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FEMLAB SOFTWARE APPLIED TO ACTIVE MAGNETIC BEARING ANALYSIS

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This paper presents how the FEMLab package can be used to perform the magnetic field analysis in the Active Magnetic Bearing (AMB). The AMB is an integral part of the industrial rotational machine laboratory model. The electromagnetic field distribution and density analysis allow verifying the designed AMB and the influence of the shaft and coil current changes on the bearing parameters.

Keywords: electromagnetic field, active magnetic bearing, finite element method

1. Introduction

In recent years a number of rotary machines with Active Magnetic Bearings have been designed in order to eliminate the lubricant medium, vibration and noise, and to achieve high velocities and loads. These systems are complicated due to the construction of mechanical, electrical and electronic circuits. A wide range analysis is required during the design procedure – from the construction stage up to the development of a control algorithm architecture. The finite-element method can be a tool for magnetic field analysis. Many scientists working on magnetic bearings or self bearing motors use this method at the design stage. The numerical analysis allows us to check if the new AMB structure is effective with respect to levitation forces, magnetic field properties and electro-mechanical interactions (Maslen, 1999). The hetero-polar LWG-type Active Magnetic Bearing was analyzed in (Gosiewski and Falkowski, 2003), with the discussion of magnetic field properties at the desired current level and numerical aspects. The finite-element method was also used to analyze the air gap flux and radial forces in miniature self bearing motors (Kanebako and Okada, 2002; Ohmori *et al.*, 2002). In small-sized systems, essential modeling errors are often caused by leakage and nonlinear effects that could be neglected in larger systems.

1.1. FEMLab Software

FEMLab (2002) is an interactive environment for modelling and solving scientific and engineering problems involving partial differential equations. The underlying mathematical structure with which FEMLab operates is a system of partial differential equations and it is possible to set up models as stationary or time dependent, linear or nonlinear, scalar or multicomponent. The package also performs eigenfrequency and eigenmode analyses.

The FEMLab user interface integrates seamlessly with MATLAB, the package that provides the computational engine behind FEMLab. As a matter of fact, FEMLab frequently uses MATLAB's syntax and data structures.

It is possible to save and export FEMLab models as MATLAB programs that run directly in that environment or combine them with other products in the MATLAB family. For example, it is possible to create a finite-element model in FEMLab and then export it to Simulink or to the Control System Toolbox, where the model becomes an integral part of the simulation of a dynamic system.

When solving PDEs that describe a model, FEMLab applies the finite-element method. FEMLab runs that method in conjunction with adaptive meshing and error control, as well as a variety of numerical solvers.

This paper is focused on a two-dimensional magnetostatic analysis of the AMB. In the 2D mode, the shapes (subdomains) are partitioned into triangles. The sides of the triangles are called mesh edges, and their corners are mesh vertices. A mesh edge must not contain mesh vertices in its interior. Similarly, the boundaries defined in the geometry are partitioned (approximately) into mesh edges, the so-called boundary elements, which have to conform to the triangles if there is an adjacent subdomain. For a defined mesh, a set of approximations to the dependent variables is introduced. A function approximating a variable is defined by a finite number of parameters (called the degrees of freedom, DOFs). This approximation is used in a weak form of an equation and a set of DOF system equations is given.

1.2. Physics

Magnetostatic problems are problems in which the fields are time invariant. To solve such a problem in the static case, Maxwell's equations (Rothwell and Claud, 2001)are presented in the following form:

$$\nabla \times H = J,$$

$$\nabla \cdot B = 0,$$

and the relationship

$$B = \mu_0 \mu_r (H + M) = \mu (H + M)$$

is used, where B is the magnetic flux density, H is the magnetic field intensity, J is the current density, M is the magnetization vector, μ is the material permeability, μ_0 is the permeability of vacuum, and μ_r is the relative permeability of the material.

Since the magnetic flux density is divergence free, there exists a magnetic vector potential A such that $B = \nabla \times A$, which gives the potential formulation

$$\nabla \times \left(\frac{1}{\mu} \nabla \times A - M \right) = J.$$

2. Active Magnetic Bearing

The main goal of the AMB is to produce desired electromagnetic forces to levitate the ferromagnetic rotor (shaft) located in the bearing. The electromagnetic force generated by the electromagnet is the gradient of the magnetic field energy and depends on the air gap size

$$F = -\frac{\partial W}{\partial a}, \quad W = \frac{1}{2} \int BH \, \mathrm{d}V,$$

where F is the electromagnetic force, W is the magnetic field energy, and V is the air gap volume.

The electromagnetic force is a nonlinear function of the coil current and the distance between the shaft and the electromagnet. The control algorithm produces an electromagnetic force acting on the shaft using the power interface and electromagnet coil. The control system is an integrated part of the AMB. The control algorithm can stabilize the rotor at the bearing centre with a programmable or an automatically adjustable stiffness change, actively damp vibrations coming from the rotating shaft and a change in the shaft position in the bearing area.

A simplified, two-dimensional model of the AMB is considered, where the effects associated with the stator and shaft lengths are omitted. The AMB geometry and effects coming from the shaft movement are under consideration.
Four areas can be considered in the analyzed example (cf. Fig. 1):

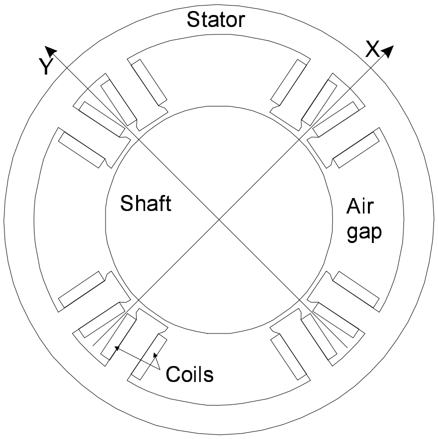

Fig. 1. Active Magnetic Bearing elements.

- Two ferromagnetic elements: the stator and the shaft. The stator core is built up of thin laminated electrical steel plates for the purpose of reducing eddy current effects and characterized by a nonlinear function of the relative permeability. The shaft is made of an iron block.
- Air gap that fulfils the area between the stator, the rotor, the coils and the shaft. The air gap is assumed as a paramagnetic region.
- The coils made of copper wire wound up on the stator pole shoe. The magnetizing current is required to set up a given magnetic flux in the iron circuit. The number of turns and the current level determine the flux intensity and the electromagnetic force, respectively. The coil and pole shoe together make an electromagnet called the solenoid actuator.

The AMB construction considered has the following parameters:

Parameter	Value
Number of pole pairs	4
Nominal radial air gap	0.8 [mm]
Rotor outer radius	42.2 [mm]
Coil turns	200
Nominal current	2.0 [A]
Area of pole	256,0 [mm^2]

2.1. Magnetic Field Analysis of the Bearing

First of all, the discrete form of the bearing shape has to be created. The geometry is partitioned into small units represented in 2D as triangles (Fig. 2). The mesh is a starting point for the finite-element method (Hammound and Sykulski, 1994). The generated mesh is dense (triangles are smaller) in the critical areas of the active magnetic

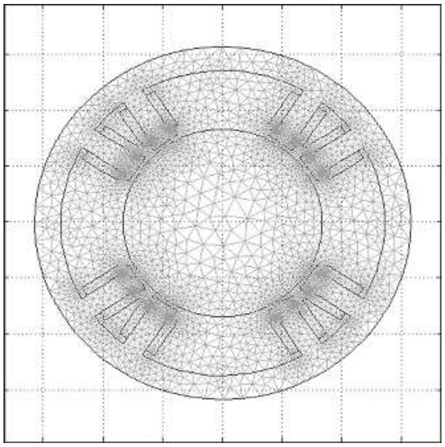

Fig. 2. Discrete form of the AMB area – triangular mesh.

bearing: the air gap between the stator and the rotor and at the contact of the coil and pole shoe.

For the desired coil parameters (the number of turns, current value and coil intersection surface) it is possible to calculate the current density J. To obtain realistic results of calculations, the nonlinear function of electrical steel magnetization obtained from the manufacturer will be used in the sequel. The performed analysis of the magnetic flux flow through the magnetic core shows that the areas with the highest flux density are concentrated at contacts of the coils and pole shoes. Especially, the sharp edges of the surface create a high flux concentration. Such places are exposed to magnetic core saturation (Fig. 3).

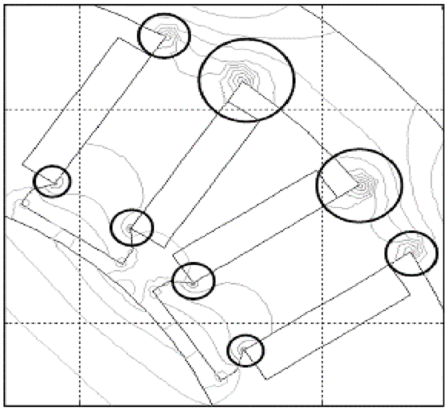

Fig. 3. Flux density in the pole shoes and critical areas.

Changes made in the stator construction (the replacement of sharp edges with smooth ones) result in the elimination of flux concentration (Fig. 4). The highest density of the magnetic flux is located in the stator pole shoes and the flux direction flow is determined by the coil current direction (Fig. 5).

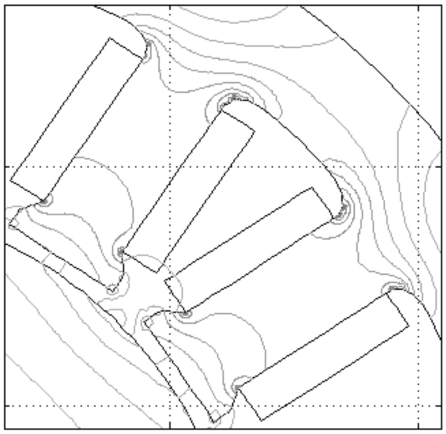

Fig. 4. Elimination of magnetic core saturation in the stator.

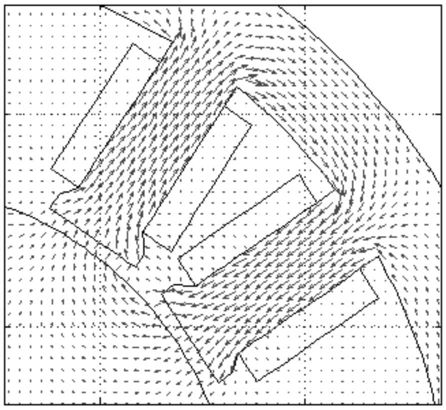

Fig. 5. Density and direction of the magnetic flux.

Figure 6 presents the potential of the magnetic field calculated for the AMB. All coils are powered by the current at the same level, and thus the polarization depends on the coil construction only. A negative polarization exists inside electromagnets and is positive outside them.

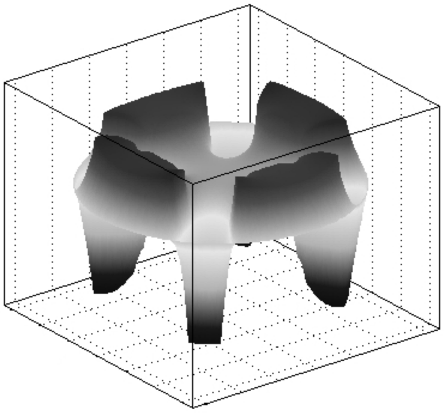

Fig. 6. Potential of the magnetic field calculated for the active magnetic bearing.

2.2. Rotor Influence on the Magnetic Field

The research that follows is focused on the shaft movement influence on the magnetic field in the AMB. Figure 7 presents the potential of the magnetic field while the rotor is located at the bearing centre. Two shaft movements are analyzed:

- in the direction of the X axis – axially, according to the upper and lower electromagnet axis (Fig. 1),
- in the vertical direction – vertically, according to the bearing centre.

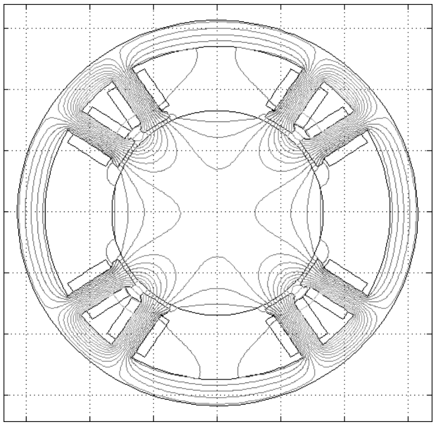

Fig. 7. Potential of the magnetic field for the rotor located at the bearing centre.

In the case of an axial movement, the air gap width changes under the pole shoes in the axis considered. In the other axis, the air gap change is very small and almost linear due to the circular shaft shape and the air gap size with respect to the shaft diameter.

When wider pole shoes are used (in the configuration where one electromagnet occupies a quarter of the stator), changes in the air gap shape size are much larger and more nonlinear. The calculation results show that when the shaft movement is about 68% of the nominal bearing air gap, the magnetic flux change strongly depends on the distance between the shaft and the pole shoe. Thus, when the air gap decreases the magnetic flux increases, and vice versa (Fig. 8).

Another calculation for the vertical shaft movement of about 68% of the nominal bearing gap size, which gives the 42% air gap change under pole shoes, shows that there exist cross couplings between the pole shoes and energy can be exchanged between them. This exchange is much weaker for thinner pole shoes than for wider ones, because of the electromagnet surface and the distances between pole shoes. On the other hand, less iron is used in the case of small pole shoes than in that of wider ones (Fig. 9).

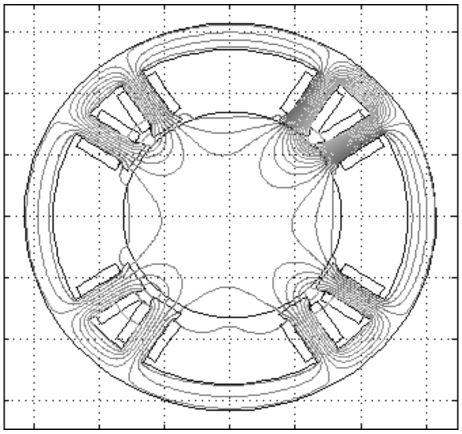

Fig. 8. Magnetic flux change during the axial shaft movement.

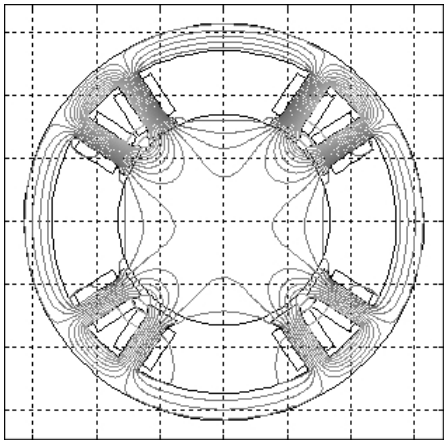

Fig. 9. Magnetic flux change during the vertical shaft movement.

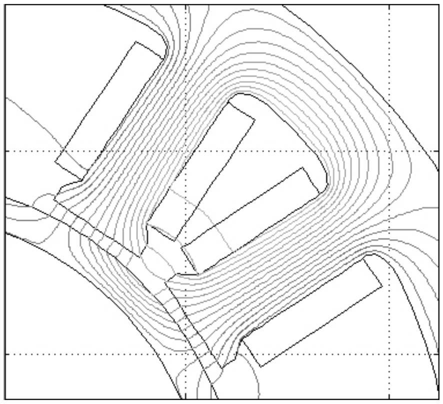

Fig. 10. Magnetic flux change during the vertical shaft movement.

Finally, a construction change was made in the rotor. The solid rotor was replaced by a steel-tube with the thickness of 5 mm (Fig. 10). To obtain the same parameters of the AMB operating mode, the nominal coil current should be reduced to 87 mA. This may have consequences in the construction of the coil current actuator unit.

The appropriate AMB construction is thus a trade-off between many requirements and should be specific for different applications. The development stage of a machine equipped with the AMB demands the co-operation of many experts in mechanics, materials science, electronics and control. The proper machine construction, an optimal AMB structure and a dedicated control algorithm allow us to achieve a modern industrial unit.

3. Conclusions

Calculations based on the finite element method give a deeper insight into the phenomena observed in Active Magnetic Bearings. The performed analysis plays an important role in the design procedures of AMB and helps to verify the construction assumptions. It is essential to use appropriate materials for the shaft and the stator. The pole shoes arrangement, their sizes and coil parameters strongly influence the electromagnetic force value produced by the electromagnet.

The available force range is one of the most important parameters of the active magnetic bearing and strongly affects the bearing stiffness. The character of the produced electromagnetic force has to be taken into account during controller design because of the energy consumption.

The design procedure of the AMB is a complex task consisting of a few elements: an analysis of the AMB operating mode parameters, the calculation of the electromagnetic force, the selection of materials and the calculation of magnetic field properties to obtain the desired force value, and the choice of a controller architecture. Thus the magnetic field analysis plays an important role in the AMB development process.

Future research will be focused on 3D modelling and field analysis to validate the assumptions made for 2D modelling. Structure optimization will be studied in static and dynamic cases in order to examine the AMB behaviour in a real operation environment. Another research direction will be concerned with the magnetic field analysis when the current changes are simulated as real reactions to perturbations coming from shaft movements.

The application of the FEMLab package gives a possibility to establish a connection with Simulink, with data imported and exported as mat and m files. This is very useful when the pole analysis is connected with control algorithm design. The computational effort strongly depends on the mesh density. The possibility to import DXF files allows the user to import shapes designed in other CAD applications. The user must check the mesh quality and size after the termination of the import procedure from the file to the FEMLab environment because of the defined accuracy and different DXF formats. Sometimes it is necessary to modify the shape manually to eliminate superfluous mesh densities.

Acknowledgements

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