that at rest the system will be slightly radially unstable and axially stable. Therefore, some mechanical back-up bearings have to be present. After achieving a certain rotational speed, the whole system also becomes stable in the radial direction.

4 Comparison: air-coil bearings vs. reluctance forces using bearings

The principle of operation is the same as for the preceding system. However, in this case reluctance restoring forces come in action. Generally, for the same magnitude of magnetic field and current, the reluctance forces are stronger than the Lorentz forces. Furthermore, due to the presence of the ferromagnetic core Halbach magnetic circuits are better closed and consequently, the flux density within the air gap will be stronger. As a result, the induced voltage in the loops will also be higher.
The laminated core is provided with radial slots as in case of an induction motor. Copper wires are passed through these slots, parallel to the system axis. It is not necessary in this case to use HF-litz wires, because the wires are not placed inside a magnetic field. The magnetic flux is routed through the ferromagnetic core aside of wires.

It is also possible to still further increase the bearing stiffness by using saturation capabilities of the ferromagnetic core material. When the current passes over a certain value, e.g. near the peak current, the core saturates and its current limiting properties almost disappear. Nevertheless, the required phase shift between the induced voltage and current remains intact.

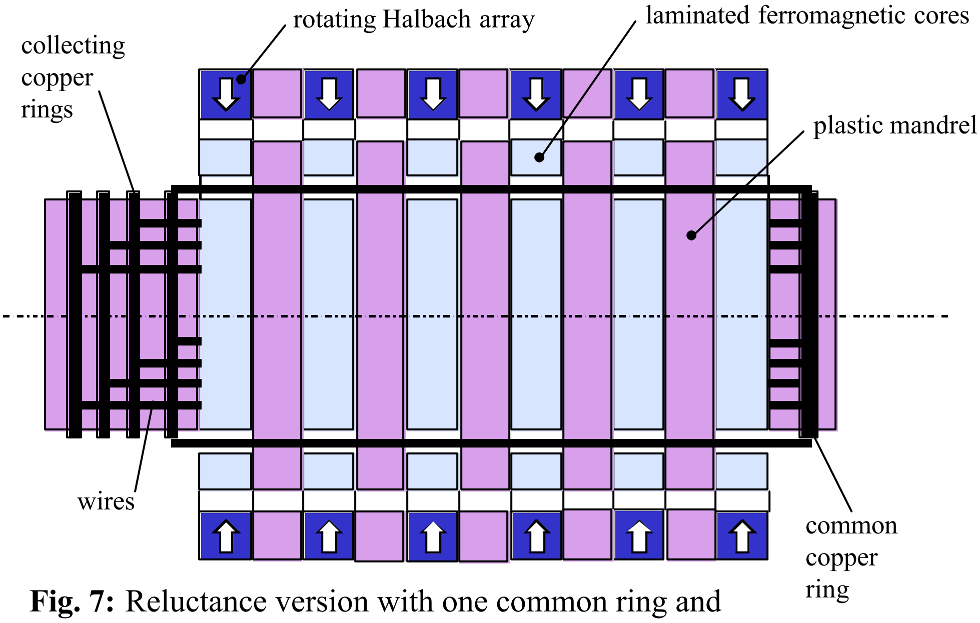


Fig. 7: Reluctance version with one common ring and several collecting rings (not all wires and rings are shown).

5 Conclusion

In comparison with air-coil electrodynamic PMBs, bearings using reluctance forces produce much stronger restoring forces for the same coil current and can operate at lower speeds without necessity of additional inductors. Thus a fairly compact bearing design is easily possible. However, the strong radial instability has to be compensated by additional permanent magnet rings. As for air-coil PMBs, a restoring force is only required, when a deviation from equilibrium occurs. At the centered position there are practically no losses. The full stability is only achieved in the rotating state. A certain minimal speed is required in order to attain a convenient lift-to-drag ratio. Above this transition speed, restoring forces approach a constant value, while drag forces decreases inversely with speed.

6 Acknowledgment

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7 References

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