Impact of Magnetic Nonlinearities and Cross Coupling Effects on Properties of Radial Active Magnetic Bearings

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***Abstract*— The current and position dependent flux linkages and forces of radial active magnetic bearings are determined by the finite element method. The results obtained are incorporated into the dynamic model of active magnetic bearings in order to evaluate the influence of magnetic nonlinearities and cross coupling effects on their dynamic and static properties. The presented results show that the magnetic nonlinearities and cross coupling effects can change the electro motive forces considerably. These cross coupling effects are calculated and can be implemented in the control design as additional compensations.**

INTRODUCTION

Active Magnetic Bearings (AMB's) are a system of controlled electromagnets which enable contact-less suspension of a rotor [1]. The electromagnets of the discussed AMB's [2] are placed on the common iron core, which means that their behavior is magnetically nonlinear. Moreover, the individual electromagnets are magnetically coupled.

For the control design of the AMB's the linearized dynamic models are commonly used, where magnetic nonlinearities and cross coupling effects are not considered [1]. The nonlinearities can be taken into account, for example by the nonlinear force characteristics and dynamic inductances [3]. The influence of the disturbing cross coupling effects is neglected in the majority of the dynamic AMB models, which are available in the literature, although the efficient cross coupling compensation is important to get better closed-loop dynamic behavior of the device.

In this paper, the impact of the magnetic nonlinearities as well as cross coupling effects on the properties of AMB's is evaluated. The characteristics of flux linkages and radial forces are determined by using the Finite Element (FE) method and verified by measurements in the entire operating range of the bearing. The determined characteristics are incorporated in the dynamic AMB model. The obtained dynamic model is used to evaluate the impact of magnetic nonlinearities and cross coupling effects on the properties of AMB's. The proposed dynamic model is appropriate for the nonlinear control design.

FINITE ELEMENT COMPUTATION

The geometry and the magnetic field distribution of the studied AMB's is shown in Fig. 1, while the AMB circuit model is shown in Fig. 3.

The magneto-static computation was performed by 2D FE method using (1), where **A** denotes the magnetic vector potential, ν is the magnetic reluctivity, and **J** is the current density.

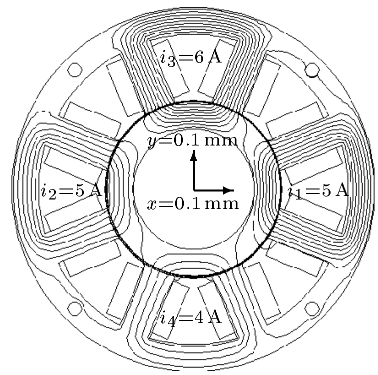

Fig. 1. The AMB geometry and magnetic field distribution.

$$\nabla \cdot (\nu \nabla \mathbf{A}) = -\mathbf{J} \tag{1}$$

The flux linkages ψ_1, ψ_2, ψ_3 and ψ_4 were calculated in the entire operating range from average values of the magnetic vector potential in the stator coils for different control currents $i_{x\Delta}$ and $i_{y\Delta}$, and for different rotor displacements in the x- and in y-axis. The radial forces F_x and F_y were calculated by Maxwell's stress tensor method.

DYNAMIC AMB MODEL

The dynamic AMB model is according to the circuit model presented in Fig. 3 given by (2) and (3):

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \\ u_4 \end{bmatrix} = R \begin{bmatrix} I_0 + i_{x\Delta} \\ I_0 - i_{x\Delta} \\ I_0 + i_{y\Delta} \\ I_0 - i_{y\Delta} \end{bmatrix} + 2 \begin{bmatrix} \frac{\partial \psi_1}{\partial i_{x\Delta}} & \frac{\partial \psi_1}{\partial i_{y\Delta}} \\ \frac{\partial \psi_2}{\partial i_{x\Delta}} & \frac{\partial \psi_2}{\partial i_{y\Delta}} \\ \frac{\partial \psi_3}{\partial i_{x\Delta}} & \frac{\partial \psi_3}{\partial i_{y\Delta}} \\ \frac{\partial \psi_4}{\partial i_{x\Delta}} & \frac{\partial \psi_4}{\partial i_{y\Delta}} \end{bmatrix} \begin{bmatrix} \frac{di_{x\Delta}}{dt} \\ \frac{di_{y\Delta}}{dt} \end{bmatrix} + \begin{bmatrix} \frac{\partial \psi_1}{\partial x} & \frac{\partial \psi_1}{\partial y} \\ \frac{\partial \psi_2}{\partial x} & \frac{\partial \psi_2}{\partial y} \\ \frac{\partial \psi_3}{\partial x} & \frac{\partial \psi_3}{\partial y} \\ \frac{\partial \psi_4}{\partial x} & \frac{\partial \psi_4}{\partial y} \end{bmatrix} \begin{bmatrix} \frac{dx}{dt} \\ \frac{dy}{dt} \end{bmatrix} \tag{2}$$

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = m \begin{bmatrix} \frac{d^2x}{dt^2} \\ \frac{d^2y}{dt^2} \end{bmatrix} \tag{3}$$

where u_1, u_2, u_3 and u_4 are the supply voltages, I_0 is the bias current, $i_{x\Delta}$ and $i_{y\Delta}$ are the control currents in the x- and in y-axis. R stands for the coil resistances. F_x and F_y are the radial forces in the x- and in y-axis, respectively. The characteristics $\psi_1(i_{x\Delta}, i_{y\Delta}, x, y)$, $\psi_2(i_{x\Delta}, i_{y\Delta}, x, y)$, $\psi_3(i_{x\Delta}, i_{y\Delta}, x, y)$

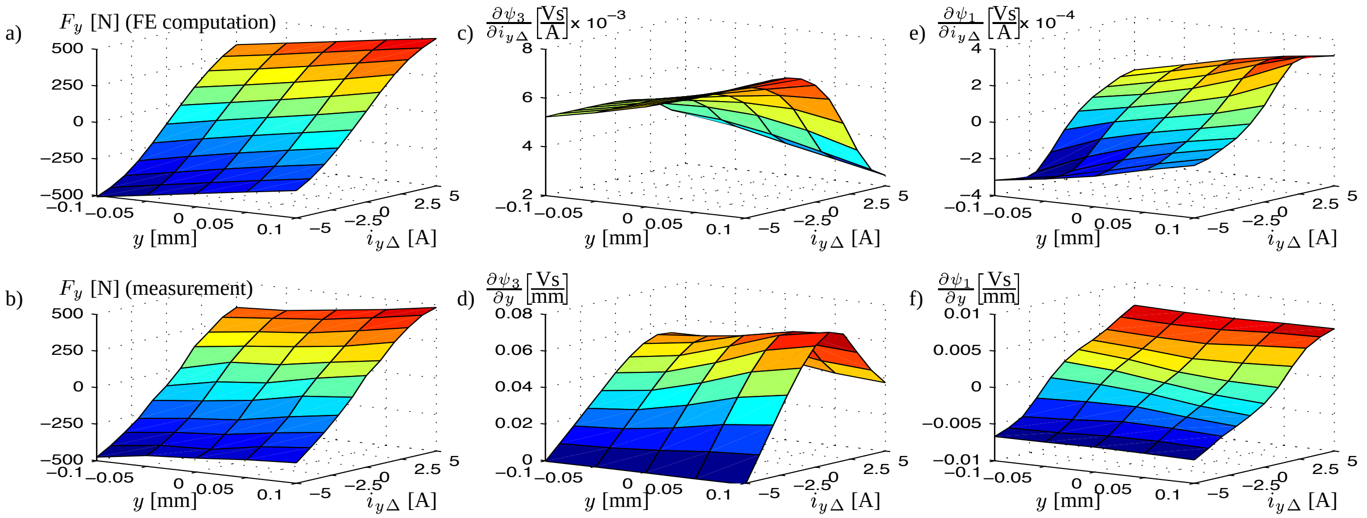

Fig. 2. Results ($x = 0$ mm, $i_{x\Delta} = 0$ A and $I_0 = 5$ A): a) computed force $F_y(i_{y\Delta}, y)$, b) measured force $F_y(i_{y\Delta}, y)$, c) partial derivative $\frac{\partial\psi_3}{\partial i_{y\Delta}}(i_{y\Delta}, y)$, d) partial derivative $\frac{\partial\psi_3}{\partial y}(i_{y\Delta}, y)$, e) partial derivative $\frac{\partial\psi_1}{\partial i_{y\Delta}}(i_{y\Delta}, y)$, f) partial derivative $\frac{\partial\psi_1}{\partial y}(i_{y\Delta}, y)$

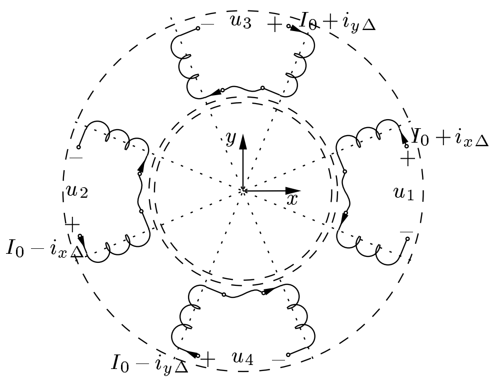

Fig. 3. The circuit AMB model.

and $\psi_4(i_{x\Delta}, i_{y\Delta}, x, y)$, as well as $F_x(i_{x\Delta}, i_{y\Delta}, x, y)$ and $F_y(i_{x\Delta}, i_{y\Delta}, x, y)$ were determined by FE computations. The current and position dependent partial derivatives of flux linkages required in (2) have been determined numerically. Therefore, the magnetic nonlinearities and cross coupling effects are incorporated into the dynamic AMB model (2), (3) by the current and position dependent flux linkages and forces.

In standard AMB models the terms like $\frac{\partial\psi_3}{\partial i_{y\Delta}}$ and $\frac{\partial\psi_3}{\partial y}$ are constant, the terms like $\frac{\partial\psi_1}{\partial i_{y\Delta}}$ and $\frac{\partial\psi_1}{\partial y}$ are neglected, while the forces are given by the linearized functions. Therefore, the dynamic model proposed in this paper is much more consistent in comparison with the standard AMB models.

Results

A good agreement between the computed and measured forces can be seen in Fig. 2a) and Fig. 2b). The partial derivatives $\frac{\partial\psi_3}{\partial i_{y\Delta}}$, $\frac{\partial\psi_3}{\partial y}$, $\frac{\partial\psi_1}{\partial i_{y\Delta}}$ and $\frac{\partial\psi_1}{\partial y}$ are shown in Fig. 2c) – Fig. 2f). The flux linkages were determined by the FE method, while the partial derivatives were calculated numerically. The presented results are given for the case when the control current $i_{x\Delta}$ and the rotor position in the x-axis are equal to zero.

From the computed results shown in Fig. 2c) – Fig. 2f) can be seen that the current and position dependent partial derivatives of flux linkages are different from zero. As a consequence, the electro motive forces (emf's) can vary in a range up to 16 % when compared to those, obtained by the standard AMB models.

Conclusion

The impact of magnetic nonlinearities and cross coupling effects on the properties of radial AMB's is studied in the paper. It has been shown that the results of the FE computations can be used to improve the standard AMB models. In this way, the magnetic nonlinearities and cross coupling effects are considered in the proposed dynamic model, which is appropriate for the evaluation of static and dynamic behavior of the AMB's. The presented results show that the influence of magnetic nonlinearities and cross coupling effects is not negligible. In the case of the discussed AMB's, the emf's can vary due to the magnetic nonlinearities and cross coupling effects in the range up to 16 % in comparison with those data obtained by the standard models. These effects have to be considered in the nonlinear control design as cross coupling compensations. Therefore, the closed-loop dynamics can be improved in the best possible way.

References

[1] G. Schweitzer, H. Bleuler and A. Traxler, *Active magnetic bearings*. ETH Zürich: Vdf Hochschulverlag AG an der ETH Zürich, 1994.

[2] G. Štumberger, D. Dolinar, U. Pahner and K. Hameyer, "Optimization of radial active magnetic bearings using the finite element technique and the differential evolution algorithm," *IEEE Transaction on Magnetics*, vol. 36, no. 4, pp. 1009–1013, 2000.

[3] M. Antila, E. Lantto and A. Arkkio, "Determination of forces and linearized parameters of radial active magnetic bearings by finite element technique," *IEEE Transaction on Magnetics*, vol. 34, no. 3, pp. 684–694,1998.