FORCE CALCULATION OF THE LABORATORY IMPLEMENTATION OF A RADIAL ACTIVE MAGNETIC BEARING

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***Abstract** – Performances of the controlled active magnetic bearings, can be sufficiently improved with the exact knowledge of the bearing force in the entire operating range. Therefore the magnetic force calculation of the laboratory implementation of a radial magnetic bearing, using 2D finite element method is presented in the paper. Two methods for the force calculation are used, where both, i.e. the Maxwell's stress tensor method and the virtual work method, give very close results. The verification of the bearing force calculation is performed through the comparison with measurements. Obtained results make it possible to perform a robust control design in the entire operating range.*

Introduction

Active magnetic bearings are technical applications of stable rotor levitation based on controlled electro–magnetic circuits [1]. Two electromagnets on the opposite sides of the ferromagnetic rotor pull the rotor in the opposite direction. As such a system is unstable, a rotor position control is required to stabilize it. Due to their non-contact operation, active magnetic bearings offer significant advantages. Higher speed, no friction, no lubrication, precise position control and active vibration damping make them particularly appropriate for high–speed rotating machines. The mentioned performances can be sufficiently improved with the exact knowledge of the bearing force in the entire operating range. If we want to consider also relevant and possible uncertainties, we have to perform the finite element method (FEM) for the force calculation [2].

In this work, the magnetic force calculation of the laboratory implementation of a radial magnetic bearing is presented. The bearing force is a non-linear function of the currents and the rotor position, therefore the differential driving mode is performed. Furthermore, the FEM procedure for the force determination is described using a non-commercial programming environment described in [3]. The bearing force is determined by using the Maxwell's stress tensor method and the virtual work method. There is no essential difference between results obtained by both methods. Also the data fitting of the air gap is considered in the force calculation. The described procedure for the bearing force calculation is verified by measurements, which gives very good agreement between calculated and measured force. Obtained results determine the bearing force in the entire operating range and make it possible to perform a robust control design which will be applied in the next step of development.

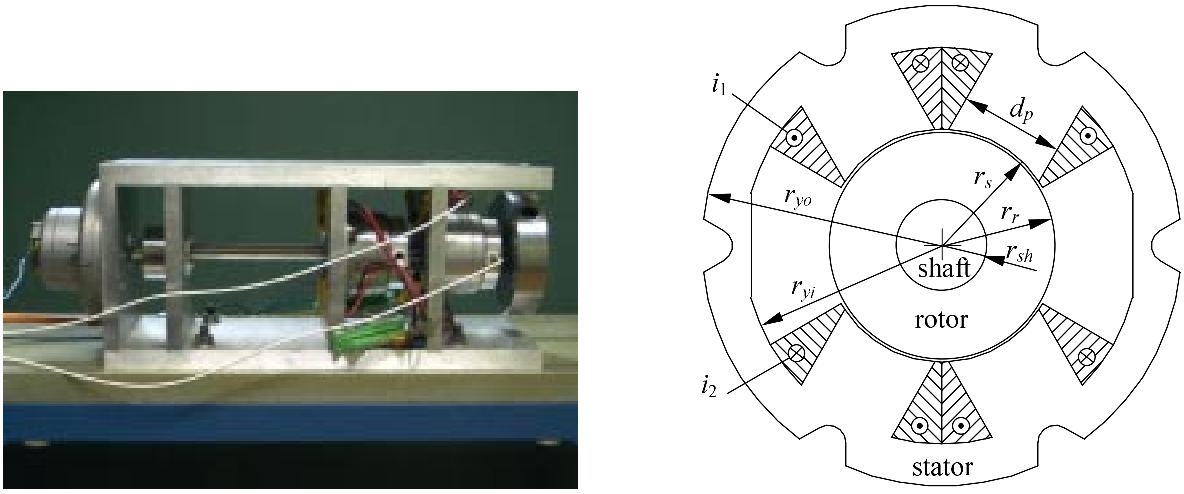
Laboratory Implementation of Active Magnetic Bearings

The discussed system of active magnetic bearings is presented in Fig. 1a). It is highly simplified, consisting of a pair of radial magnetic bearings placed at one end of the shaft and a ball bearing placed at the other end. Each of the magnetic bearing is used to stabilize the shaft movement only in one direction. The rotor and the four–pole stator are made out of laminated steel, while windings are connected and supplied in such a way that they can be considered as two "horse–shoe" electromagnets. The geometry and data are presented in Fig. 1b) and in Table 1.

In the mathematical modeling of the radial magnetic bearing the rotation of the rotor and the non-linear iron properties are neglected, while windings of all electromagnets are assumed to be ideal and identical. In equation (1) the non-linear dependence of the resultant electromagnetic force F on the currents of both electromagnets i_1 and i_2 and the rotor position y is expressed. δ denotes the nominal air gap, k represents the material and geometrical properties. With the introduction of the differential driving mode (2), a bias current i_0 is operating the winding of both electromagnets. Force control is performed by superposing a control current i_Δ to the winding of one electromagnet and subtracting it in the winding of other one, where $i_\Delta \leq i_0$. In spite of constant losses due to the bias current the chosen driving mode is justified, since the force–current dependence becomes linear for small rotor displacements. If we want to consider the influence of non-linear iron properties, local saturation and magnetic flux leakage, we have to use FEM-based numerical calculations.

$$F(i_1, i_2, y) = k\left(\frac{i_1^2}{(\delta - y)^2} - \frac{i_2^2}{(\delta + y)^2}\right) \tag{1}$$

$$i_1 := i_0 + i_\Delta; \qquad i_1 := i_0 - i_\Delta \tag{2}$$



a) b)

Fig. 1. a) Laboratory implementation of active magnetic bearings, b) geometry of the radial magnetic bearing.

Table 1. Data of the radial magnetic bearing

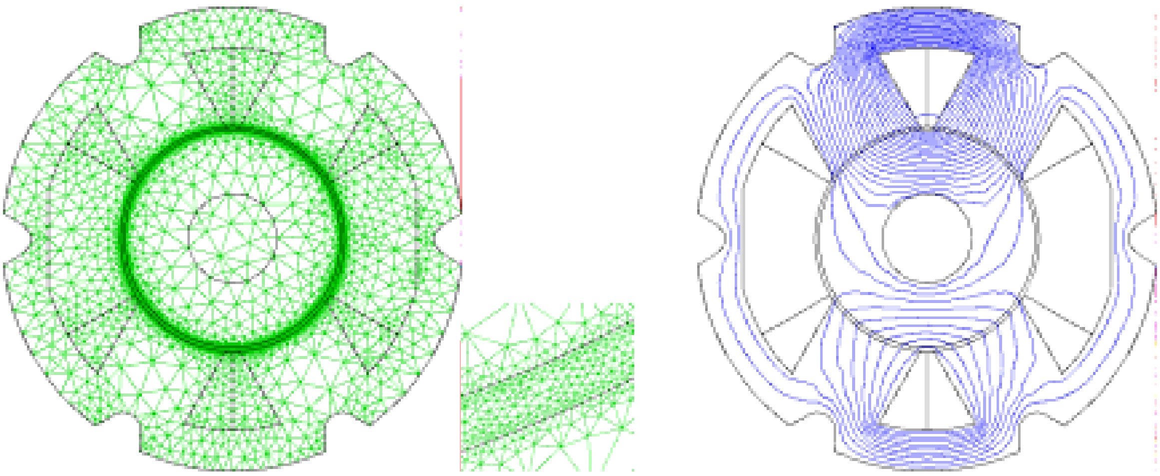
data	parameter	value
shaft radius	r_{sh} [mm]	8.00
rotor radius	r_r [mm]	19.25
stator radius	r_s [mm]	19.85
yoke inner radius	r_{yi} [mm]	33.80
yoke outer radius	r_{yo} [mm]	41.00
pole width	d_p [mm]	17.80
bearing length	l [mm]	30.70
angle between two poles	2α [rad]	$\pi/3$
number of turns per pole	$N/2$	50
bias current	i_0 [A]	2.5

Force Calculation

In this section the procedure for calculating the force of the radial magnetic bearing is presented. The FEM-based calculation is implemented in the programming environment, which is described in [3]. The calculation for the chosen points (i_Δ, y) is carried out in four steps.

- **Step 1:** Task definition. The bearing geometry, the material, the current densities, and the boundary conditions are parametrically defined.
- **Step 2:** The initial discretization of the model is performed. An *a priori* error estimator is used, where the largest allowed element edge is explicitly defined in the air gap region. In this way very fine discretization of the region is achieved avoiding *a posteriori* mesh adaptation, which reduces the calculation time by 40%. In Figs. 2a,b), the bearing mesh and the air gap mesh are shown.
- **Step 3:** The non-linear solution of the magnetic vector potential A is obtained by means of 2D calculation based on the FEM. The problem is formulated by Poisson's equation (3), where ν represents the magnetic reluctance, J is the applied current density, and ∇ is Hamilton's differential operator. The solution, i.e. the magnetic field distribution is presented in Fig. 2c).

$$\nabla \cdot (\nu \nabla A) = -J \qquad (3)$$



a) b) c)

Fig. 2. a) Mesh of the whole bearing, b) mesh of the air gap, c) magnetic field distribution (i_Δ=1A, y=0.1mm).

- **Step 4:** The radial bearing force is determined by two methods. First by the Maxwell's stress tensor method, following equation (4). B_y and B_x are normal and tangential flux densities in the air gap, μ_0 is the permeability of vacuum, and l is the axial bearing length. The integration is performed over the contour C placed in the middle of the air gap. The force is calculated also by the virtual work method, described by equation (5), where ΔW_{co} is the co-energy difference, and y is the rotor position.

$$F = \frac{l}{2\mu_0} \oint_C \left(B_y^2 - B_x^2\right) ds \qquad (4)$$

$$F = \frac{\partial W_{co}}{\partial y} \approx \frac{\Delta W_{co}}{\Delta y} \qquad (5)$$

Results

Due to the manufactured rotor steel sheets the magnetic active air gap is bigger than the geometric air gap. Therefore, data fitting was considered in the force calculation. In our case the air gap was increased from 0.6mm to 0.663mm. In the FEM procedure the rotor radius was varied until the calculation agreed with the measured value for the typical case ($i_\Delta = 1$A, $y = 0$mm). Since results of the calculation in all other points of the operating range agreed with measurements (Fig 3a), this approach can be accepted. The increase in the air gap for 0.063mm can be compared with the findings of authors in [2]. Results of the FEM-based bearing force calculation are presented in Fig. 3b). The bearing force was determined by using the Maxwell's stress tensor method and the virtual work method. The relative difference between results obtained by both methods was below 0.5% in the entire operating range. This result is expected due to the fine discretization of the integration region, when using the Maxwell's stress tensor. Therefore it is better to use the Maxwell's stress tensor method for the magnetic bearing force calculation, because it takes less calculation time.

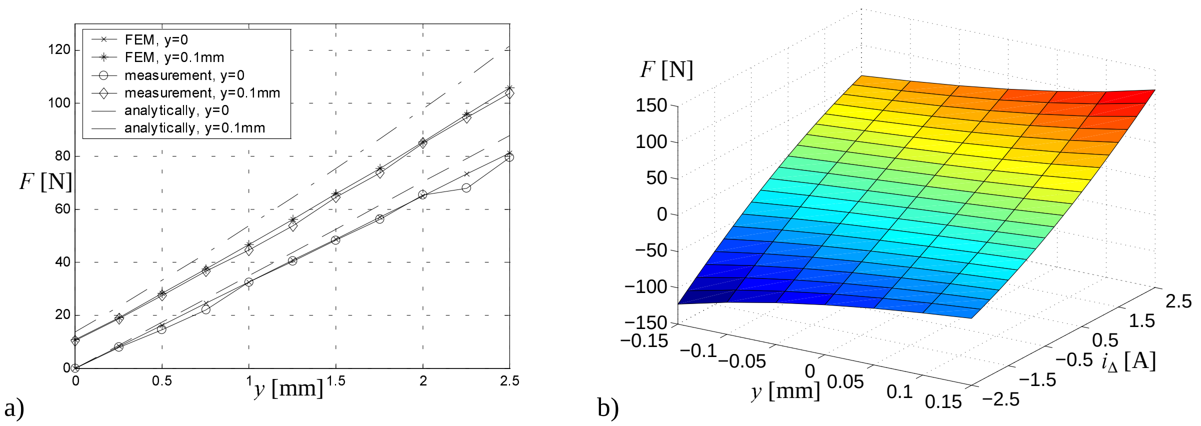


Fig. 3. a) Data fitting of the FEM-based force calculation, b) results of the FEM-based force calculation $F(i_\Delta, y)$.

Conclusion

An analysis of the laboratory implementation of the radial magnetic bearing is presented in the paper. The bearing force is determined by FEM-based calculations using the Maxwell's stress tensor method and the virtual work method. Since results of both methods practically do not differ, it is better to use the Maxwell's stress tensor method. To update the model uncertainties the data fitting is performed. The verification of the force calculation is performed by measurements. Obtained results determine the bearing force in the entire operating range including only relevant and possible model uncertainties. This makes it possible to perform a robust control design in the entire operating range.

References

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