INVESTIGATION OF PASSIVE MAGNETIC BEARING WITH HALBACH-ARRAY

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Abstract: The paper has describes the complete design and investigation processes of permanent magnetic bearing. The passive magnetic bearing (PMB) rotor suspension rig employing no active control components was calculated, designed, constructed and tested. In order to increase the radial passive magnetic bearing stiffness, the Halbach-array configuration was used. The main purpose of the work was developing the nonlinear model of the PMB. Therefore, the magnetic flux circuit of the PMB was analytically calculated by using the Ohm and Kirchhoff methods. The nonlinear effects of the discrete 3D model of the PMB was analyzed using Finite Element Method (FEM). Finally, the very well matched experimental and analytical static characteristics of the passive magnetic suspension were carried out.

1. INTRODUCTION

The nowadays industrial rotor machines are more flexible and often operating with ultra-high speed. Therefore, the suspension systems must to advanced and high reliable. Another problem is connected with power consumptions, the modern suspensions should be low-power systems.

Active magnetic bearings have many disadvantages connected with complicated control hardware, such as expensive digital processors, amplifiers with limited bandwidth, sensitive sensors, and software. Thus, these systems are itself low reliable and have high energy loss index.

Passive magnetic bearings do not require control and measure hardware and advanced software, thereby they have the potential to increase system efficiency and reliability. Another advantage of PMBs is positive stiffness and self-stability. What more, they can operate with larger rotor-stator gaps since the levitation force for active magnetic bearings is inversely proportional to the square of the rotor-stator gap. The disadvantage of PMBs is lack of stiffness control due to e.g. rotor displacements and lower damping than similar size active magnetic bearings.

The beginning of the development of magnetic bearing combined with the first patent of American scientist Jesse Beams from University of Virginia during the Second World War (Beams, 1964). Passive magnetic levitation receiving one degree of freedom by using permanent magnets was achieved and described by Jansen and Di Russo (1996), Ohji et al. (1999) and Fremerey (2000). The use of superconductors in the art of passive magnetic bearings was described by Hull and Turner (2000) and Hull et al. (1994). Several papers were also published on research of the coefficients of stiffness and damping of passive magnetic bearings. Their creators are Satoh (1996), Ohji (1999) as well as previously mentioned Jansen and Di Russo (1996).

This paper concerns the design, implementation, and research studies of the PMB which consists of the permanent magnets based on the Halbach-array configuration. The main objective of this study was to design and execution of the analytical model, experimental tests and model verification of the passive magnetic bearing based on permanent magnets (Fig. 1). For this purpose the PMB test rig was designed and constructed. The experimental characteristics of the magnetic force due to radial rotor displacement were measured in the passive bearing plane and compared with the analytical one.

1.1. Halbach arrays

Using the passive magnetic bearings in certain applications, we need to take into account the occurrence of radial component in the case of axial bearings and axial component in the case of radial bearings. Journal bearings, in addition to passing load forces of the rotor, rotor weight and damping must take into account the existence and impact of this negative component forces. Therefore, in the design of passive bearings Halbach-arrays are introduced. Halbach-array is a special setup and configuration of permanent magnets, so that you can get the concentration of magnetic flux in a specific, desired items, and remove it from less important or unwanted places (Halbach, 1980).

![Fig. 1. Sample Halbach-array configurations, a) 180° and b) 90°](image1)

![Fig. 2. Cross-section of the PMB with Halbach-array configuration](image2)
Among the Halbach arrays, to guide the magnetic field in the desired way, we can distinguish boards between 180° and 90°. These terms relate to the relationship between the magnetization vectors.

In the construction of the passive radial magnetic bearing 180° Halbach-array was used. This kind of magnetic bearings belongs to the repulsive magnetic bearings. Full configuration of constructed Halbach-array is presented in Fig. 2.

2. DESCRIPTION OF DESIGNED RIG

The examined passive magnetic bearing is composed of four pairs of the Neodymium-iron-boron (NdFeB) magnets rings. These rings are axially magnetized, which means that magnetic poles are placed on the flat circle sides of the magnets (see Fig. 2). The dimensions of the magnets are shown in Tab. 1.

<table>
<thead>
<tr>
<th>Tab. 1. Magnets dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Outer ring</td>
</tr>
<tr>
<td>Inner ring</td>
</tr>
</tbody>
</table>

Magnetic parameters of the magnets are grouped in Tab. 2.

<table>
<thead>
<tr>
<th>Tab. 2. Magnetic parameters of magnets</th>
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<tbody>
<tr>
<td>Parameter</td>
</tr>
<tr>
<td>Material</td>
</tr>
<tr>
<td>Remnant flux density</td>
</tr>
<tr>
<td>Coercivity</td>
</tr>
<tr>
<td>Magnetic energy</td>
</tr>
<tr>
<td>Temp. of work</td>
</tr>
<tr>
<td>Magnetic flux</td>
</tr>
</tbody>
</table>

3. SIMULATION RESULTS

To analyze the magnetic bearings and to estimate their radial force distribution, 3D models of the passive magnetic bearing were built. Simulation calculations were made by using the FEM via Comsol Multiphysics ver. 3.5a software. The magnetostatic module of Comsol environment was used to analyze the magnetic field distribution of the passive magnetic bearings with Halbach-array.

3.1. FEM magnets model definition

Analysis of the magnetic field of magnetic bearing is a magnetostatic problem with no current. This problem we can solve using a scalar magnetic potential. In regions with no current, where:

\[
\nabla \times H = 0
\]

where: \(H\) – magnetic field, \(\nabla\) – nabla operator.

We can define the scalar magnetic potential \(V_m\), from the following relation:

\[
H = -\nabla V_m
\]

It is analogous to the definition of the electric potential for static electric field.

Using the major relation between the magnetic flux density and magnetic field, which is described by:

\[
B = \mu_0 (H + M)
\]

where: \(B\) – magnetic flux density, \(M\) – magnetization vector.

Together with equation:

\[
\nabla \times B = 0
\]

We can simply derive an equation for \(V_m\).
\[-\nabla (\mu V + \mu_0 M_0) = 0 \quad \text{(5)}\]

Equation (3) supplemented by the following expressions:
- first Maxwell equation for current-less area:
  \[\mu_0 \text{rot} H = 0 \quad \text{(6)}\]
- or first Maxwell equation for conducive area:
  \[\text{rot} H = J \quad \text{(7)}\]

where: \( J \) – current density,
- magnetic field source-less condition:
  \[\text{div} B = 0 \quad \text{(8)}\]

These equations are true for stationary magnetic field of the permanent magnet in an environment of soft ferromagnetic. In order to design model of magnetic field of passive magnetic bearing, the above conditions should be applied. The analytical model of magnetic phenomena will be developed by using Comsol Multiphysics, and 3D discrete model of the PMB will be presented.

### 3.2. Boundary conditions

Along the boundaries far away from the two pairs of magnets (Fig. 5), the magnetic field should be tangential to the boundary as the flow lines should form closed-loops around the modeled magnets. The natural boundary condition is expressed by:

\[n (\mu_0 \nabla V - \mu_0 M_0) = n B = 0 \quad \text{(9)}\]

where: \( n \) – boundary normal pointing out from the inner magnet rings.

![Fig. 5. Finite element model - magnets geometry](image)

Therefore the magnetic field is made tangential to the boundary by a Von Neumann condition on the magnetic potential. Along the symmetry boundary below the magnet, the magnetic field should be tangential, and thus we can apply the same Von Neumann condition there.

Against, the magnetic field should be normal to the symmetry boundary, which is located at the front of the magnet rings cross-plane (see Fig. 5). Thus, the magnetic flow lines have formed of the closed-loops rings around the magnet.

This means that the magnetic field is symmetric with respect to the boundary. This can be achieved by setting the potential to zero along the boundary, and thus making the potential anti-symmetric with respect to the boundary.

### 3.3. Subdomain settings

The Fig. 5 shows all highlighted subdomains in magnetic bearing finite element model. These are: magnets of stator, magnets of rotor, outer sleeve, inner sleeve and ambient air. In order to get the detailed finite element model of the PMB, the proper parameters need to be find in the right domain of the geometric model.

Selected following settings and parameters of the highlighted domains in the magnetic bearing model are presented in Tab. 3.

### 3.4. FEM calculations

Next, the PMB mesh model is developed. Setting the relevant parameters the mesh model is extremely important to correctly estimate all properties of the magnetic bearings and determine the maximum radial force of the bearing. Mesh was concentrated in the most important places of the magnetic bearing model, which are air gaps between pairs of stator and rotor magnets. As the most optimal mesh element tetrahedron was used. The maximum size of the mesh element was defined as 5-7% of the smallest dimension of the geometric domain. Maximum element size scaling factor was chosen as 0.5. Mesh curvature factor was set as 0.25. In the magnetic bearing air gaps, inner and outer sleeves, the gap element was used. Gap element is the special kind of mesh element. It is particularly important whenever a big impact on the field distribution have air gaps in model. Gap element reduces the growth of algebraic matrix equations in the calculations. To reduce the size of the field surrounding the magnet rings model, the infinite element was used, which improves the results of calculations by a few percent and reduced the number of elements in finite element model.

The magnetostatic solver was used to calculate the radial force and predict the distribution of magnetic field in the PMB with Halbach-array. The 3D magnetic bearing mesh model is illustrated in Fig. 6. The model have 1282681 elements. To compute magnetic forces and torques in the AC/DC Comsol Module, four methods are available. The most general method is to use the Maxwell Stress tensor described below. Force and torque calculations using Maxwell’s stress tensor are available in the application modes for electrostatics, magnetostatics, and quasi-statics. In case of the magnetostatics and quasi-statics the Maxwell Stress tensor
is given by:

\[ n_1 T_2 = -\frac{1}{2} n_1 (H \cdot B + n_1 \cdot H)B^T \]  

(10)

where: \( n_1 \) – outward normal from the object.

The Maxwell stress tensor was integrated over the inner magnets surface.

Fig. 6. 3D mesh model of passive magnetic bearing

![3D mesh model of passive magnetic bearing](image)

Fig. 7. Magnetic flux density in cross section of magnetic bearing

![Magnetic flux density in cross section of magnetic bearing](image)

Fig. 8. Displacement stiffness characteristic of the PMB

![Displacement stiffness characteristic of the PMB](image)

Three-dimensional model of magnetic bearings was used to compute the magnetic potential, magnetic flux density and magnetic energy in the air gap.

In Fig. 7 we could observed places in air gap where the field reaches the highest values and where it falls significantly. This is caused by build Halbach-array. The gaps in magnetic field observe in Fig. 7 are typical for this kind of Halbach-arrays.

Depending on the movement of the rotor in the magnetic bearing plane, the air gap is changed, and therefore the repulsive force of the magnets changed too. For the different positions of the rotor in the bearing plane, the power calculations were made based on a reduced finite element model of the PMB. The results obtained are summarized and presented in the form of static characteristics (Fig. 8).

4. EXPERIMENTAL TESTS

The experimental study have allowed to verify the finite element model of the PMB and to analyze the design and assessment of its fairness and accuracy of design assumptions bench. The lab test rig is presented in Fig. 9. The lab stand consists of rotor with electrical drive and elastic clutch, the rotor is supported by one ball bearing and passive magnetic bearing located at the end of the rotor. In order to measure the magnetic radial force, the tensometer force sensor was assembled. The radial displacement of the rotor was measured in two directions \( x-y \) by using inductive sensors.

The total weight of the rotor is 1.07 kg, and total length of 0.4 m. The nominal radial air gap is equal to 0.001 m. The actual physical model has become a reference for early design and simulation tests.

![Test rig](image)

Fig. 9. Test rig

Fig. 10. Measured and calculated PMB stiffness

![Measured and calculated PMB stiffness](image)

The first stage of the experimental tests were static stiffness measurements with no rotating rotor. As a result, the values of the magnetic repulsive forces in the radial direction due to change of the air gap were determined. Depending on the rotor load, measured by electronic scales, the value of its shipments and dial indicator has been observed using inductive sensor.
Next, the measured radial magnetic bearing force due to rotor displacements in the range of the air gap was compared with the FEM calculations (see Fig. 10).

Fig. 10 shows the rotor displacement as a function of radial load for the experimental data and finite element model. The slopes (stiffness) of these curves match quite well and equals $1.28 \times 10^5$ N/m. The finite element model of the PMB is sufficiently consistent with the laboratory model. Thus, the finite element method, with appropriate choice of parameters, a careful analysis and accurate modeling, may be used with quite good results in the design of passive bearings and to assess the pre-load magnetic bearing.

The axial stiffness of the passive magnetic bearing is more stronger than in radial direction and is not presented in this paper.

5. SUMMARY

A completely passive magnetic bearing rig was designed, constructed, and tested in this work. The experimental and simulation results are well matched, thus the finite element methods can be used to accurately design the size and number of the magnets for the radial support of the bearings.

The implementation of the passive magnetic bearing requires a careful analysis of the magnetic field generated by permanent magnets and assesses their material aspects. Obtained and desired distribution of magnetic field strength determines the values of the bearings, radial and axial component. The introduction of the Halbach-arrays allows the adequate orientation of the magnetic field in the placenta, and to reduce the negative impact of the active component forces. The use of Halbach-arrays and a thorough assessment and analysis of magnetic bearings, allow to develop and to implement the high performance passive magnetic bearings. Submission of the magnets in different directions of polarisation is a very difficult task and unfortunately expensive too, thus always some assumption should be taken into account.

REFERENCES

2. Beams J. (1964), Magnetic Bearings, Paper 810A, Automotive Engineering Conference, Detroit, Michigan, USA, SAE.