Excerpt from the Proceedings of the 2011 COMSOL Conference in Stuttgart

Simulation of Passive Magnetic Bearing using COMSOL Multiphysics

Krzysztof Falkowski
Military University of Technology
*Corresponding author: Kaliskiego 2, 00-908 Warsaw, Poland, krzysztof.falkowski@wat.edu.pl

Abstract: The article presents the process of verification of the passive magnetic bearing by the Comsol Multiphysics program. There is shown construction of the radial passive magnetic bearing PMB60x85x20-5, which was designed in the Military University of Technology. The distribution of the magnetic flux density and the static characteristic of the bearing were estimated by using Comsol Multiphysics. The stiffness coefficient was obtained from the static characteristic.
The author shows fundamental laws of magnetism and presents magnets for the radial, axial passive magnetic bearing and radial passive magnetic bearing with Halbach's array.

Keywords: permanent magnet, magnetic bearing, rotor.

1. Introduction

The magnetic bearings are used in different application, where the elimination of the friction is necessary. They are applied in the machine tool with high speed rotors, in the engine turbine, in the fly wheel energy storage, etc. Additionally, the magnetic bearings can work in the aggressive atmosphere (liquefied oxygen and methane, etc.), sea water and vacuum. The magnetic suspend system of rotor eliminates system of cooling and lubrication. Therefore, the magnetic bearing ensures increase reliability and efficiency of the turbo-machines.

These bearings divide into active magnetic bearing and passive magnetic bearing. The active magnetic bearing (AMB) uses the feedback loop between position of rotor in the air gap and the magnetic force. There consists of rotor position sensor in the air gap, the system of automatic control position of rotor in the air gap, the power amplifiers and electromagnetic actuators. The active magnetic system ensures high precision location of rotor in the air gap, but this system is the most expensive solution.

The passive magnetic bearing (PMB) has not feedback loop as the active magnetic bearing. The position of rotor is superposition of the magnetic repelling forces and external forces [2, 3]. It does not ensure high precision location of the rotor. There is steady state error, which is proportional to external forces. However the passive magnetic bearing has meaningful advantage, it is cheaper solution compared with the active magnetic bearing [1, 2, 3].

The passive magnetic bearings are built from the permanent magnets. They make use of repelling or attractive magnetic forces between magnets to magnetic levitation. The repelling forces are used in a large majority of application. The configuration of the passive magnetic bearing with attractive magnetic forces menaces loss of magnetic levitation [3, 4].

The design of the passive magnetic bearing is very difficult. The magnets generate no uniform magnetic field. The value and direction is different in the space around the magnets. The electrotechnics method (Ohm's and Kirchhoff's laws) is unhelpful for design the passive magnetic bearings. Only the finite elements method is useful for design and verification project of passive magnetic bearing.

The author uses the loop with molecular current as a mathematical model of passive magnetic bearing. The finite elements method is used to verification this model.

2. Construction of passive magnetic bearing

The passive magnetic bearing was built from the magnets or assembly magnets with different orientation of vector of magnetization. The magnets with the radial orientation of vector of magnetization are used by the radial passive magnetic bearing (the radial forces of capacity) and the magnets with the axial orientation of vector of magnetization are used by the axial passive magnetic bearing (the axial forces of capacity). The radial passive magnetic bearing with the Halbach's array uses radial and axial magnets. The array of magnets generates strong field in the selected space around the magnets. The configuration of magnets of Halbach's array is presented on the figure 3 [4, 5]. The magnets in the passive magnetic bearing are presented on the figure 1 and 2.

The passive magnetic bearings are built from two magnet or assembly of magnets. The first magnet is mounted in the case of machine. It doesn't move and it is a source of magnetic field. The second magnet is connected with the rotor and it moves with the rotor in the external field generates by the unmovable magnet. The division for movable and unmovable magnets is fundamental law for understanding construction of passive magnetic bearing.

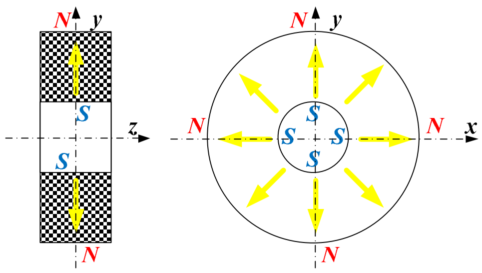

Figure. 1. The ring shaped magnet with radial orientation of vector of magnetization.

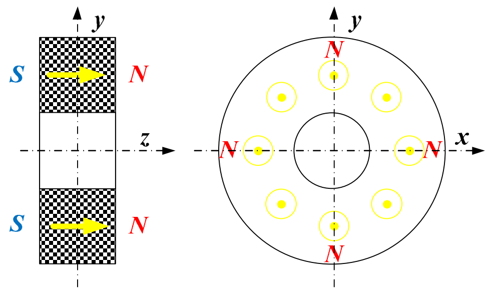

Figure. 2. The ring shaped magnet with axial orientation of vector of magnetization.

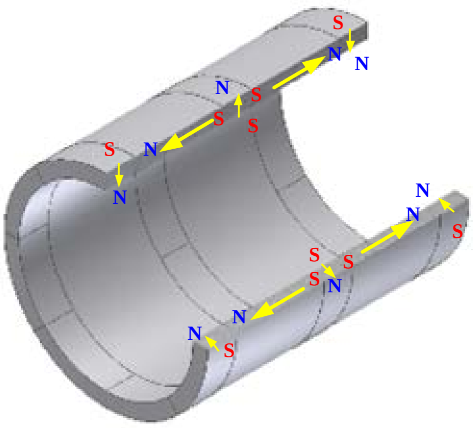

Figure. 3. The Halbach's array for the passive magnetic bearing.

3. Magnetic forces

The main law in the magnetism is the Lorenz's force [6, 7]:

$$\vec{F} = \int \left(\vec{\mathbf{K}} \times \vec{B}\right) da \qquad (1)$$

where: $\vec{K}$ – a vector of surface current density, $\vec{B}$ – a vector of external magnetic flux density, da– an elementary element of surface.

The all magnetic moments of atoms of magnet position parallel during the magnetization of magnet. The freely electrons of atoms generate molecular current in the magnet. The resultant current is equal zero inside magnet because the freely electrons have got opposite direction of move (fig. 4). The molecular current is different than zero only in the wall of magnet because the freely electron have got this same direction (fig. 4 and 5). The molecular surface density current $\vec{K}$ in the wall of magnet is equal [6, 7]:

$$\vec{K} = \vec{M} \times \vec{n} \qquad (2)$$

where: $\vec{M}$ – vector of magnetization of magnet, $\vec{n}$ – normal vector to the wall of magnet. The molecular surface current occurrences only in parallel wall to the vector of magnetization.

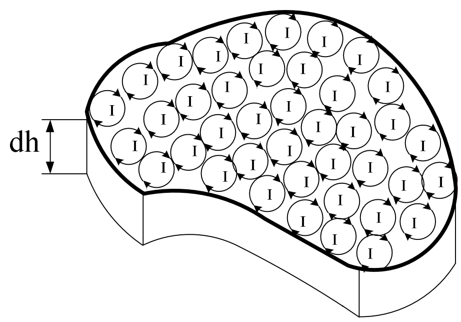

Figure. 4. The cross-section of magnet after magnetization.

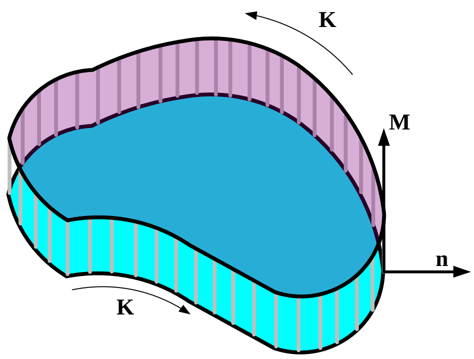

Figure. 5. The molecular surface current density in the wall of magnet.

The molecular surface current in unmovable magnet generates magnetic field. The magnetic flux density generates by unmovable magnet can be estimated by Biota-Savarta law:

$$\vec{\boldsymbol{B}}(\boldsymbol{r}) = \frac{\mu_0}{4\pi}\int \frac{\overrightarrow{\boldsymbol{K}(\boldsymbol{r'})}\times\hat{\boldsymbol{R}}}{|\vec{\boldsymbol{R}}|^2}\, d\boldsymbol{a} \quad (3)$$

where: $\vec{\boldsymbol{B}}(\boldsymbol{r})$ – magnetic flux density in the point **r**, $\vec{\boldsymbol{R}}$ – vector which connect point **r** and **r'**, **da'** – elementary surface of wall of unmovable magnet, **r'** – point on the wall of unmovable magnet, **r –** point on the wall of movable magnet.

The equation (1), (2) and (3) can be used to obtain the magnetic forces in the passive magnetic bearing. This approach directs to very difficult solution of elliptic integral. The author elaborates the math model of bearing after assumptions. The assumptions arise from configuration of magnet, geometric relation between magnets and small air gap.

The simply way to solution this problem is used the numerical method. Especially, the finite elements method is useful.

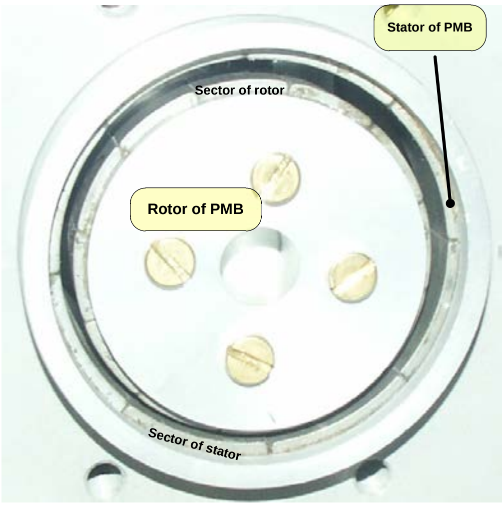

Figure 6. The passive magnetic bearing PMB60x85x20-5.

3. Use of COMSOL Multiphysics

The Comsol Multiphysics takes full in two cases. The first case, the Comsol is used to verification mathematical model of the magnetic bearing in the research laboratory. The basic calculations of construction of the passive magnetic bearing make from mathematical model of the passive magnetic bearing. The author applies the loop with molecular current as a model of the ring shaped magnet. The second case, the Comsol is used to verification designed passive magnetic bearing. There is presented the numerical analysis construction of the radial passive magnetic bearing PMB60x85x20-5. The bearing has got inner diameter of rotor (movable magnet) 60 [mm], outer diameter of stator (unmovable magnet) 85 [mm], height of ring 20 [mm] and the total clearance 5 [mm]. The construction of passive magnetic bearing is presented on the figure 6.

The radial passive magnetic bearings were built from the ring shaped magnets with radial orientation of vector of magnetization. The ring shaped magnets with radial orientation of vector of magnetization is very difficult to buy. The ring was made from sectors with the radial orientation of vector of magnetization. The stator's sectors have got inner diameter 60 [mm], outer diameter 70 [mm], arch 30^0 and the rotor's sectors have inner diameter 75 [mm], outer diameter 85 [mm] and arch 45^0. The magnets of stator and rotors are mounted in the aluminum rings as is presented on the figure 6.

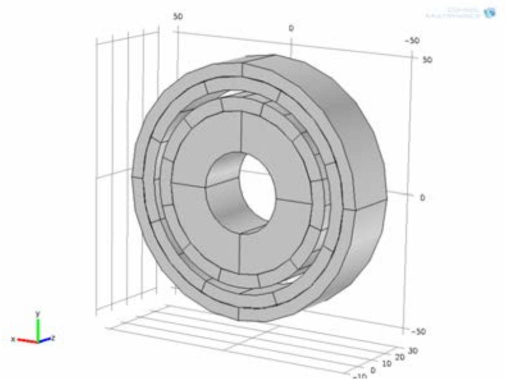

Figure 7. The geometry of PMB60x85x20-5 in the Comsol Multiphysics.

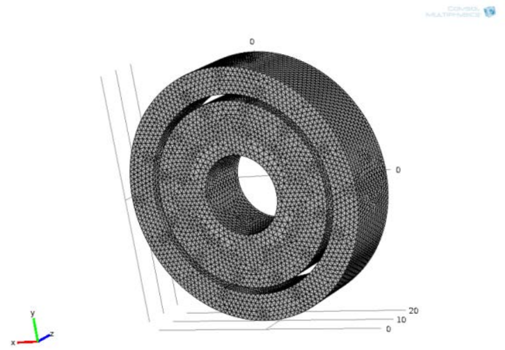

Figure 8. The mesh generated with Comsol Multiphysics.

Comsol Multiphysics was used to estimate the static characteristic the passive magnetic bearing and the stiffness coefficient of suspension.

The physics “Magnetic field, No current” and static study were used to estimate the static characteristic of the passive magnetic bearing. The model was designed in 3D space. The geometry of the passive magnetic bearing was shown on the figure 7. There is an aluminium ring of stator with sectors of unmovable magnet and an aluminium ring of rotor with sectors of movable magnet. In this project, there are three group materials: magnets, air and aluminium. The mesh was generated automatically as tetrahedral elements. The elements of mesh were predefined as extremely fine (figure 8).

4. Test the passive magnetic bearing in the COMSOL Multiphysics

The distribution the magnetic flux density and resultant magnetic forces was used to evaluation the passive magnetic bearing. The first experiment tested the distribution of the vector of magnetization in the magnets of the passive magnetic bearing. The vector of magnetization in an intersection Oxz is presented on the figure 9 and in an intersection Oxy on the figure 10.

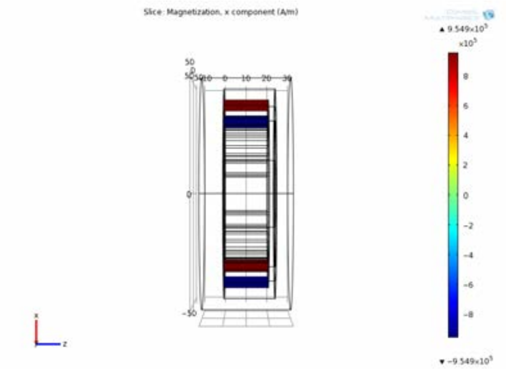

Figure 9. The vector of magnetization in the intersection Oxz.

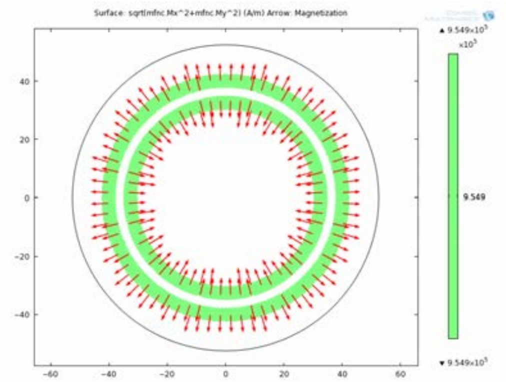

Figure 10. The vector of magnetization in the intersection Oxy.

The unmovable magnet has got the vector of magnetization directed outside and the movable magnet has got the vector of magnetization directed inside (figure 10). The magnets have got same value of magnetization in radial direction. The distribution of vector of magnetization confirms the model of magnets.

The above test confirms the distribution of magnetic field in the magnets. The next test is shown the distribution of magnetic field in the passive magnetic bearing. This test evaluates the mathematical model, which author uses to design the bearing.

The distribution in the Ox axis is presented on the figure 11. The magnetic flux density has got direction, which depend from the orientation of vector of magnetization in the magnet. The distribution magnetic flux density in the Oy axis is presented on the figure 12.

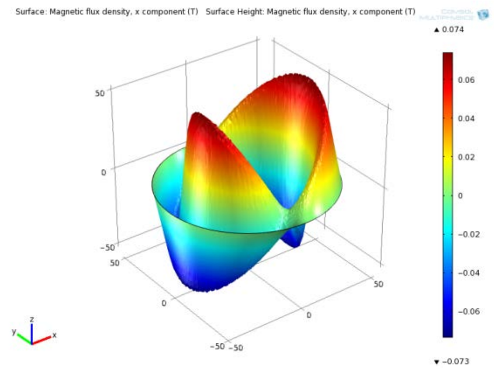

Figure. 11. The distribution of magnetic flux density in the Ox axis.

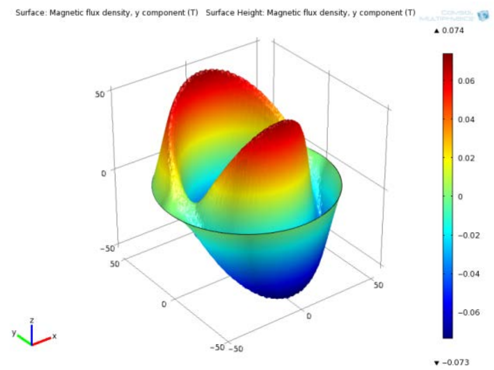

Figure 12. The distribution of magnetic flux density in the Oy axis.

The distribution in the Oy axis was measured for different position movable magnet in an air gap of the magnetic bearing. There was measured distribution for change position movable magnet in an air gap between -2 [mm] to 2 [mm]. The result is shown on the figure 13.

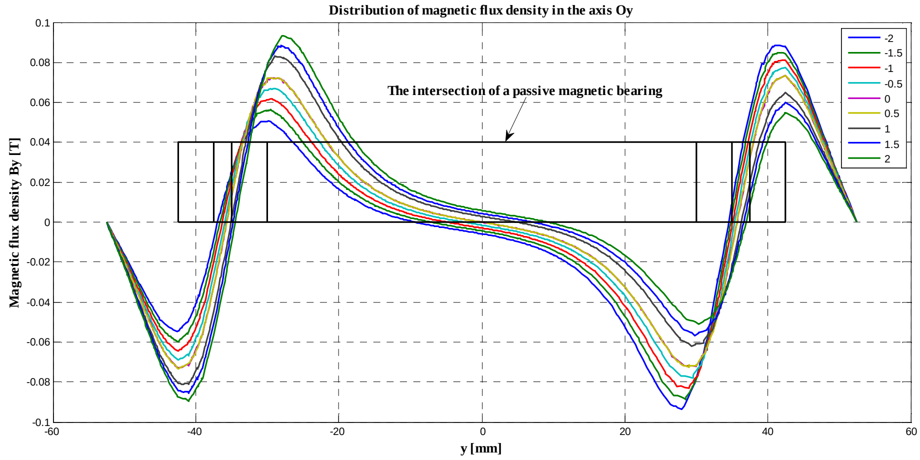

Figure 13. The distribution of magnetic flux density for different position movable magnet in the air gap – axis Oy.

The last test was served to obtain the magnetic force and the stiffness coefficient of bearing. There was used the Maxwell's stress tensor. The distribution of Maxwell's stress tensor for Oy axis was presented on the figure 14, 15 and 16. The Maxwell's stress tensor for nominal position of movable magnet is presented on the figure 14. The module of tensor is the same, but direction of tensor in down part of movable magnets is positive and in upper part is negative. The movable magnet is compressed by magnetic force and the resultant magnetic force is equal zero. If the movable magnet changes position the Maxwell's stress tensor increases for the air gap decreases and decreases for the air gap increases. The resultant magnetic force for first case equals zero (figure 14) and the force is different than zero for other cases (figure 15 and 16).

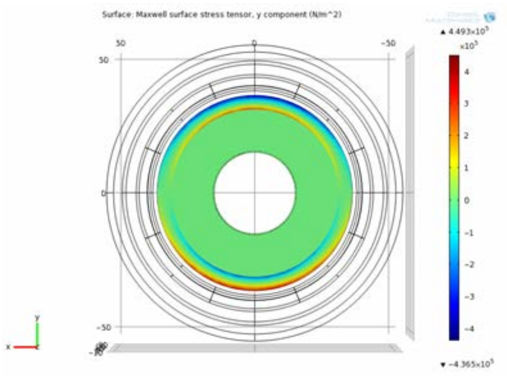

Figure 14. The Maxwell's stress tensor for nominal position of movable magnet in the air gap.

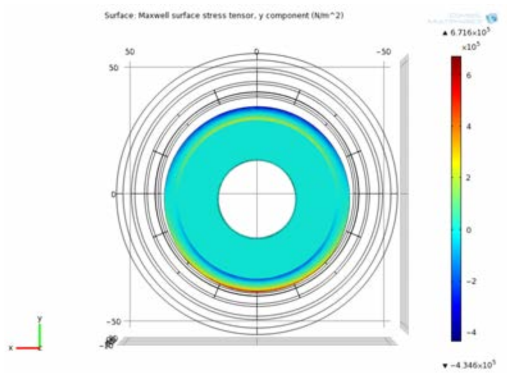

Figure 15. The Maxwell's stress tensor for displacement movable magnet -2 [mm].

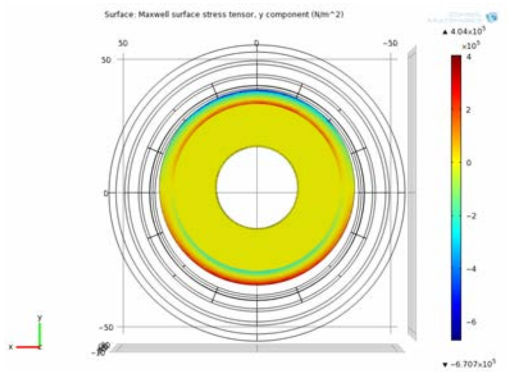

Figure 16. The Maxwell's stress tensor for displacement movable magnet 2 [mm].

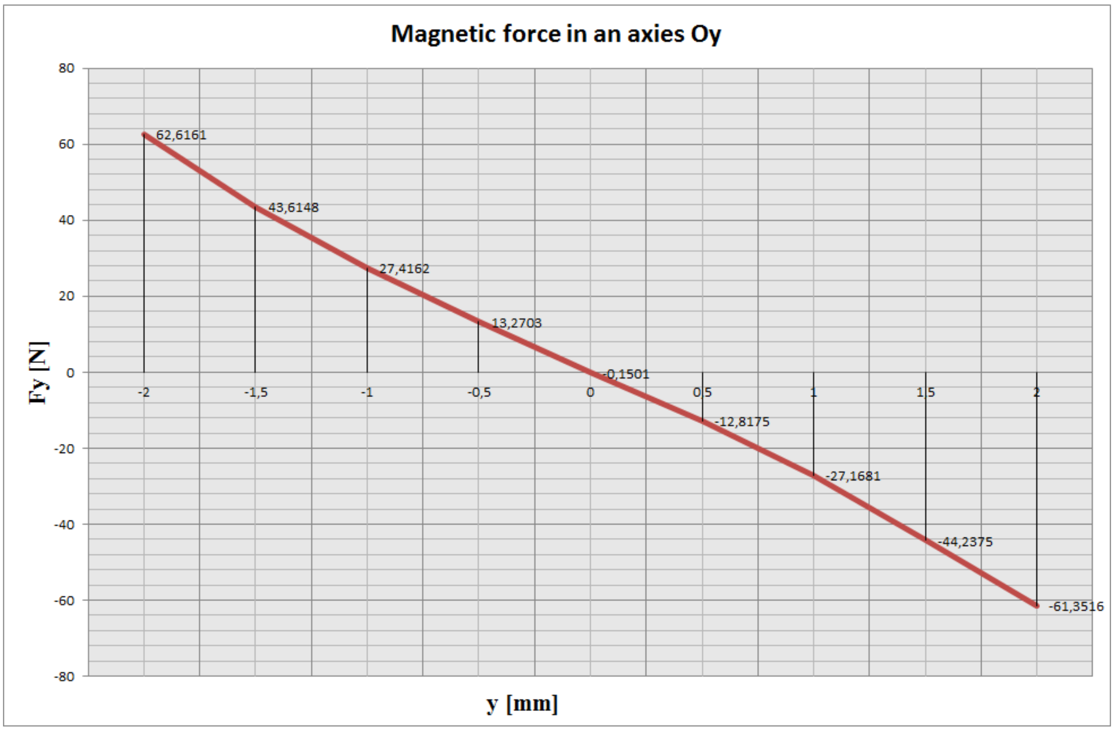

Figure 17. The static characteristic of the pasive magnetic bearing PMB60x85x20-5 for axis Oy.

The last test was used to obtain the static characteristic of the passive magnetic bearing. The geometry of the passive magnetic bearing was adapted to change position of movable magnet. The static characteristic is shown on the figure 17. This characteristic makes a decision about an operation range and the maximum capacity for the bearing. The stiffness coefficient is estimated from the static characteristic.

5. Summary

COMSOL Multiphysics is the computer added program for analysis differential physical phenomena. This program uses the finite element method for discretization the space. There is presented application the COMSOL Multiphysics to verification project the radial passive magnetic bearing. The author uses this program to numerical verification models of passive magnetic bearings.

Comsol has got a lot advantages. The great advantage is collaboration Comsol with different foreign programs. The geometry of model can be generated in the external graphical programs (Inventor, Visio, etc.) and it can imported into Comsol. The result was generated by solver, can be exported from postprocessor to external programs (Matlab, Excel, etc.). The complex problems which connect different physic phenomena can be fast solved. The next great advantage is simply and friendly interface, but the all advantages must go with an engineer experience.

6. References

1. Yonnet J. P.: „Passive Magnetic Bearing with Permanent Magnet", IEEE Transactions On Magnetic , Vol. MAG-14, No 5, 1978
2. Ravaud R., Lemarquand G., Lemarquad V.: „Force and Stiffness of Passive Magnetic Bearing Using Permanent Magnets. Part 1: Axial Magnetization", IEEE Transactions On Magnetic, Vol. 45, No 7, 2009.
3. Ravaud R., Lemarquand G., Lemarquad V.: „Force and Stiffness of Passive Magnetic Bearing Using Permanent Magnets. Part 2: Radial Magnetization", IEEE Transactions On Magnetic , Vol. 45, No 9, 2009.
4. Falkowski K.: The Identification Dynamic Characteristic of the Passive Magnetic Bearing with Halbach Array, The 6th International Conference "Mechatronic Systems and Materials", 2010.
5. Falkowski K., Henzel M.: High Efficiency Radial Passive Magnetic

Beating, SOLID STATE PHENOMENA, Vol. 164, pp. 360-365, 2010
5. Griffiths D.J.: "Introduction to Electrodynamics", PWN, 2005 (in Polish)
6. Zahn M.: "Electromagnetic Field Theory: A Problem Solving Approach", Second edition, Krieger Publishing Company, 2003.

7. Acknowledgements

The work was financed in part from the government support of scientific research for years 2010 – 2013, under grant No. O N509 032736.