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Simulation for the determination of the hybrid magnetic bearing's electromagnetic parameters

***Abstract**. Three dimensional field modelling and the simulation results for a hybrid magnetic bearing are presented in the paper. The magnetic field distributions and the values of electromagnetic parameters in the function of the current intensity and the rotor position are given. The aim of the investigation was the determination of the magnetic bearing stiffness through the calculations of the magnetic force acting on the bearing rotor and the flux linkages with the windings. The simulations are important to the actuator designing and determination of its controlling parameters for proper operation of an electric drive system.*

Streszczenie.** W artykule przedstawiono trójwymiarowe modelowanie pola oraz wyniki symulacji dla hybrydowego łożyska magnetycznego. W pracy podano rozkłady pola magnetycznego oraz wartości parametrów elektromagnetycznych w funkcji prądu i położenia wirnika. Celem badań było określenie sztywności łożyska magnetycznego poprzez obliczenia siły magnetycznej działającej na wirnik łożyska oraz strumienia skojarzonego z uzwojeniami. Symulacje są istotne w procesie projektowania siłownika oraz przy określeniu parametrów sterowania dla właściwej pracy elektrycznego systemu napędowego. **Trójwymiarowe modelowanie pola oraz wyniki symulacji dla hybrydowego łożyska magnetycznego

Keywords: hybrid magnetic bearing, permanent magnet, 3D field analysis, electromagnetic parameters, bearing stiffness.
Słowa kluczowe: hybrydowe łożysko magnetyczne, magnes trwały, 3D analiza pola, parametry elektromagnetyczne, sztywność łożyska.

Introduction

The important features of magnetic bearings, which differ them from other types of bearings are: contactless operation, lack of lubrications, operation in harsh environment and very low losses. These properties contribute to usage of magnetic bearings in many devices such as: flywheel energy storages, electrospindles, blowers, blood pumps and wind generators [1-2].

The principle of the active magnetic bearing operation is very similar to an electromagnet action, because the magnetic force arises due to magnetic flux in air gap of the ferromagnetic circuit. Magnetic bearings are inherently unstable devices, so that a position of the bearing rotor must be controlled. For this purpose the magnetic flux is divided into two components: the control flux and bias one.

The bias flux establishes the so called point of operation for the magnetic circuit. It can be generated by an additional winding with constant current [3] or by additional constant current exceeded in the control winding [4]. Unfortunately, these methods cause significant power losses in windings and power electronics.

An alternative method of magnetic flux generation are permanent magnets. However, the electrical machines should be developed including the thermal field [5]. The permanent magnets work with electromagnets. They are incorporated in the hybrid magnetic bearings (HMBs). In the HMB actuator the permanent magnets generate the bias flux, while the windings provide the control flux to stabilize position of the rotor.

Due to the permanents magnets installation, the mechanical construction of the magnetic circuit is more complicated in comparison to an active magnetic bearing. Currently, there is a few constructions of the HMB actuators described in the research papers [6-8]. In these constructions, the magnetic circuit of the stator or rotor is intentionally divided to enable insertion of the permanent magnets. Such an approach can cause imprecise manufacturing of the actuator and impairs the symmetry of the generated magnetic force.

In this paper, we have analysed the construction of HMB actuator with the magnets which are placed in the closed off slots. The grooves were previously cut in the sheets of the stator poles. This approach allows an easy process of manufacturing and a relatively precision assembling of the stator. The parameters of the HMB actuator have been calculated based on simulation model employing 3D finite element method (FEM).

Description of the hybrid construction of the magnetic bearing

The outline of proposed construction of the HMB is depicted in Fig.1. The magnetic bearing actuator consists of a stator and rotor. The stator has three poles with permanent magnets and three poles with windings. This structure creates the six-pole magnetic bearing.

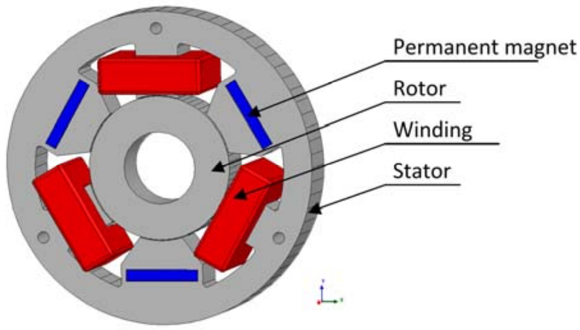

Fig.1. Construction of the HMB actuator

The stator and rotor have been stacked from sheets of non-oriented steel M530-50A in order to significantly reduce the eddy current effects. The thickness of the electrical steel sheets is 0.5mm and the saturation value of the flux density equals to 1.83T. In the HMB actuator, three permanent magnets N38 have been mounted. The energy density of them equals to 298.3 kJ/m^3 and they are magnetized along the shortest edge of them.

The main dimensions of the HMB actuator are presented in Tab. 1.

Table 1. Main dimensions of the HMB actuator

Parameter	Value [mm]
Stator outer radius r_{s1}	43,0
Stator inner radius r_{s2}	20,0
Stator length l	25,0
Rotor outer radius r_{r1}	19,7
Rotor inner radius r_{r2}	10,0
Pole width w_{th1}	12,0
Pole width w_{th2}	23,0
Permanent magnet width l_{m1}	20,0
Permanent magnet height l_{m2}	3,0

Similarly to the system of the permanent magnets, the electromagnets have created the three-pole arrangement. Each electromagnet winding has 100 turns, and the air gaps in the magnetic circuit have the length of 0.3 mm. Fig. 2. presents the paths of the magnetic flux created by the permanent magnets and windings of electromagnets.

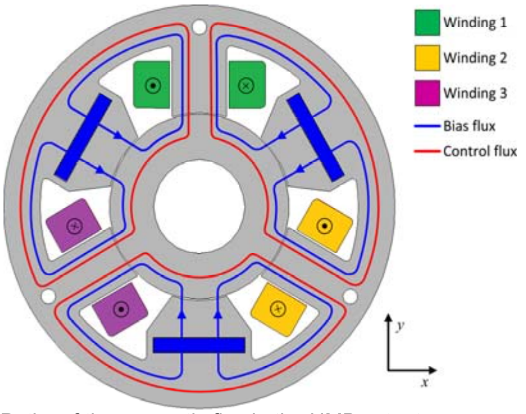

Fig.2. Paths of the magnetic flux in the HMB actuator

Three poles with permanent magnets are generating the bias fluxes, which determine the so-called operation point of the magnetic circuit. The flux of each pole splits into two components and each of them is crossing the stator and rotor and returns through the adjacent pole of the electromagnet. For the central position of the rotor, the value of magnetic field density in the air gap is even and the magnetic force generated by the HMB actuator is equal to nil.

Three wounded poles can generate the control fluxes, which flow along the wounded poles as well as the stator yoke and within the rotor. This is because of low permeability of permanent magnets, which caused high magnetic reluctance of the magnets in comparison with the wounded poles. The magnetic field density in the air gap of permanent magnet poles is almost constant during the actuator operation and the fluxes of these poles nearly do not participate in the control process.

The magnetic flux in the air gap of wounded poles is adjustable by currents i_1, i_2, i_3, as the resultant magnetic field is the sum of the bias flux and the control flux generated by the currents. The presented HMB actuator can be controlled in two different ways: In the first way, each electromagnet is controlled independently by its own regulator. The aim of the controller is to stabilize the rotor surface in the distance from this pole of the electromagnet. The distance should be equal to the assumed air gap length. The rotor position can be measured by three proximity sensors or can be calculated using signals from two proximity sensors [10]. In the second way - the position of the actuator's rotor is controlled in two geometrical axes: x and y. The rotor position is provided from two proximity sensors. For this purpose, we have to introduce two control currents i_x and i_y, respectively. The control currents are determined using two controllers. The currents of electromagnets are calculated from the values of the control currents i_x, i_y according to the formulas:

$$\textbf{(1)} \quad i_1 = i_y, \qquad i_2 = -\frac{1}{2} i_y + \frac{\sqrt{3}}{2} i_x, \qquad i_3 = -\frac{1}{2} i_y - \frac{\sqrt{3}}{2} i_x$$

The second way of the control has a significant advantage over the first one because for the windings connected with the star, the HMB actuator can be powered using three-phase inverter, which is commonly used for induction motors.

Simulation results

In the presented construction of HMB, the length of the end-winding almost equals to the length of the segment in the stator slot. Such a shape of the winding exerts a 3-dimensional mathematical model for the magnetic field analysis. It is due to the relatively significant leakage flux from the ends of the windings.

Due to lamination of the stator and rotor bodies, the eddy currents can be neglected in the magnetic circuit. Thus, we were able to carry out the magnetic field analysis, with using the nonlinear B-H characteristic of the material, for the magnetostatic field determination. Demagnetization of the permanent magnets is small and difficult to evaluation. That is why we haven't taken into account this phenomenon in the modelling.

In order to reduce the calculation area, only half volume of the symmetrical HMB has been discretized and incorporated in the simulation procedure. This simplification has reduced the number of tetrahedral elements to 310 thousand. External surfaces of the simulation model have been fixed 40mm from the actuator body. At the external surfaces of the calculation volume, Dirichlet's boundary conditions have been assumed, while at the symmetry surface Neumann's boundary condition has been applied.
For such geometry the calculation time of the magnetic field analysis lasted ca. 1.5 hour. The calculation model has been prepared in Maxwell 3D software of Ansys package [9].

Fig. 3 presents the magnetic field distribution inside the HMB magnetic circuit, for the rotor fixed in the central position in the case of the currents lack. The magnetic field distribution is uniform in whole cross section of the HMB actuator and the magnetic flux density of each pole is equal to 0.81 T.

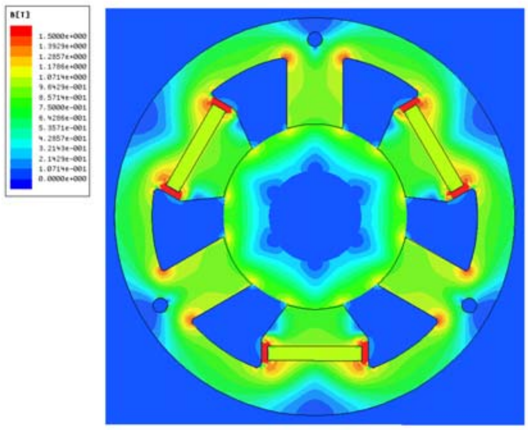

Fig.3. Magnetic flux density distribution in the HMB under central position of the rotor currents $I_1 = I_2 = I_3 = 0A$

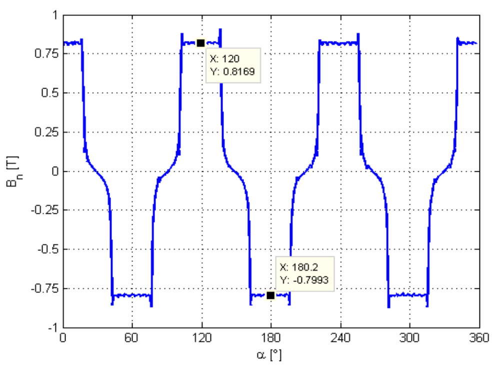

Fig.4. Normal component (to the stator surface) of flux density, in the air gap, for the central position of the rotor and currents. $I_1 = I_2 = I_3 = 0A$

Fig. 4. shows the chart of the normal component of the magnetic flux density in the air gap. The values have been calculated in distance of 0.1mm from the stator's poles. The magnetic flux density in the air gap of wounded poles is slightly higher (0.81T) than in the air gap of the magnet poles (0.79T).

Fig. 5 presents the zoom of the magnetic flux in the pole of permanent magnet. It is noticeable, that the small areas of the pole are saturated. This is due to the fact that the magnetic flux produced by permanent magnet avoids the rotor and flows back through the pole. This is the leakage flux, which can't be eliminated in presented construction of the HMB actuator. The leakage flux amounts to 50% of the whole magnetic flux produced by permanent magnet. Despite of the significant leakage flux, the permanent magnets fulfil their task very well. The permanent magnets are protected against the demagnetization from the control flux. It is due to high magnetic reluctance of the permanent magnet and partially saturation of the magnetic circuit.

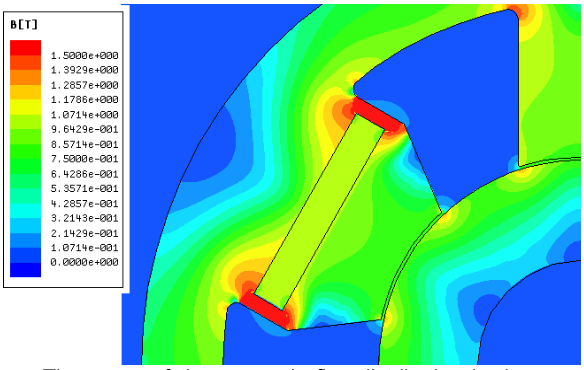

Fig. 5. The zoom of the magnetic flux distribution in the area of permanent magnet pole

Fig. 6 shows the magnetic flux distribution in the HMB actuator for the current value of I_1 = 2A and for the central position of the rotor. The magnetic flux density of the first wounded pole has increased to 1.41T, while the magnetic flux density in other wounded poles has decreased slightly.

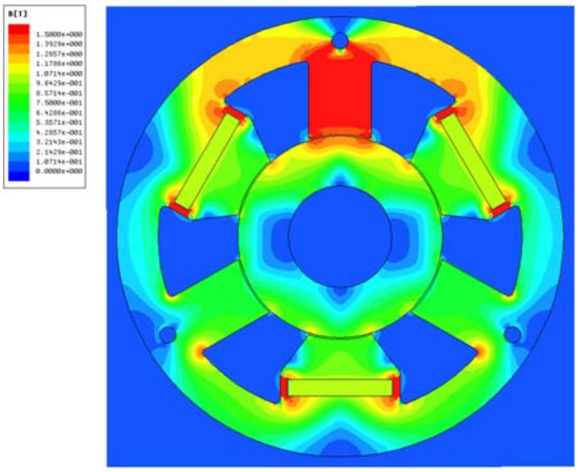

Fig.6. Flux density distribution in the HMB for central position of the rotor and currents I_1 = 2A, I_2 = I_3 = 0A

The chart of the normal component (to the stator surface) of the flux density in the air gap is presented in Fig. 7. The magnetic flux density in the air gap of the first wounded pole has increased from 0.81T to 1.34T, while the magnetic flux density in the gap of the other wounded poles have decreased to 0.62T. The magnetic flux density in the air gap of the permanent magnets' poles marginally increased to 0.82T (from 0.79T). The difference in magnetic flux distribution causes the generation of the magnetic force which equals to 191N, and is directed towards the first electromagnet.

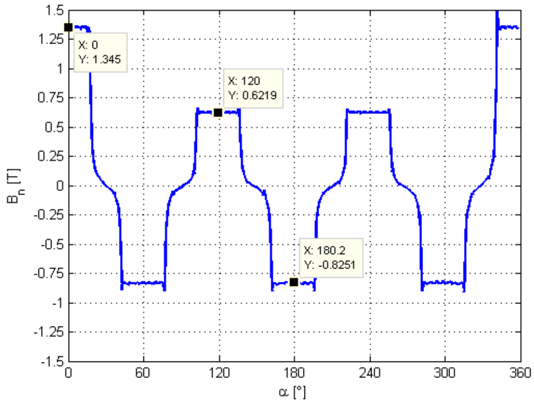

Fig.7. Normal (to the stator surface) component of the magnetic flux density in the air gap for central position of the rotor and currents I_1 = 2A, I_2 = I_3 = 0A

The presented simulation model has been used to calculation of all electromagnetic parameters of the HMB actuator, especially the magnetic force and flux linkage. The calculations have been carried out over whole operating range of the actuator. For the first electromagnet, they have been executed for values of the current I_1 = (-2A, 2A) and the rotor position y = (-0.1mm, 0.1mm).

Fig. 8 presents the values of magnetic force F_1 in function of the rotor position y and the current I_1. Magnetic bearings with permanent magnets characterise an initial force, which is generated without current excitation in windings. The value of initial force varies from -83.54N for the position y = -0.1mm to 113N for the position y = 0.1mm. Apart from the gravity force this is an additional component, which has to be overcame during the magnetic bearing start.

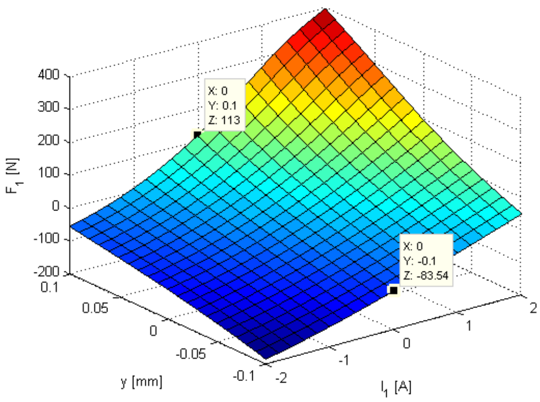

Fig.8. Magnetic force F_1 in function of the current I_1 and the rotor position y

Fig. 9 shows the flux linkage Ψ_1 in function of the rotor position y and the current I_1. For the central rotor position the flux linkage varies from 4.35 mWb (for I_1 = -2A) to 42.93 mWb (for I_1 = 2A). The permanent magnets generate the flux linkage which is equal to 23.78mWb.

Due to symmetry of the HMB actuator, the characteristics of the magnetic force and flux linkage are shown only for the first electromagnet. For the other ones they are similar to the first one.

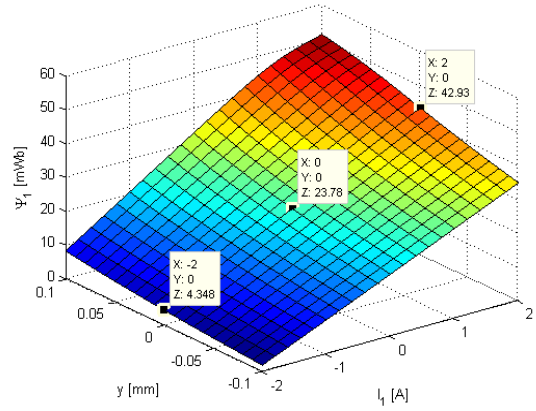

Fig.9. Flux linkage Ψ_1 in function of the current I_1 and rotor position y

Characteristics of the magnetic force and the flux linkage have been used to calculation of the magnetic bearing parameters like the current k_i and position k_s stiffness, dynamic inductance L_d as well as velocity induce voltage e_v.

Fig. 10 and Fig. 11 present characteristics of the current k_i and position k_s stiffness in function of the current I_1 and rotor position y. For the control purposes, these characteristics should be linear over whole operating range.

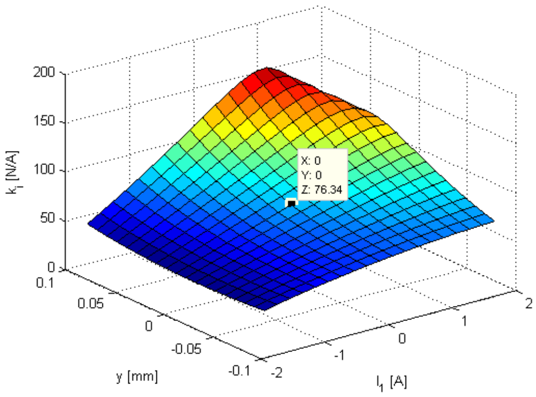

Fig.10. Current stiffness k_i in function of the control current I_1 and rotor position y

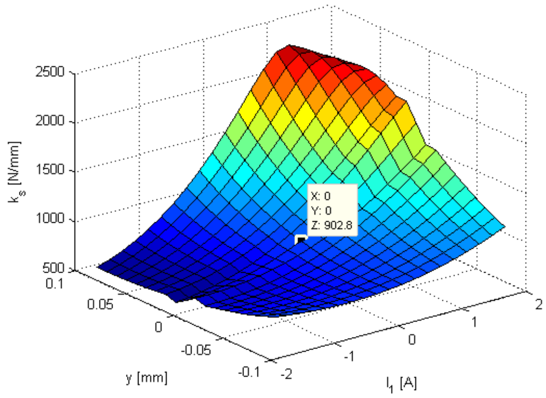

Fig.11. Position stiffness k_s in function of the control current I_1 and rotor position y

Parameters of the HMB actuator calculated for one electromagnet under central position of the rotor are presented in Tab. 2.

Table 2. Parameters of the HMB actuator

Parameter	Value
Current stiffness k_i	76.34 N/A
Position stiffness k_s	902.8 N/mm
Dynamic inductance L_d	9.75 mH
Velocity induce voltage e_v	67.53 Vs/m

Conclusions

Presented construction of the HMB actuator characterizes the high value of the position and current stiffness as well as the high value of the generated magnetic force. These parameters decide about usefulness of the HMB actuator.

The usage of permanent magnets for generation of the bias flux results the reduction of the windings' cross-section and overall volume of the bearing.

Magnetic bearings with permanent magnets are more energy efficient in comparison to active magnetic bearings. Slots in the stator causes the simplification in the permanent magnets' installation and ensure the mechanical stiffness of the whole stator construction.

An advantage of the described 6 pole HMB actuator in comparison to the other types of magnetic bearing actuators is the opportunity of usage of the simple supplying system.

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REFERENCES

[1] Schweitzer G., Maslen E. H.: *Magnetic bearings, Theory, design and application to rotating machinery*. Spinger, Berlin, 2009
[2] Gołębiowski L., Gołębiowski M., Mazur D., Humer M.: *The gearless, grid-connected, 6-phase asymmetric wind turbine generator system, Archives of Electrical Engineering*, Vol. 64(3), pp. 391-403 (2015),
[3] Budig P. K.: *Magnetic bearings and some new applications*. XIX International Conference on Electrical Machines – ICEM 2010, Rome
[4] Mystkowski A., Energy Saving Robust Control of Active Magnetic Bearings in Flywheel, Acta Mechanica et Automatica, Vol. 6, No. 3, 2012, pp. 72-75
[5] Gołębiowski L., Gołębiowski M., Mazur D.: Thermal Coupling Analysis of the Permanent Magnet Synchronous Generator, vol.324, pp. 135-147, 2015 Springer - Verlag,
[6] Cheng S., Olles M. W., Burger A.F., Day S.W.: Optimization of a hybrid magnetic bearing for a magnetically levitated blood pump via 3-D FEA. Mechatronics, 21, 2011 pp.1163-1169
[7] Jinji S., Jiancheng F., A novel structure of permanent-biased-biased radial hybrid magnetic bearing, Journal of Magnetism and Magnetic Materials, 323, 2011. pp. 202-208
[8] Yong L., Wei L., Yongping L., Computer-aided simulation analysis of a novel structure hybrid magnetic bearing, IEEE Transactions on Magnetics, Vol. 44, No. 10, 2008, pp. 2283-2287
[9] Ansoft, Maxwell 3D v12 User Guide, Pittsburg, 2008
[10] Piłat A., PD Control Strategy for 3 Coils AMB, Proceedings of the Tenth International Symposium on Magnetic Bearing, 21-23.08.2006, Switzerland