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The influence of the micropump`s winding shape and magnetic circuit configuration on the generated electromagnetic torque characteristic. Part I: FEM analysis

***Abstract**. In this article is shown the research process of electromagnetically driven blood micropump winding shape as well the configuration of magnetic circuit influence on its generated electromagnetic torque. Analysis of the winding shape is intended to increase the electromagnetic torque values generated by the micropump and to assure more smooth torque characteristic versus angular displacement of blood chamber. This analysis is based on a spatial field model of an electromagnetically driven pulse micropump and have been made using the finite element method.*

Streszczenie.** W niniejszym artykule przedstawiono proces analizy wpływu kształtu uzwojeń oraz konfiguracji obwodu magnetycznego napędu mikropompy do przetaczania krwi na generowany moment elektromagnetyczny. Celem tej analizy jest zwiększenie wartości generowanego momentu elektromagnetycznego napędu mikropompy oraz uzyskanie charakterystyki o stałym momencie w zależności od kąta położenia części ruchomej komory krwi. Analizę momentu elektromagnetycznego napędu mikropompy przeprowadzono na bazie przestrzennego modelu polowego.* ***Analiza wpływu kształtu uzwojeń oraz konfiguracji obwodu magnetycznego napędu mikropompy do przetaczania krwi

Słowa kluczowe: MES, napęd elektromagnetyczny, mikropompa, sztuczne serce.
Keywords: FEM, electromagnetic drive, micropump, artificial heart.

Introduction

The electromagnetically driven pulse micropump is a project of an TAH (*Total Artificial Heart*) device for blood transfusion. Motivation for this article is to improve the parameters of the magnetic circuit and increasing the generated torque by modifying the shape of the stator windings at the same power supply parameters. Another important element of this work is to parameterize the micropumps drive, parameters such as dimensions of electric and magnetic circuit and the number of windings and permanent magnets.

In the existing solutions of cardiac assist devices they are two types the TAH and LVAD (*Left Ventricular Assist Device*) devices. From a medical point of view this type of devices can be placed extracorporeally or completely orthotopically implanted, while their drives can be classified as pneumatic driven or electromagnetic driven. Next there are two types of LVAD devices due to his type of drive: axial flow rotary pump and a centrifugal rotary pump. An example of the first type of device is the DeBakey LVAD 2G axial flow rotary pump designed by MicroMed Technology, which is driven by a motor with permanent magnets placed in the rotor blades and stator windings placed around the rotor. In this type of pump inlet and outlet are located on the same axis and blood flow is oriented in the same direction. The second type of drive can be presented as an example of the DuraHeart 3G LVAD developed by Japanese corporation Terumo. In this type of pump the blood flow is caused by the centrifugal force, where the inlet and outlet are placed perpendicular to each other and the blood flow path is oriented at the right angle. The DeBakey LVAD 2G and DuraHeart 3G LVAD devices and their direction of blood flow shown by arrows are presented in Figure 1 [1 - 6].

The total types of artificial hearts device can be divided due to his type of drive, in following way:

- pneumatic driven TAH device. An example of a pneumatic driven TAH is the POLTAH artificial heart as an result of research on the Polish artificial heart.
- and electromagnetic driven TAH device. The AbioCor artificial heart is an example of an electromagnetic driven TAH device.

Both of these devices are completely orthotropic implantable, and the blood flows in and out through the artificial heart valve [7].

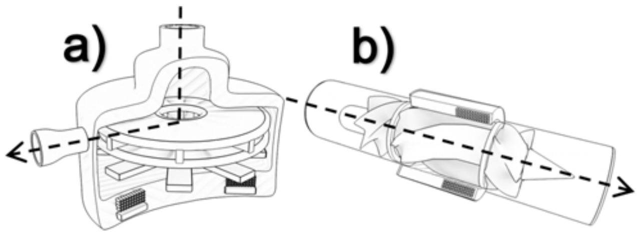

Fig. 1. a - DuraHeart 3G LVAD centrifugal rotary pump; b - DeBakey LVAD 2G axial flow rotary pump.

All such of cardiac assist devices and TAH devices aim to improve the comfort of the patient that is awaiting for a heart transplantation. The use of pulsatile blood flow similar to the humans natural hemodynamic heart cycle, will significantly increase the patient's comfort [10, 11].

In this article will be considered various kinds of coil windings and permanent magnets configurations of the discussed micropump drive. The shape and the number of coil windings will be modified so as to increase the generated torque. For each of these cases will be created a spatial field model, which will be by the FEM method analyzed for the influence on the generated electromagnetic torque characteristics. Construction of the micropump drive is based on the concept of the popular VCM (*Voice Coil Motor*) motors, which are used in hard disc drive actuators.

Construction of the micropump and her electromagnetic drive

The discussed concept of the electromagnetically driven pulse micropump is based on VCM motor. This type of drive design was chosen because of its high dynamic, simple structure and small dimensions which are characterized by a VCM motor [8, 9]. These types of features are necessary in the construction of the artificial heart, which should be characterized by high reliability and low failure rate [10].

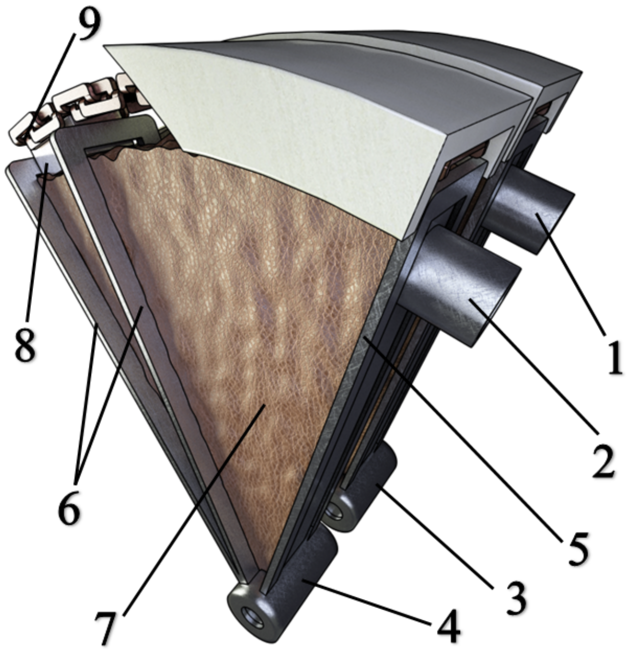

Fig. 2. 3D model of the electromagnetically driven pulse micropump.

Figure 2 presents the spatial model of the micropump, that has two independently controlled chambers so-called VAD`s (Ventricular Assist Device), the right and left VAD`s. The right inlet/outlet is denoted by (1) and the left inlet/outlet by (2), right and left bearing – (3 and 4), rigid wall of the micropump – (5), flexible blood chamber – (7). The rotor denoted by (6) is fixedly connected with the permanent magnet – (8). The stator windings – (9) with stator core are permanently connected with the rigid wall of the pump. With the independently controlled artificial heart chambers the blood can be alternately transfused or synchronous transfused where both chambers are working in parallel. The blood transfusion can be classified into two stages, in the first stage the chamber will be filled with blood through the artificial valve. In the home position the angle of the rotor is equal to zero and the volume of the chamber is minimal, next by increasing the angle of the rotor to the maximum position the chambers volume will be gradually increased to the maximum volume. In the next stage follows the ejection of the collected blood from the chamber into the bloodstream. It means that the rotor returns back to the home position by decreasing the rotor angle and gradually reducing volume of the chamber, that generates the necessary pressure for the blood ejection through the artificial valve. The maximum volume of the chamber is 140 cm^3 and the total range of angular movement of the rotor is from 0 ° to 28 °, and the dimensions of the micropump is 135 mm x 95 mm x 60 mm.

Figure 3 shows the electromagnetically driven pulse micropump drive, this drive is composed of neodymium (NdFeB) permanent magnet type – (1), and the stator windings – (2). For better visualization of the drive the upper permanent magnet was removed in this figure. The magnetization vector directions of the permanent magnet poles is indicated by the arrows in Figure 3. Stator winding are composed of eighteen independently controlled coils, which provides different kind of connection configuration of these coils together. The spread angle between the active sides of the coil is located between the center of the N pole and center of S pole of the permanent magnet, the angle is equal to 4.72 degree.

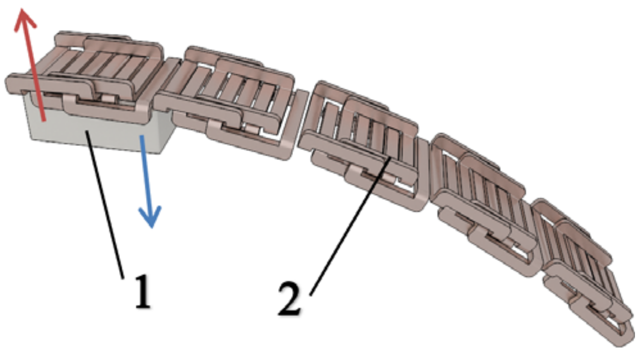

Fig. 3. The electromagnetic drive of the micropump.

These coils are formed in a specific way, such that the active sides of the next two coils lie on the same plane. Only the active sides of the coils participate in the torque generation, an example of the coil are shown in Figure 4, active coil sides – (1).

Fig. 4. 3D model of the one characteristic formed coil.

The field model of the analysed electromagnetic drive

In this chapter the analysis of the discussed pulse micropump drive will be done. On the basis of the spatial model of the drive shown in Figure 3, has been created a simplified model in which there are only two permanent magnets and the several coil windings configurations. To simplify the calculations of the field model in FEM method were used only the geometry of the active coil sides. In the following Figure 5 are the four disputed cases presented: one coil – (a), with two coils – (b), three coils –(c) and four coils – (d).

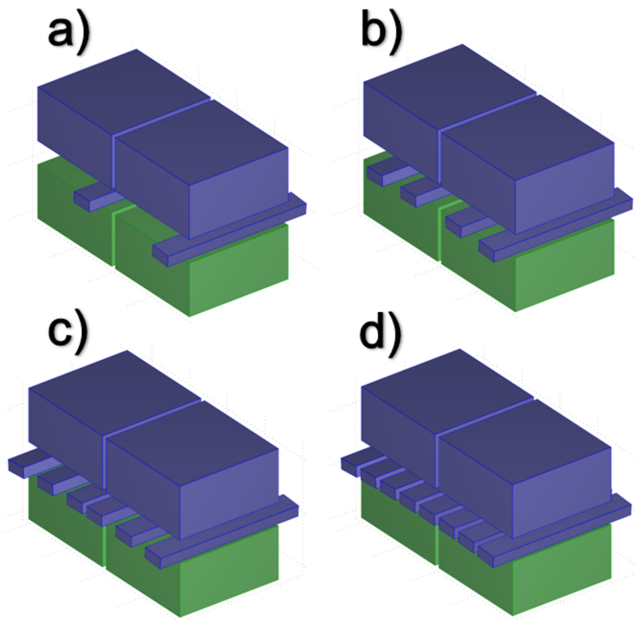

Fig. 5. Four configuration cases of the drive windings.

The geometrical dimensions of presented drive for the permanent magnets are 20 mm x 10 mm and a thickness of 5 mm and for the active sides of the coils 1 mm x 2 mm x 14 mm with a number of turns equal to 240.

The geometrical dimensions of permanent magnets that were used in the simulation are the dimensions of commonly available magnets. While the dimensions of coil windings have been pre-selected to maximize the number of possible coils in the geometry and to increase the generated torque by the drive. The offset angle between next two sides of the coil configuration with one coil is 4.72 degree, for the two coils is 2.36, 1.77 for the three coils and for the four coils is 1.18 degree. The proposed simplification reduced the number of finite elements, reduced the memory consumption and finally accelerated the FEM calculation.

The following Figure 6 shows the spatial model of finite element for an example configuration of four windings drive.This field model is characterized by a finite number of elements equal to 105,350, and the number of degrees of freedom equal to 147,356 and the single finite element is a tetrahedral type. For better visualization of the field model in Figure 6, the outer geometry of the air was removed.

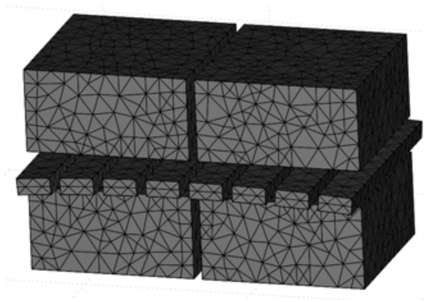

Fig. 6. Meshed model of the micropump drive.

The air gap in the model for all windings configurations between the upper and lower permanent magnet is 2.2 mm. The permanent magnets material type is N38M, this type of material have the magnetic remanence B_r equal to 1.2 T and the coercivity ${}_{B}H_C$ = 923 kA/m. Outer space around the drive model is the material type Air, and the active sides of the coils are the copper material type.

The result of the calculations for module of magnetic induction in the middle of the air gap is shown below in Figure 7 and the maximum magnetic flux density is equal to 0.674 T.

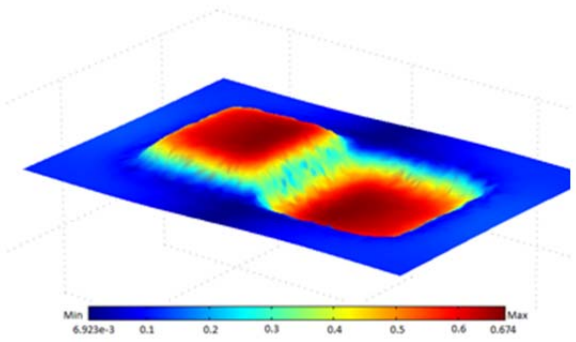

Fig. 7. Distribution of the module of magnetic flux density.

The average value of magnetic flux density in the middle of the air gap was calculated on the volume of the active side coil for the listed four cases. The magnetic flux density was averaged on the volume of the active coil side according to the following formula:

$$B_{AV} = \frac{1}{N_c v_c} \int B_z dv \tag{1}$$

where: B_z – "z" component of magnetic flux density vector $\boldsymbol{B}$, v_c - volume of one coil side, v – volume, N_c - number of coil sides for different cases of the drive. The volume of a single side is equal to $2.8 \cdot 10^{-8}$ m^3 and the number of coil sides of different cases is given for:

- the case of one coil N_c it is equal to 1,
- case of two coils N_c is equal to 2,
- case with three coils N_c is equal to 3,
- case with four coils N_c is equal to 4.

The figure below shows the resulting average value of magnetic flux density in the middle of the air gap for the given cases. The angular range of the motor in this simulation is between 0 degrees and 4.72 degrees in increments of 0.236 degrees.

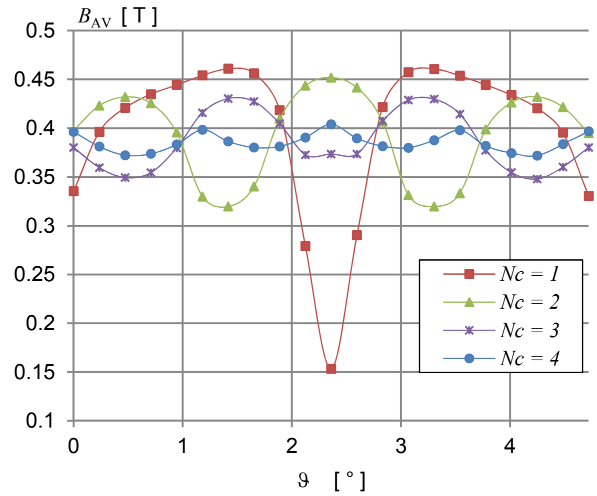

Fig. 8. Average magnetic flux density B_{AV}.

As we can see in the figure above, increasing the number of active sides of the coil (the N_c parameter) will be average the value of magnetic flux density in the middle of the air gap, as a function of the angular position of the rotor. But, the smaller values of N_c parameters, as we can see is characterised by greater differences in the magnetic flux density for each angle position of the rotor. Most smoothed magnetic flux density characteristics is for a number of sides equal to 4, which will be better visible on the characteristics of the generated torque.

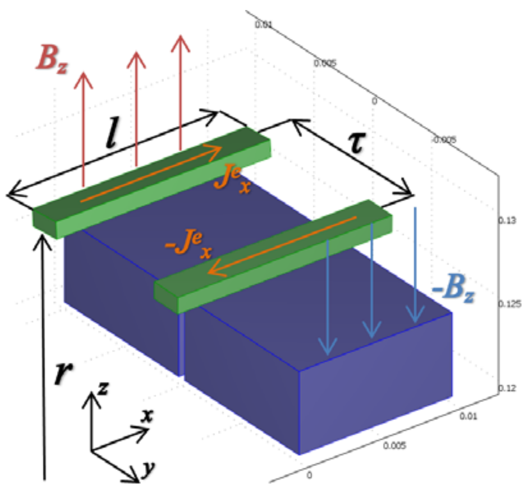

Fig. 9. Simplified spatial model with marked parameters of the drive.

Figure 9 shows a simplified spatial model of the micropump drive, for better visualization only a single winding are used and the upper permanent magnet was removed. A parameterized model of the electrical circuit is characterized by a parameter l which is the total length of single active side of the coil, the parameter τ describes the distance (coil pitch) between the sides of the coils and are expressed in degrees. J^e_x - current density vector „x" component. The parameter r is the radius at which the rotor is moving and is measured from the center of the bearing micropump to the top of the rotor. The total torque generated by the drive in this configuration is given by the following formula:

(2) $$T_e = 2N_c NB_{AV}(\vartheta)\, rl \cdot i$$

where: N - numbers of coil turns, $B_{AV}(\vartheta)$ - magnetic flux density angular distribution surrounding the coil, r - the radius on which the rotor moves, l - total length of single active side of the coil, N_c – number of coils, i – current. For the case of a single coil where N_c parameter is equal to 1 the equation (2) takes the following form:

(3) $$T_e = 2NB_{AV}(\vartheta)\, rl \cdot i$$

The relationship between the magnetic field surrounding the drive coil and the geometric dimensions and number of turns of the coil is defined as a torque coefficient and it is expressed as:

(4) $$k_t = 2NB_{AV}(\vartheta)\, rl$$

This coefficient determines the ability to torque generation resulting from the geometric parameters of the drive.

In this way parameterized the electromagnetic micropump drive and the given total torque equation (2) of the drive, allows to estimate the characteristics of the generated torque as an function of angle of the rotor. The geometric parameters of the drive are summarized in the table below, which where the distance between sides of the coils is reduced, and the coils number of electrical circuit will be increased. Constant parameters for all four cases, is the length of the active side, the number of turns, and the radius of movement of the rotor. The parameters of the magnetic circuit are also the same for the analyzed models and the current in the calculation is equal to 400mA.

Table 1. The geometrical parameters of the analysed grive

The analysed case	The geometrical parameters			
	N	r [mm]	l [mm]	τ [°]
N_c = 1	240	124	14	4.72
N_c = 2	240	124	14	2.36
N_c = 3	240	124	14	1.77
N_c = 4	240	124	14	1.18

From the previously computed characteristics of the average magnetic flux density angular distribution $B_{AV}(\vartheta)$ in the center of the air gap as shown in Figure 8, and using equation (2) they are calculated the torque values for all four cases, in the position of the rotor angular range from 0 degree to 4.72 degree and the rotor radius equal to 0.124 m. The calculation results are shown below in the Fig. 10. As can be seen with the increased number of windings the generated torque have a greater average value, and the shape of the characteristic is smoother. The average value of the generated torque for the whole angular range for the case of single coil is 0.133 Nm, for the two coils is 0.263 Nm, for the three coils is 0.387 Nm and four coils is equal to 0.514 Nm.

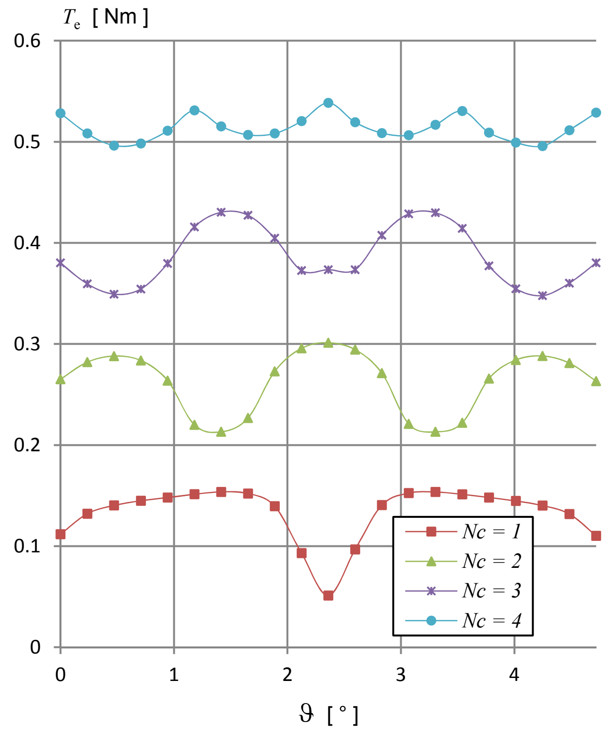

Fig. 10. The generated torque characteristic of the drive.

Summary

This article presents the design of an micropump with pulsatile nature of blood flow and its drive with multiple stator windings, and neodymium magnets in the rotor. The drive was classified by the four cases, for each case the field model of these drives was done. The field calculation was done by the finite element method, to obtain and averaging the values of magnetic flux density in the middle of the air gap. The parameterized model of the electrical circuit is characterized by the geometric parameters of the drive, which was necessary to the equation formulation of the total torque generation of the drive. Based on the results of FEM calculations and the resulting parametric model the torque values were calculated for different angles of the rotor position. Estimation of torque characteristics as a function of the angular position of the rotor at constant parameters of the magnetic circuit and power supply parameters, it was to determine the differences in the shape of the torque characteristics due to the configuration of the electrical circuit that is, the number of used coils and the angular distance of sides of the individual coils.

The aim of this work was to obtain a smoother characteristic with less torque pulsations, and to increase the rotors swing force, what is seen on the average torque. The best drive configuration obtained by this criterion is for the model of four coils and the spacing between the sides of at 1.18 degree. Shape of the torque generated by the drive translates to the shape of the outlet pressure of the transfused blood and the swing force on the maximum value of this pressure.

Further reflection on the work should focus on the design of the magnetic yoke made in 3D printing technology based on a plastic material with flecks of neodymium, that will allow the closure of the magnetic field and increasing the generated torque by the same circuit parameters. Should be to make the FEM analysis of pressure distribution within the pump chamber and the outlet pressure based on the results obtained torque. Expanding the existing drive model by the pump flow

model. Developing a motor control algorithm with multiple stator windings to get the constant torque as a function of angle, which will be the basis in the shaping of the pump outlet pressure which will be close to the natural pulse of the human heart.

Annotations. Presented pump design is the subject of patent application number P.413744.

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REFERENCES

[1] Gieras I. A., Gieras J. F.: Recent Advancements in Permanent Magnet Motors Technology for Medical Applications; *ROCEEDINGS OF ELECTROTECHNICAL INSTITUTE*, Issue 229, 2006, p.7-20.

[2] Ramachandran D.P., Luo C., Ma T.S., Clark J.W.: Modeling Study of the Failing Heart and its Interaction with an Implantable Rotary Blood Pump; *Engineering in Medicine and Biology Society, EMBC, Annual International Conference of the IEEE*, Boston, Massachusetts, USA, 2011, p. 2403 - 2409.

[3] Qian K.X., Zeng P., Ru W.M., Yuan H.Y.: New concepts and new design of permanent maglev rotary artificial heart blood pumps, *Medical Engineering & Physics,* vol. 28, 2006, p.383 - 388.

[4] Huachun Wu, Ziyan Wang, Xujun Lv: Design and Simulation of Axial Flow Maglev Blood Pump, *I.J. Information Engineering and Electronic Business*, vol.2, 2011, p.42-48.

[5] Huzlik R., Lapčik J.: Magnetic bearing in blood pump systems, *Zeszyty Problemowe – Maszyny Elektryczne*, Nr 88, 2010, p. 225-227.

[6] Ostberg B. N., Ostberg G. N.: Total artificial heart design with integrated electric motor. *Med. & Biol. Eng. & Comput.*,1987, 25, 345-346, 53 Temple Street, Heyfield 3858, Victoria, Australia.

[7] http://www.texasheart.org

[8] Trawiński T., Kluszczyński K., Kołton W.: Model obwodowy dwuuzwojeniowego silnika VCM dla systemów pozycjonowania głowic dysków twardych, Przegląd Elektrotechniczny, R. 87 NR 12b/2011, s.184-187.

[9] Trawiński T.: Verification of the mathematical model of Voice Coil Motor with high range of angular motion. *Research and Education in Mechatronics KTH*, Stockholm, Sweden June 15-16, 2006.

[10] Bartel S., Trawiński T.: Design issues of electromagnetic micropump. *15th International Workshop on Research and Education in Mechatronics* (REM), 9-11 September 2014, El Gouna, Egypt. Piscataway: Institute of Electrical and Electronics Engineers, 2014, p. 1-7

[11] Mitamura Y., Mori Y.: Magnetic Fluid-Driven Artificial Hearts. *World Congress on Medical Physics and Biomedical Engineering 2006, IFMBE Proceedings*, Vol 14, 2007, pp. 4149-4152.