HIGH SPEED PASSIVE MAGNETIC BEARING WITH INCREASED LOAD SUPPORTING CAPABILITIES.

Jan Sandtner
Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland, jan.sandtner@epfl.ch

José-Luis Bermudez
Swiss Federal Inst. of Technol. Lausanne (EPFL), Switzerland, jose-luis.bermudez@epfl.ch

Hannes Bleuler
Swiss Federal Institute of Technology Lausanne (EPFL), Switzerland, hannes.bleuler@epfl.ch

ABSTRACT

The presented passive magnetic bearing comprises an inherent ironless power generator provided with three coil systems per control axis. The energy coming from the generator is transferred via a simple passive signal-processing unit to an actuator, which is similar to those typically used in ordinary active magnetic bearings. As the actuator is located at the close vicinity to the generator, the energy need not be transported over great distances.

The bearing possesses load capacity and stiffness characteristics that are similar to those of conventional active magnetic bearings without need of expensive and complicated sensors, amplifiers, control systems and wiring. It is capable to supply power needed to control the rotor position of some few tens of kilowatts.

The bearing can be conceived for almost arbitrary available power and stiffness requirements. As long as the rotor is at the radially centered position, practically no losses are present. The bearing does not comprise active elements, nevertheless, it does use some semiconductor components in the presented design, but only passive ones (diodes).

INTRODUCTION

Rotating machines are indispensable elements of modern civilization. Essential to all such machines are their bearings. In almost every such machine mechanical bearings are used, involving lubrication, wear, energy losses due to friction, and finite life.

For example, the oil-lubricated bearings for a 40 kW electric motor typically dissipate approximately 1 % of the input electric power [4]. Over the lifetime of the motor this added energy cost would amount to nearly as much as the initial cost of the motor, assuming a 10-year service life. Bearings represent an important part of the maintenance costs of motors, turbines or compressors.

It would be very significant, both from an energy efficiency standpoint, and from the standpoint of reduced maintenance and waste, if it was possible to replace such bearings with non-contacting, near-zero friction, maintenance-free bearings.

Active magnetic bearings with their sensors and control electronics are now readily used in some industrial applications. They need an external power supply, power amplifiers, sensors and sophisticated control electronics with all the associated reliability problems.

Recently *supraconductive passive magnetic bearings* have been developed and designed. They demonstrate stable passive magnetic systems having extremely low friction losses. However, it seems questionable that this technique can be applied to standard rotating machinery, owing to cost considerations and the necessity for continuously operating cryogenic systems.

Ambient-temperature passive magnetic bearings would seem to represent an almost ideal replacement for the mechanical bearings in many types of industrial machinery. The passive magnetic bearings eliminate the need for position sensors, control electronics, and high-power amplifiers. They provide bearings that are much simpler and less expensive than competing active bearings. However, the passive magnetic bearings generally provide less stiffness when compared to active bearings.

BASIC CONCEPTS

To circumvent this obstacle, we introduce here a novel design, in which *rotational kinetic energy is converted to radial restoring forces* [3]. By separating the current inducing portion (generator) from the restoring force generating portion (actuator) of the system, most parameters, such as generator's available power or

actuator's restoring forces, can be independently devised. If the rotor is situated at the centered position and its weight is sustained by permanent magnet means, no energy is wasted and the rotor can be carried without losses.
It is therefore an object of this new design to provide a magnetic bearing system, which includes the advantages of the active magnetic bearings, while eliminating their respective weaknesses.

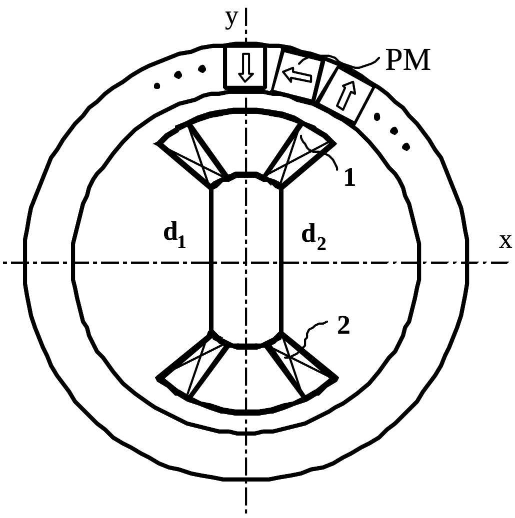

FIGURE 1: Power generator with Halbach array

The basic concepts involved are: The bearing comprises a sort of *an inherent electric ironless generator* (**Fig. 1**) provided with three air coil systems (reference coils, signal coils and compensating reference coils). The generator serves for following purposes:
The first air coil system supplies energy needed to produce restoring forces (*reference coils*). This energy does not depend on the deviation from the centered position (*additionally connected coils*).
The second air coil system (*signal coils*) provides an additional information about the amount and direction of this deviation from the centered position (*differentially connected coils*). In case of rotor's radial deviation, it als o supplies a part of this energy.
The third air coil system (*compensating reference coils*) serves - after subsequent rectifying - to compensate the generator output current, which would circulate through the load even if there is no deviation from the centered position. The energy, like in the first coil system, does not depend on the deviation from the centered position (*additionally connected coils*). Therefore, and this should be emphasized, *as long as the rotor is at the radially centered position, no output current is flowing and practically no losses are present.*
Two passive full-wave rectifiers, located in the stator, transfer energy arriving from the generator to the pertinent actuator coil so that restoring forces are attained (*polarity sensitive coils*).

The bearing comprises an actuator (**Fig. 2**) capable of operating in at least two diametral directions, e.g. along x- and y-axes.
It is sufficient, if stability of the rotating system is only achieved in the rotating state. That is, some mechanical means have to be used to insure stable levitation at low speeds or at rest.
According to principles of rotor dynamics, the system power losses occur almost exclusively in the stator part and not in the rotor part. This condition is essential for stability.

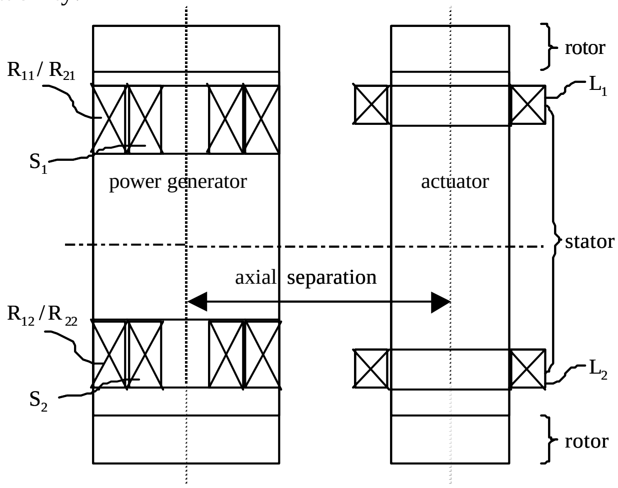

FIGURE 2: Power generator and actuator

DESCRIPTION

Like every bearing, the passive magnetic bearing system according to the presented design has a stator assembly and a rotor assembly (**Fig. 1** and **Fig. 2**). Both configurations, either inner rotor or outer rotor are possible. *This description will be limited to the case of an outer rotor and an inner stator.*

Our group at EPFL has developed a kind of passive bearings, which do not contain an intrinsic power generator, i.e. bearings based on the electrodynamic principle that are composed of permanent magnets and conductive surfaces (or short-circuited coils) in relative motion to each other. They could be very compact, less complex, less subject to failure, and, potentially, far lower in cost. The bearing stability is only achieved in the rotating state. *Sensing and force generation is collocated, i.e. located spatially at the same axial place.* However, their restoring forces and stiffnesses cannot be designed independently from the existing destabilizing forces due to a mutual attraction between permanent magnets and/or soft ferromagnetic parts of the system (if such parts are present).
For some applications this fact does not represent a serious problem. However, in systems, where large stiffnesses are required, the separation of the current generating function and the actuator function may be advantageous.

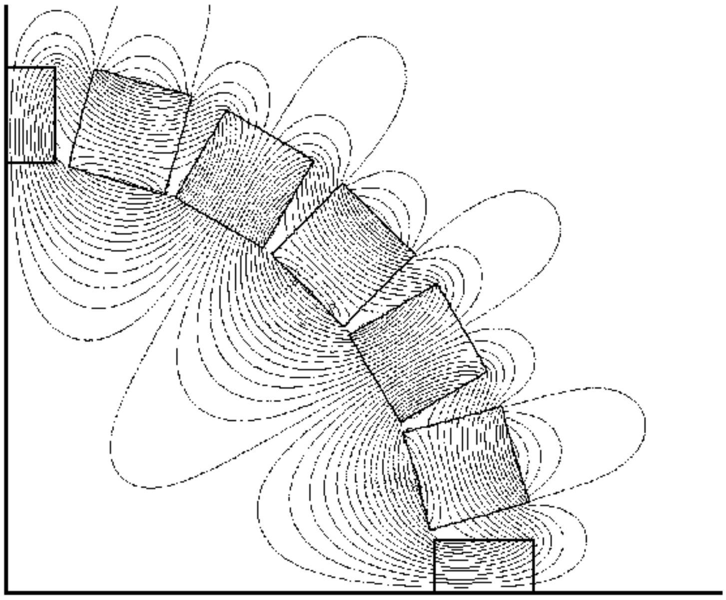

FIGURE 3: Field lines of a multipolar Halbach array (24 magnets)

Therefore *parameters, such as generator's available power or actuator's restoring forces and stiffnesses, can be independently devised*. This will be the subject of the following description.

Power Generator

The bearing comprises an inherent ironless generator (**Fig. 1**) provided with three air coil systems [3], [7]. In case of rotor's deviation from the centered position, two of the air coil systems supply energy needed to produce restoring forces, the remaining air coil system provides an additional information about the amount and direction of this deviation from the centered position.
There are two full-wave rectifiers located within the stator (**Fig. 5**). The first one $\mathbf{FWR_1}$ rectifies the AC output coming from the first ($\mathbf{R_{11}}$, $\mathbf{R_{12}}$) and the second coil systems ($\mathbf{S_1}$, $\mathbf{S_2}$). At the output of the second full-wave rectifier $\mathbf{FWR_2}$, which is connected to the third coil system ($\mathbf{R_{21}}$, $\mathbf{R_{22}}$), the compensating DC voltage is obtained. This voltage is further subtracted from the DC voltage at the first full-wave rectifier output in order to achieve zero losses at the centered position.
The actuator is located axially in close vicinity of the generator (**Fig. 2**) but not exactly at the same place, i.e. at this portion of the axis *the rotor have to be considered as rigid*. In systems, where large stiffnesses are required, the separation of the current generating function and the actuator function may be advantageous.

Halbach Array

As shown in **Fig. 1**, the rotor of the bearing is composed of an array of permanent magnets **PM** made of a material with very high coercivity, such as NdFeB. These permanent magnets are arranged in the close vicinity of the generator air gap in a so-called Halbach array [1], [2]. In general, *such an array has the property to concentrate the magnetic field on one side, while nearly canceling it on the other side of the array.*
In case of a circular Halbach array the field can be concentrated either inside or outside of the circle. For our purpose *we use the field concentration inside the Halbach array.*

Bipolar Halbach Array. A Halbach array can be designed as a source of a homogenous magnetic field inside the circle area enclosed by the array - a bipolar field. *The intensity of this field does not depend on the location within the circle.* The bipolar field is often used as an ideal solution for ironless permanent magnet synchronous motors.

Quadrupolar Halbach Array. Another possibility is to design an array producing a quadrupolar field, and as *the magnetic field vanishes at the circle's center*, its intensity depends on the radial distance from the array.
Multipolar Halbach Array. Furthermore, in case of a multipolar array, *the field's magnitude depends strongly on the radial distance from the array* (see **Fig. 4**). This dependence represents an exponential function, its steepness is given by the number of Halbach array magnets and their shape (a square- or rectangular shaped cross-section may be used, the sector shape would be ideal). The corresponding equations for the field distribution can be found in references [1], [2], [5] and [7].

Such a multipolar Halbach array is proposed here in order to detect the radial deviations from the centered position of the rotor.

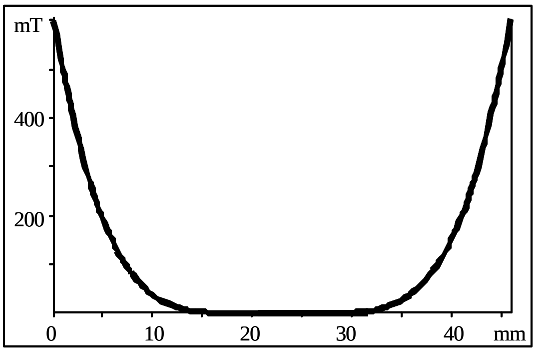

FIGURE 4: Multipolar Halbach field vs. radius

SIGNAL PROCESSING

In order to obtain restoring forces at right places, the information arriving from the generator has to be further processed. Two full-wave rectifiers (**Fig. 5, FWR_1** and **FWR_2**) are used; one (**FWR_1**) as a source of pulsed DC voltage containing information about the rotor radial position, the other (**FWR_2**) as a compensation of a steady current, which would circulate even at the rotor's centered position.

In order to satisfy the bearing control requirements *a passive PID two-port* may be introduced between generator and actuator parts (between terminals **1, 1'** and **2, 2'**, not shown in **Fig. 5**). The most convenient way may be using a two port (composed of two resistors and two condensers) with two poles and two zeros in the complex plane.

Supplementary, smoothing condensers connected parallel to the full-wave rectifier outputs can substitute for the PID integrating operation.

Alternatively, especially for constant speed applications, the system coil reactance can be advantageously counterbalanced by *series condensers located in the AC parts of the system*, so that the system's available power might be considerably increased. The LC circuit's figure of merit may be used to determine the time constant of integration.

Air coil systems

Inside the circular area of the Halbach array (**Fig. 1**) in a diametral direction there are at least two stationary air coil systems (stator), eg. along two orthogonal axes, one system along the x-axis and the other along the y-axis. Each air coil system (i.e. coils without any ferromagnetic core) consists of three separate windings (*only the y-axis coil system is shown:* upper coil system **1** and bwer coil system **2**). As the coil systems are located within a relatively strong alternating magnetic field, the coils are wound either with very thin wires or with a HF-litz, in order to decrease losses due to parasitic eddy currents within the cross-section of the wires. (The litz-wire is composed of a multistranded bundle of fine strands of insulated copper wire).

Both upper and lower coils **1** and **2** are connected diametrally, **d_1** and **d_2**, in such a way that in the first pair the induced voltages within the coils are added (**R_{11}**, **R_{12}**), while in the other pair the voltages are subtracted (**S_1**, **S_2**). There is a third pair of coils in the coil system **1** and **2**: the compensating reference coils **R_{21}** and **R_{22}**. Like in the coils **R_{11}** and **R_{12}**, the induced voltages are added. The connection can be seen in **Fig. 5.**

In this way the AC output voltage of the first coil pair, **R_{11}**, **R_{12}** (reference coils), does not depend on the radial position of the rotor, while the AC output voltage of the other coil pair, **S_1**, **S_2** (signal coils), depends *strongly* on the radial position, being zero when the rotor is exactly at the centered position. The coils' polarity in **Fig. 5** is marked by the dots. Thus if the rotor moves in one radial direction, say upwards, the signal voltage **S_1/S_2** is in phase with the reference voltage **R_{11}/R_{12}**, while if it moves in the opposite direction, i.e. downward, the signal voltage is 180 degrees phase-shifted against the reference. Thus information about the radial displacement is acquired.

The AC output voltage of the remaining pair of coils **R_{21}** and **R_{22}** (compensating reference coils), which are connected in addition, is in phase with the reference voltage **R_{11}/R_{12}**.

ACTUATOR

The actuator is located axially in close vicinity of the generator but not exactly at the same place (**Fig. 2**), i.e. at this portion of the axis the rotor have to be considered as rigid.

The actuator is designed in a way similar to actuators used for conventional active bearings. The rotor is separated from the stator by a thin air gap. Both the rotor and the stator is made of a soft ferromagnetic material, which is finely laminated in order to suppress eddy current within the core. The actuator's coil system is composed of at least two stationary coil pairs (**L_1** and **L_2**, *only y-axis system is shown*) located along stator's diagonals, e.g. along two orthogonal axes, one system along the x-axis and the other along the y-axis. The number and the distribution of the actuator's coil systems should correspond to that of the generator.

Polarity Selective Coils

At the output of two differentially connected full-wave rectifiers **FWR_1** and **FWR_2** either a pulsed DC voltage can be found or no voltage at all. This depends on the rotor position: at the centered position, the DC output voltage will be zero; if the rotor is displaced, say, upwards, a positive voltage may be found; if downward, a negative one.

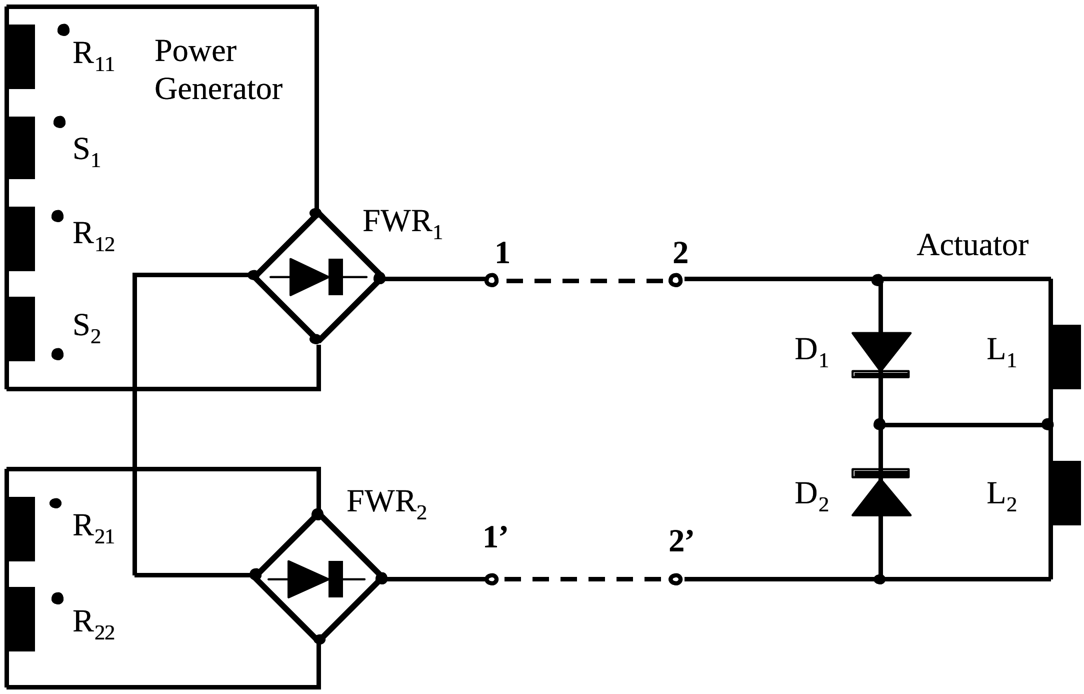

FIGURE. 5: Signal-processing between power generator and actuator

Output voltage of a given polarity will produce a current in that coil, which is then able to create a restoring force counteracting the rotor's primary displacement. The connection of the coils to the pertinent diodes and diode's polarity in the one-axis circuit can be seen from **Fig. 5**. Thus, in order to achieve this; parallel diodes $\mathbf{D_1}$ and $\mathbf{D_2}$ are connected to each coil $\mathbf{L_1}$ and $\mathbf{L_2}$. With such a configuration a proper operation of the bearing can be achieved.

Axial stiffness. In the bearing described above, *there is no axial stabilization present*, when the rotor is exactly in the radially centered position. During radial deviations from the centered position, however, the axial stabilization is achieved , because in this case the restoring forces are effective radially as well as axially.
The axial stabilization has to be attained by other means. The presented radial system may be also conceived for the axial operation using the same principles simply by changing the geometry of the system (e.g. using planar Halbach systems and an axially operating actuator, the rest of the system may remain the same).
Some axial stiffness may be achieved by introducing a ferromagnetic core within the Halbach generator or biasing the actuator with DC currents or permanent magnets. This will cause some additional power losses during the rotation at high speeds, introduce a potential source of radial instability, and thus a reduction of the radial stiffness. That means, the bearing's radial stiffness has to be designed with regard to the required axial stabilizing properties.

Damping. The damping of the described bearing is represented by hysteresis and eddy current losses within the actuator's ferromagnetic core and dissipations within the coils' and diodes' ohmic resistances. As the losses are intentionally devised to remain low, the resulting damping may turn out to be insufficient. Introducing conducting structures in relative motion to homopolar permanent magnets, such as systems of permanent magnet rings and coaxial copper tubes can acquire some additional eddy current damping.
Another possibility to suppress destabilizing effects, such as e.g. transfer whirl modes, is to introduce *anisotropy into the bearing stiffnesses* [4], [5]. This may be done by designing different actuator's air gaps in x and y directions or by different properties of generator's x and y reference/signal coils.

CONCLUSION

This novel passive magnetic bearing can be designed for very wide range of rotational speeds, load capabilities and stiffnesses. Even for small systems the generator's available power may achieve some few tens of kilowatts and this power need to be transferred only over very short distances. The bearing does not comprise active elements.
Actuator's restoring forces, system power losses, etc., can be conceived separately. Attainable force densities can be in the order of 40 N/cm^2 of the air gap area, or even more, depending on saturation properties of the ferromagnetic material. The bearing's stiffnesses can be designed in the range from 10^5 up to 10^7 N/m of the air gap displacement.

It must be taken into account that sensor and actuator operations are not located at the same place. Thus along the axial length of the bearing the rotor has to be considered as rigid.

For a given size of the bearing, the bearing's properties are limited only by saturating capabilities of ferromagnetic material, its hysteresis losses and specific resistivity. Using HF-litz composed of a great number of very fine wires, the generator's eddy current losses may be held extremely low. By choosing coil voltages high enough in comparison with the diodes' forward voltage drop the losses due to the full-wave rectifiers and polarity sensitive coils may be neglected. Powder metal cores with high permeability, providing low reluctance and eddy current suppressing capabilities in all directions, can replace actuator's laminated cores.

The system power losses occur almost exclusively in the stator part and not in the rotor part. This condition is essential for stability.

Using only passive components and providing an intrinsic power supply in connection with a short distance between the source and the load results in an increased reliability of the system.

ACKNOWLEDGEMENT

The preparation of this paper was supported by The Swiss Commission for Technology and Innovation (CTI).

REFERENCES

1. Merritt, B. T. et al., Halbach Array Motor / Generator – A Novel Generalized Electric Machine, LLNL Pub. #22561, Feb. 1995.
2. Merritt, B. T. et al., Halbach Array DC Motor / Generator, US Patent #5,883,499.
3. Pinkerton, J. P., Magnetic Bearing System Including a Generator, US Patent #5,545,848.
4. Post, R. F. et al., Research on Ambient-Temperature Passive Magnetic Bearings at the Lawrence Livermore National Laboratory, LLNL Pub. #901394 & #231803, Apr. 1997.
5. Post, R. F. et al., Ambient-Temperature Passive Magnetic Bearings: Theory and Design Equations, LLNL Pub. #232382, Dec. 1997.
6. Conrad, A., Magnetic bearing Arrangement for a Rotor, US Patent #5,777,414.
7. Post, R. F., A Combination of a Passive Magnetic Bearing Element and Generator / Motor, Patent WO 99/39424.