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USING HALBACH MAGNET ARRAYS TO INCREASE THE OUTPUT FORCE OF FERROFLUID ACTUATORS

BY

CAMELIA PETRESCU*

“Gheorghe Asachi” Technical University of Iaşi
Faculty of Electrical Engineering

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Abstract. The paper presents a ferrofluid actuator whose structure is modified by adding ring magnets in Halbach or quasi-Halbach pattern in order to increase the resulting force. A survey of existing tubular actuator models with Halbach permanent magnet array, based on the Laplace force, is also presented. The newly introduced actuator is put in motion by the force acting on a pre-magnetized material (the ferrofluid), exposed to the field of a command coil, and proves to increase the resulting force by 9.2% compared to the case when only axial pre-magnetization is used.

Key words: actuators; Halbach arrays; magnetic forces; numerical analysis of magnetic fields.

1. Introduction

Actuators are electromechanical devices that use electromagnetic energy in order to produce motion, translations or rotations. The main demand for these devices is to maximize the force or torque in a given configuration by using a proper choice of materials and shape/dimensions of its components. Currently there are reported in literature actuator models that produce forces from a few mN up to thousands of newton. The main applications of linear actuators are in the fields of transportation, precision positioning devices, machine tool drives, medical devices (such as artificial hearts), test stands, etc.

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* *e-mail*: campet@ee.tuiasi.ro

Focusing on linear actuators it is clear that, in order to obtain an increased output force, a high magnetic flux density is required. Considering the two main sources of producing a magnetic field in power applications, permanent magnets (PM's) and coils, it is obvious that PMs have the advantage of zero electric energy consumption and they do not need cooling systems.

The invention of high energy density magnets, based on neodymium-iron-boron alloys (Nd-Fe-B) increased the usage of PM's in actuator design. Moreover, the solution of arranging magnets with similar magnetizations in an alternatively periodical pattern, either in Cartesian or in polar coordinates, called a Halbach array, proved to increase the magnetic field on one side of the array and decrease it on the other side. This effect was first described by J.C. Mallison in 1973. The term "Halbach array" was coined by the physicist Klaus Halbach who used the effect in the construction of particle beam accelerators (Halbach, 1981).

Several models of actuators that use Halbach PM arrays are reported in literature (Jang *et.al.*, 2005, 2007; Choi *et.al.*, 2008; Yan *et.al.*, 2013; Jin *et.al.*, 2014). Since the aim of this study is to investigate the merits of using a PM Halbach array in the case of a cylindrical ferrofluid actuator, only the significant references concerning tubular actuators that use Halbach arrays are surveyed here.

Ferrofluid actuators are low-energy, precision positioning devices that gained a niche due to their simplicity and reliability and due to the possibility to control the position of a mobile non-magnetic body levitating in a magnetic fluid by the current in a command coil. Moreover, as shown in our previous papers (Olaru *et.al.*, 2012, 2013; Petrescu *et.al.*, 2009) for a proper design configuration these actuators exhibit a linear force-current and displacement-current characteristic.

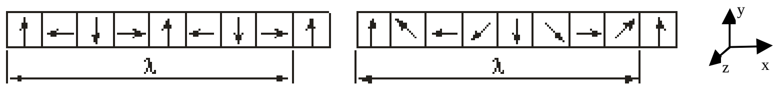
The present paper is structured in five sections. Section **2** presents the structure of a typical Halbach pattern in cylindrical and in planar coordinates and gives the general outline for the analytical field solutions as well as the field spectrum obtained by numerical simulation. Section 3 presents some typical tubular actuators reported in literature and their characteristic features. Section 4 presents the model of a new ferrofluid actuator with Halbach PM array, introduced by Petrescu *et.al.*, (2014), and gives the force-current characteristics for several configurations of the PM pattern. Section **5** emphasizes the conclusions of the research.

2. Typical Halbach Array Configurations

Two typical planar Halbach PM arrays in Cartesian coordinates are illustrated in Fig 1 *a* and 1 *b*.

The magnitude of the magnetization is the same in all the domains, but the orientation varies periodically. If the array extends to infinity in directions *Ox* and *Oz*, the solution for the magnetic flux density is of the form (Chen Li *et* *al.*, 2013):

$$B(x,y) = \left[A_1 \sin\left(\frac{2\pi}{\lambda}x\right) + A_2 \cos\left(\frac{2\pi}{\lambda}x\right) \right] e^{-\alpha y} . \quad (1)$$



a *b*

Fig.1 – Typical planar Halbach arrays.

Assuming the magnetization of each magnet is known, the constants A_1, A_2, α in the subdomains can be determined by imposing the boundary conditions (continuity of normal flux density and that of tangential magnetic field).

In Fig. 2 the magnetic field spectrum obtained with COMSOL Multiphysics for a planar Halbach array formed of 8 cubic magnets 1 cm high is plotted.

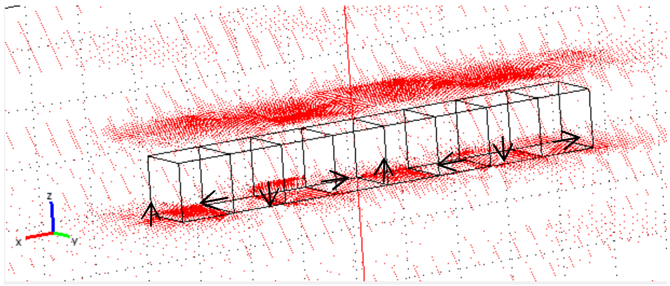


Fig. 2 – Magnetic field spectrum of a planar Halbach array.

Fig. 3 plots $|B(z)|$ in the middle of the Halbach array, $x = \lambda$, on the face with the higher field, $y = 0$, for the magnetization patterns given in Fig. 1 *a* and 1 *b* and for $M_r = 1/\mu_0$ A/m. It is to be noted that the magnetic flux density decreases faster on the bottom side, $z < 0$. A total cancelation would be obtained if the array extends infinitely in the *y* and *z* directions.

Typical Halbach PM arrays in polar coordinates are presented in Fig. 4. The magnetization of domain (*i*), in cases *c*1 and *c*3, has the expression:

$$M = M_r \left[\pm \sin(\theta^{(i)}) e_r \pm \cos(\theta^{(i)}) e_\theta \right], \quad (2)$$

where $\theta^{(i)}$ is the angular coordinate of the domain center. It is assumed that the domains extend infinitely in direction *Oz*. Fig. 5 plots the norm of the magnetic flux density in direction *Oy*, $|B(y)|$, in cases *c*1, *c*2, *c*3 depicted in Fig. 4, for $z = h/2$, $h = 1$ cm being the magnets height. The magnets have the inner radius 3 cm, outer radius 4 cm and remanent magnetization $M_r = 1/\mu_0$ A/m. The field decreases more rapidly outside the circular array. Total field cancellation would be obtained for an array with infinite extension in the *Oz* direction.

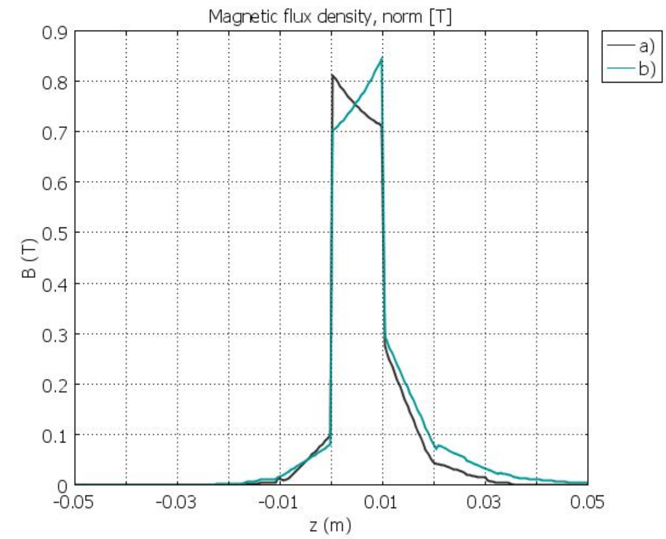
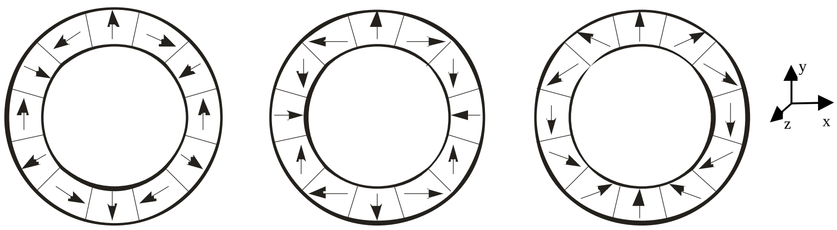


Fig. 3 – Magnetic flux density in direction *Oy* for magnetization patterns in Fig. 1 *a* and *b*.



*c*1 *c*2 *c*3

Fig. 4 – Halbach arrays in polar coordinates

3. Tubular Actuator Models that Use Halbach PM Arrays

A tubular actuator/motor that uses Halbach PMs is a cylindrical structure with a mobile part that can move in axial or in tangential direction (according to the design) and a fixed part (the stator). In most designs the mobile part is composed of PMs disposed in a Halbach array, with periodical arrangement in the *Oz* direction or in the tangential direction, depending on the intended direction of movement. The stator consists of a coil or a system of coils that can also create a Halbach like pattern. A typical tubular actuator with cylindrical Halbach array is presented in Fig. 6 (Jang *et al.* 2005). The magnetization pattern is that depicted in Fig.1 *a*, where the coordinates x and y are replaced by *z* and *r*.

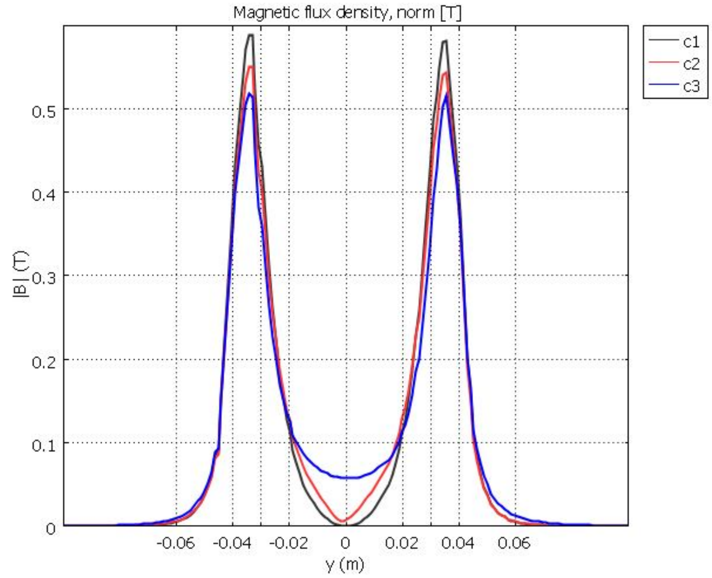


Fig. 5 – Magnetic flux density for magnetization patterns outlined in Fig. 4.

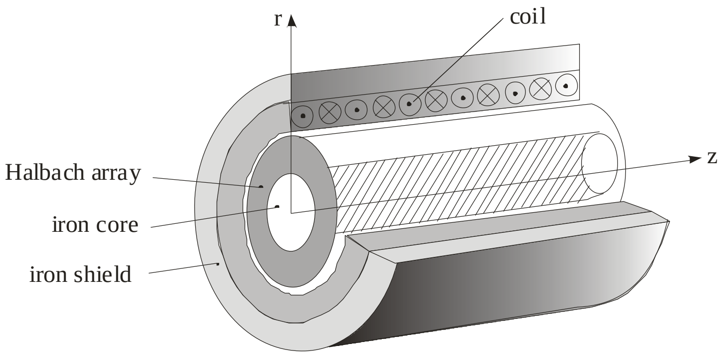
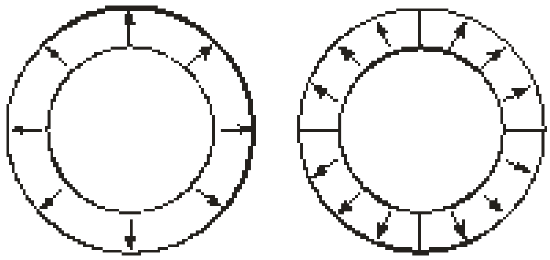


Fig. 6 – Tubular actuator with cylindrical Halbach array.

Since magnets with purely radial magnetization are more difficult to obtain, the solution of replacing these with iron rings is also used. Jang & al. suggest replacing the radially magnetized ring (Fig. 7 *a*) with the structure in Fig. 7 *b* consisting of four uniformly magnetized regions.

In Son *et al.*, (2011), a similar tubular actuator is proposed and its structure is optimized using genetic algorithms for a maximum thrust force. The usage of Halbach PM array proves to increase the resulting force by ~10% compared to the case when iron rings are used in the place of radially magnetized magnets.

The model presented by Jang *et al.*, (2005), is further analyzed by Jang *et al.*, (2007), and an analytical solution for the magnetic flux density inside the actuator is established.



a *b*

Fig. 7 – Modified radial pattern.

In Messen *et al.*, (2008), a modified structure of the Halbach pattern for tubular actuators is proposed, where the axial view sections of the magnets are changed from rectangular to trapezoidal (Fig. 8).

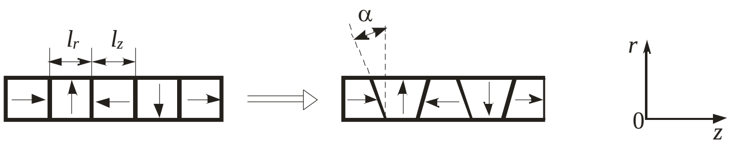


Fig. 8 – Modified axial pattern.

In an attempt to further increase the axial thrust force, a tubular linear machine with dual Halbach array is proposed and discussed by Yan *et al.*, (2013). An axial view of this actuator showing the magnetization patterns and the current pattern is shown in Fig. 9.

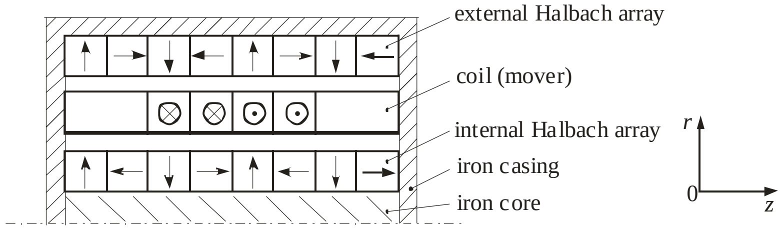


Fig. 9 – Dual Halbach array actuator.

In this model the coil system is the mobile component. The inner and outer Halbach arrays have the same magnetization in radial direction and opposite magnetizations in axial direction (Fig. 9). This arrangement leads to an increase of the radial B and a decrease of the axial B, thus resulting in an increased axial thrust force and a decreased radial vibration, given by the radial force component.

4. New Ferrofluid Actuator with PM Array

Given the interest and large usage of Halbach PM arrays in both planar and tubular actuators, and the sustained interest of the author of this paper in the study and optimization of ferrofluid based actuators, a new ferrofluid actuator that uses a Halbach PM array was proposed by Petrescu *et al.*, (2014).

The physical model of the actuator is presented in Fig.10. In the case of ferrofluid actuators the magnetic force that acts on a non-magnetic body immersed in the ferrofluid appears due to the magnetic field gradient established in the fluid by external magnets or coils. The position of this floating body, a cylinder, is controlled by the current in the command coil.

The resulting force may be obtained by integrating Maxwell's magnetic stress tensor, T_{nm}, on the body surface:

$$\begin{aligned} F_m &= F_z = \oint\!\!\!\oint_S T_{nm}\,\mathrm{d}A \\ T_{nm} &= 0.5\left(\mu_{ff} - \mu_0\right)\left(H_{1t}^2 + \frac{B_{1n}^2}{\mu_{ff}\mu_0}\right) \end{aligned} \quad . \tag{3}$$

where: μ_{ff} is the ferrofluid permeability and H_{1t} , B_{1n} represent the tangential and normal components of the magnetic field and magnetic flux density, respectively, on the surface of the non-magnetic body.

The ferrofluid actuator in Fig. 10 was analyzed numerically using COMSOL Multiphysics. The equation solved in this case in terms of the magnetic vector potential, **A**, was:

$$\nabla \times \left(\mu_0^{-1}\mu_r^{-1}\left(\nabla \times \mathrm{A} - \mathrm{B_r}\right)\right) = J_\varphi^{(e)}\mathrm{e}_\varphi \;, \; \mathrm{A} = A_\varphi \mathrm{e}_\varphi . \tag{4}$$

Several cases were investigated for the magnetization pattern and number of magnets (5, as in Fig. 10, or 4, but extending for the same length in axial direction). At the same time the importance of using two iron plates at the top and bottom of the PM array and also the presence of an iron casing (shield) was tested. Table 1 shows the thrust force F_z when the five regions in Fig. 10 have the magnetic properties:

$$\mathrm{B}_r^{(1)} = \mathrm{B}_r^{(2)} = B_{\mathrm{rem}}\mathrm{k},\; \mathrm{B}_r^{(3)} = 0,\; \mu_r = 500,\; \mathrm{B}_r^{(4)} = \mathrm{B}_r^{(5)} = -B_{\mathrm{rem}}\mathrm{k}\;, \tag{5}$$

with B_{rem} = 1.3 T. A coil with N = 1,750 wires and a current I = 2 A was considered. The geometrical parameters were: for the coil-inner radius 13.5 mm, outer radius 34.5 mm, height 35 mm; for the non-magnetic body r = 5.5 mm, h = 8 mm; for the ring magnets-inner radius 8 mm, outer radius 13.5 mm, height 5 mm; shield thickness 3 mm; iron plates height 5 mm. Results show the importance of shielding which doubles the resulting force.

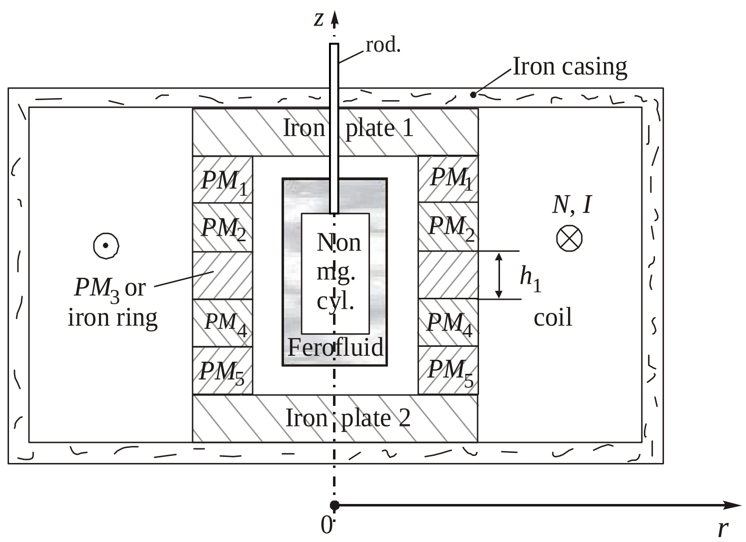


Fig. 10 – Ferrofluid actuator with Halbach PM array.

Table 1

Influence of Iron Shield and Iron Plates in Original Actuator

Configuration	F_z , [N]
No shield, no iron discs	0.205
No shield, with iron discs	0.24
With shield and iron discs	0.48

This is considered to be the original actuator configuration, where only magnets with axial magnetization are used to create a powerful magnetic field gradient. The maximum force obtained in this case, for the shielded configuration was F_z = 0.48 N.

Next, the effect of constructing a Halbach or quasi-Halbach PM array was investigated. Four identical ring magnets extending for the same height as in the previous case (5 × 5 mm = 25 mm) were considered. The magnetization patterns/magnetic properties for the significant analyzed cases are illustrated in Fig. 11, and the corresponding magnetic forces $F_z(I)$ in these cases are plotted in Fig. 12. In cases (5), (6) μ_r = 500.

As may be seen in Fig. 12 the characteristic $F_z(I)$ is linear in cases 1, 2, 3, 6 and non-linear in cases 4, 5, 7, 8. In case 8 the equilibrium position of the levitating non-magnetic body is not in the middle of the ferrofluid chamber, $F_z \neq 0$ for $I = 0$.

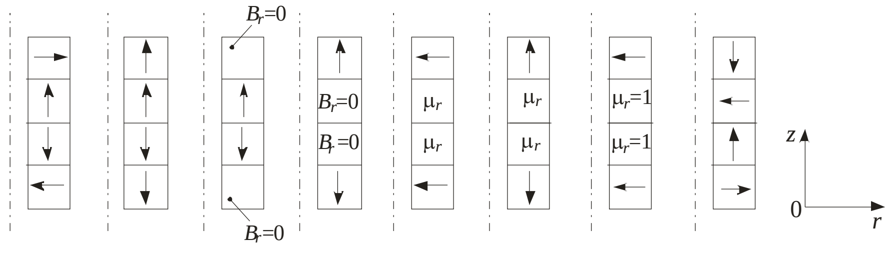


Fig. 11 – Magnetization patters for analysed configurations.

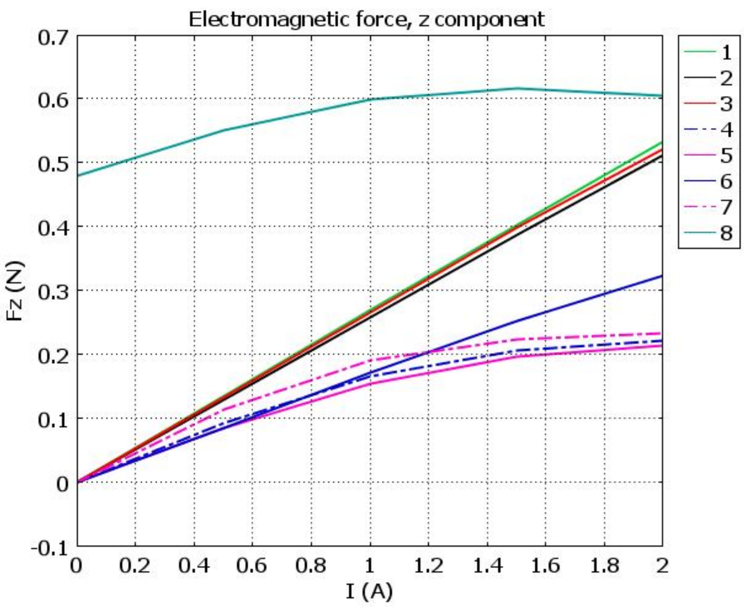


Fig. 12 – Magnetic force for the magnetization patterns outlined in Fig. 11.

An improvement of the actuator force is obtained for configurations 1, 2, 3, in these cases the linearity of the characteristic $F_z(I)$ being maintained. In the best case, (1), an increase in F_z of 9.2% is obtained, compared to the original model. Other investigated cases lead to smaller forces or to non-linear characteristics.

4. Conclusions

The references existing so far show the use of Halbach PM array in the construction of tubular as well as planar actuators, the mobile component being either the PM array or the exciting coil. Larger Laplace forces can be obtained for actuators that give axial thrust, due to the radial magnetic field produced by the PM array. Moreover, this PM array produces a magnetic field with sinusoidal variation in the axial direction, which is an important aspect for linear actuators.

Ferrofluid actuators do not use Laplace forces, but make use of the magnetic force acting on a magnetized material (the ferrofluid) exposed in exterior magnetic fields. In this respect the use of Halbach PM arrays in order to increase the force given by the ferrofluid actuator was investigated in this paper.

The objective was to identify a magnetization pattern of four ring magnets coaxial with the whole device that gives a maximum force and preserves the linearity of the force – current characteristic for the ferrofluid actuator. Indeed, the numerical simulations conducted in this study show that the characteristic force – current is linear for some magnetization patterns and non – linear for others, and that an increase in the axial force can be obtained in some cases. The results obtained so far show a maximum increase of 9.2% in the axial force rendered by the ferrofluid actuator when using a quasi – Halbach arrangement of the four ring magnets, compared to the original case (axial pre – magnetization of the ferrofluid).

The research in the field of ferrofluid actuators with Halbach or quasi – Halbach PM arrays is at the very beginning, but the first results seem promising. Further studies are necessary to optimize, if possible, the magnetization pattern and the geometrical parameters and number of magnets, considering the ferrofluid chamber and device dimensions invariable.

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UTILIZAREA MAGNEŢILOR PERMANENŢI ÎN STRUCTURĂ HALBACH PENTRU CREŞTEREA FORŢEI GENERATE DE UN DISPOZITIV DE ACŢIONARE BAZAT PE FEROFLUIDE

(Rezumat)

Se analizează un dispozitiv de acţionare bazat pe ferofluide în a cărui configuraţie s-a introdus un sistem de magneţi inelari în structură Halbach sau cuasi-Halbach în scopul creşterii forţei generate de dispozitiv de acţionare. Se prezintă şi modele de dispozitive de acţionare cilindrici care utilizează magneţi în structură Halbach a căror acţiune se bazează pe generarea unei forţe Laplace. Noul tip de dispozitiv de acţionare cu ferofluid şi magneţi în structură Halbach păstrează liniaritatea caracteristicii intrare–ieşire (curent–forţă) şi realizează o creştere cu 9.2% a forţei generate faţă de un dispozitiv de acţionare similar în care magneţii de premagnetizare a ferofluidului au doar magnetizaţie în direcţie axială.