ARCHIVES OF ELECTRICAL ENGINEERING VOL. 62(2), pp. 209-215 (2013)

DOI 10.2478/aee-2013-0016

The influence of the stator geometry on magnetic bearing parameters

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(Received: 17.06.2012, revised: 15.01.2013)

Abstract: This paper presents an analysis of the stator teeth geometry impact on the parameters of the 8-pole radial magnetic bearing. In this paper, such parameters as current gain and position stiffness have been analysed. Additionally, we have proposed criteria for evaluating the characteristics of these parameters by calculating the variability of current gain and position stiffness. The research has been performed by solving the magnetic bearing actuator boundary problem using the finite element method. Magnetic force has been calculated using the Maxwell stress tensor method. Other parameters, such as current gain and position stiffness have been calculated as partial derivate of the force with respect to control current and position of the rotor.

Key words: parameters of active magnetic bearing, the FEM method

1. Introduction

Active magnetic bearing is a special type of an electrical actuator which provides a contactless operation of rotating machines. It generates forces through a magnetic field which are induced by currents excited in the stator windings. An active magnetic bearing is a typical mechatronic system, because the mechanical components are combined with electronic elements such as a displacement sensor, a power amplifier and controllers.

The concept of magnetic bearings has been known for a long time. However, development of power electronic components and microprocessor-based control methods rendered it possible to take advantage of these bearings. Special advantages of magnetic bearings are the lack of lubrication and absence of contaminating wear. Moreover, the rotor can be rotated at high speed and its vibrations are not transmitted to the stator of a machine. Additionally, an electronic control system allows precise controlling of the rotor position and provides a relatively simple process of the machine diagnostics, even on-line. Due to many advantages, active magnetic bearings have found use in many industrial applications, such as energy storage flywheels, blood pumps, machine tools, turbo machinery etc. [1].

In the paper [2], authors have proved, that the magnetic nonlinearities and cross-coupling effect have significant impact on properties of a radial magnetic bearing. Similar conclusions have been reached by the authors of the paper [3]. Therefore, these researchers have pointed out that magnetic circuit of magnetic bearing should be optimized. In the paper [4], authors presented variations of active magnetic bearing linearized parameters and also they described a method of optimize magnetic bearing in order to obtain the smallest variation of these parameters. During optimization process, it has been changed stator yoke width, rotor yoke width and width of the poles. However, in our article we have presented the stator teeth geometry impact on the parameters of the radial magnetic bearing.

2. Parameters of the magnetic bearing and its finite element model

The most important parameters of the magnetic bearing are magnetic force F, current gain k_i and position stiffness k_s. Magnetic force is a nonlinear function of the stator current and rotor displacement, as follows [1, 5]

$$F(i,s)=\frac{1}{4}\mu_0 N^2 A_a \frac{i^2}{s^2}, \tag{1}$$

where μ_0 is a permeability of vacuum, N is the number of the coil turns, A_a is cross-section of stator pole, i is the current value in the winding, s is displacement of the rotor. Current gain k_i is obtained as the magnetic force F derivative with respect to control current i_c

$$k_i(i_s,s)=\frac{\partial F}{\partial i_c}, \tag{2}$$

while position stiffness k_s is calculated as the magnetic force F derivative with respect to the rotor displacement s

$$k_s(i_s,s)=\frac{\partial F}{\partial s}. \tag{3}$$

Since the magnetic force is nonlinear, the parameters k_i and k_s considerably vary according to the operation point. The variability of the parameter is evaluated by the differences between the nominal value and value in every point of parameter's characteristic. Equations (4) and (5) determine current gain variability Δk_i and position stiffness variability Δk_s, as follows

$$\Delta k_i=\sum_{i_s}\sum_{s}\left(\frac{\left|k_i(i_s,s)-k_{i,\ nom}\right|}{k_{i,\ nom}}\right)\cdot 100, \tag{4}$$

$$\Delta k_s=\sum_{i_s}\sum_{s}\left(\frac{\left|k_s(i_s,s)-k_{s,\ nom}\right|}{k_{s,\ nom}}\right)\cdot 100. \tag{5}$$

where $k_{i,nom}$ and $k_{s,nom}$ are the nominal parameter value, obtained for $i_c = 0$ A and $s = 0$ mm.

Parameters k_i and k_s can be calculated analytically [1]. However, calculations obtained in this method contain significant errors. It is due to omitting of the nonlinear B-H characteristic of the magnetic material and imprecise modeling of the magnetic circuit. More accurate results are obtained by using the finite element method (FEM) to determine the magnetic field distribution in AMB geometry [2]. A field model of the radial AMB has been analyzed in FEMM 4.2 software [6]. Figure 1. presents a finite element model and important parts of the magnetic bearing. On the edges of the calculation area Dirichlet boundary condition has been assumed for the magnetic vector potential *A*. We assumed the *B-H* characteristics of steel M270-50 A for the rotor and stator (Fig. 2).

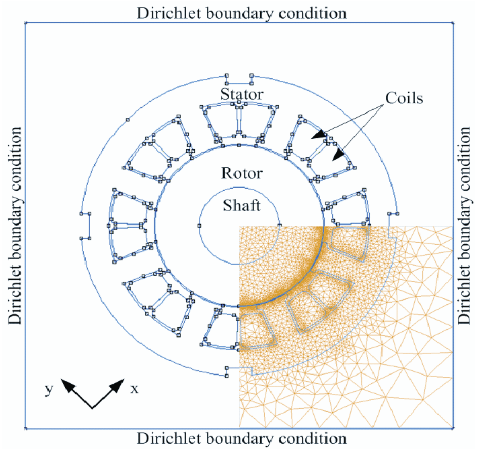

Fig. 1. Field model of the 8-pole active magnetic bearing

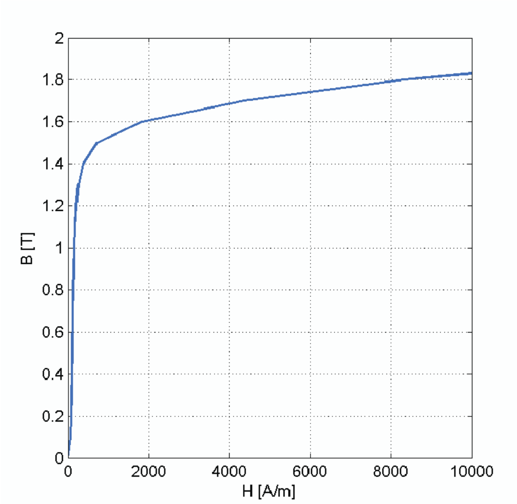

Fig. 2. *B-H* characteristics of the magnetic material of stator and rotor (M-270-50 A)

Accuracy of the obtained result is determined by a mesh density in every analyzed region [7, 8]. Therefore, we have made a series of numerical experiments focused on choosing a fine mesh. Special attention has been paid to the mesh density in the air gap, because a magnetic force is computed by the Maxwell stress tensor method. T is Maxwell's stress tensor and can be calculated from expression (6), where $\vec{\Gamma}$ is the integration surface,

$$\vec{F} = \oint_{\Gamma} T \cdot d\vec{\Gamma}. \tag{6}$$

In Table 1 selected parameters of the 8-pole radial magnetic bearing are presented. Figure 3 presents the cross section part of the magnetic bearing with geometrical parameters of the analyzed area.

Table 1. Parameters of the 8-pole radial magnetic bearing actuator

Description	Value
Rotor inner radius r_{r1}	9.50 mm
Rotor outer radius r_{r2}	19.75 mm
Stator inner radius r_{s1}	20.00 mm
Stator outer radius r_{s2}	37.00 mm
Arc width of pole teeth β_1	15°
Stator and rotor stack width	45 mm
Bias current I_b	3 A

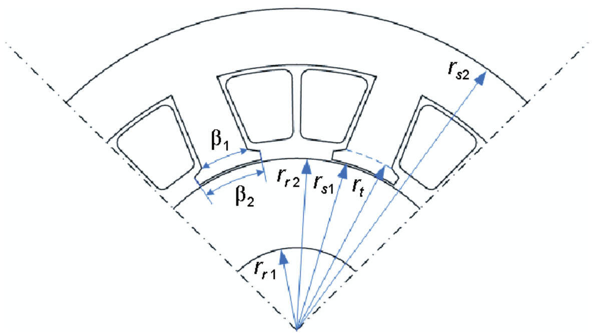

Fig. 3. Dimensions of the magnetic bearing actuator

Figures 4 and 5 present characteristics of current gain and position stiffness vs. the control current values and position of the rotor, for the pole arc width with the angle of 16°. In the case of our numerical model a high variability of the position stiffness characteristic is visible and it is reflected for the Δk_s coefficient that is equal to 51%.

Figures 6 and 7 present position stiffness and current gain in function of arc β_2. These figures show that the arc width of pole teeth has significant impact on the values of the discussed parameters. Also, it can be seen that position stiffness and current gain have peaks. Maximum value of the magnetic bearing position stiffness that is for the angle $\beta_2 = 36°$, whereas the current gain reaches maximum value for the angle $\beta_2 = 34°$.

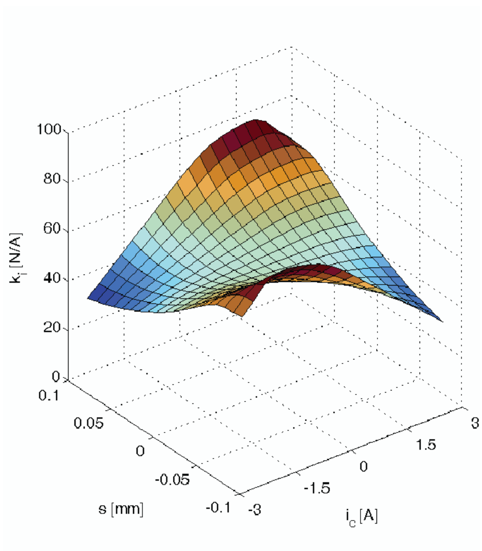

Fig. 4. Current gain value vs. the control current i_c and position of the rotor s for angle $\beta_2 = 16°$

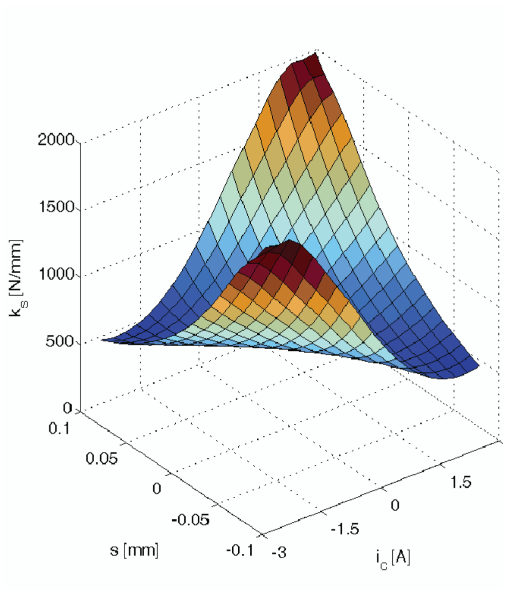

Fig. 5. Position stiffness value vs. the control current i_c and position of the rotor s for angle $\beta_2 = 16°$

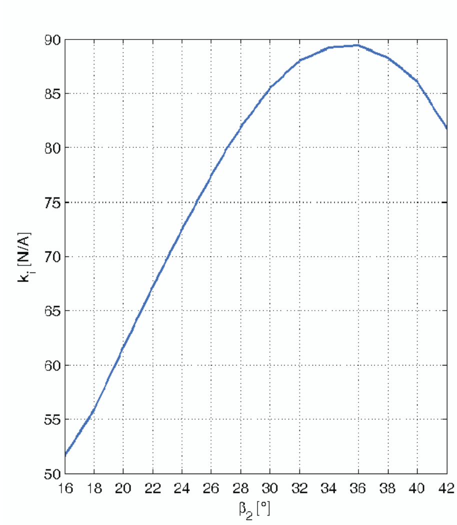

Fig. 6. Nominal current gain vs. the β_2 angle

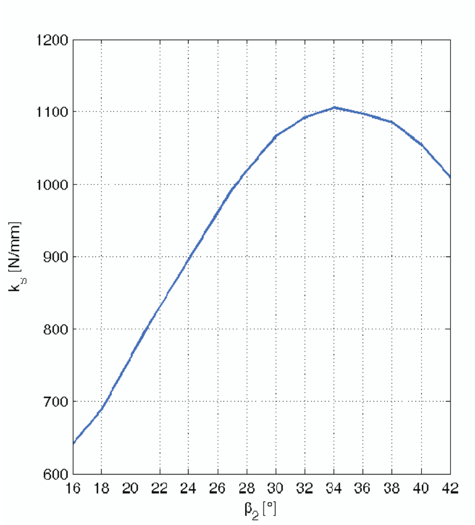

Fig. 7. Nominal position stiffness vs. the β_2 angle

Because the magnetic bearing actuator is a part of a mechatronic system, it should be characterized by the smallest variability of its parameters in the operating range. Figure 8 shows that the smallest variability of position stiffness is for $\beta_2 = 27°$. For the angle, the variability of the current gain equals to 20°. It achieves minimum value for β_2 = 20°. Thus, it can be assumed that the optimal arc width of pole tooth, with the angle β_2, occurs at the point where the both curves intersect (Fig. 8). It is for the angle β_2 = 25°. For such a shape of stator teeth the current gain k_i is equal to 75 N/A, whereas the position stiffness k_s is equal to 926.9 N/mm.

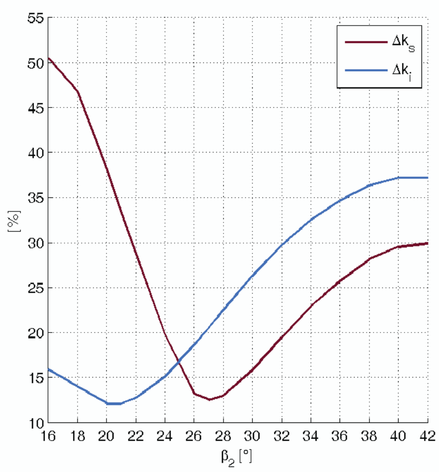

Fig. 8. The current gain and position stiffness variability vs. arc β_2

Figures 9 and 10 present characteristics of current gain and position stiffness for the arc with the angle β_2 = 25°.

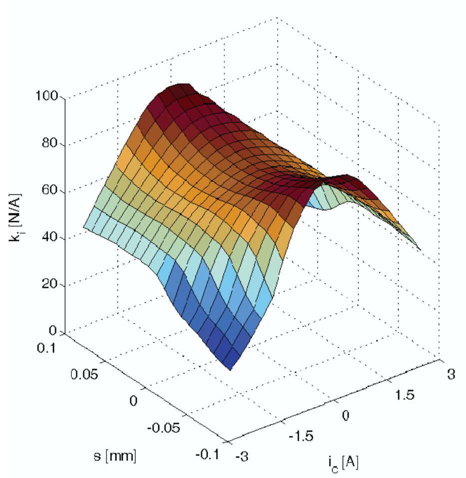

Fig. 9. Current gain vs. control current i_c and position of the rotor s, for β_2 = 25°

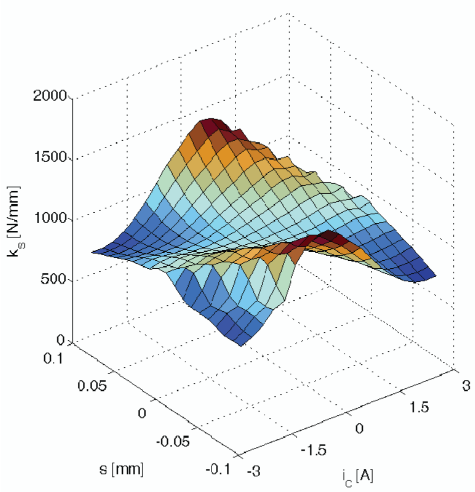

Fig. 10. Position stiffness vs. the control current i_c and position of the rotor s, for β_2 = 25°

3. Conclusions

The main aim of the paper was the determination of the optimal arc width for the pole teeth in the radial magnetic bearing. For this purpose, we have performed a finite element model that allows calculating the AMB parameters for each geometry of the stator. In order to obtain the optimal arc width of the pole teeth, we proposed coefficients describing the variability of the current gain Δk_i and position stiffness Δk_s. Minimum values of these parameters provide the optimal arc width of the pole teeth. Based on the multi-variant calculations for the stator geometry, we obtained the minimal variability of the current gain and position stiffness for the arc width where the pole teeth angle is equal to 25°. The proposed approach of the AMB stator designing is most beneficial for the control system with a linear controller, because a magnetic bearing actuator developed in this technique provides a minimum non-linearity of current gain and position stiffness in its operating range.

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