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INFLUENCE OF THE POLES SHAPE OF DC ELECTROMAGNETIC ACTUATOR ON ITS THRUST CHARACTERISTIC

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Many technical objects use the electromagnetic DC actuators, which, unlike AC actuators, are more reliable, simpler in terms of manufacturing technology and have greater wear resistance. The listed advantages are the reason for the significant use of DC actuators in various industries including application as drive mechanisms of electrical devices. The DC actuator as a part of any technical object almost always plays one of the main roles from the point of view of reliable operation of entire device. Therefore the question of studying the designs of actuators and their characteristics is a rather topical task. Three designs of forward-moving electromagnetic DC actuators with the same overall dimensions and winding data are studied. They differ in the shapes of the supporting surfaces of poles, in other words, the surfaces with flat, conical and cut-conical shapes. As established, the shape of the supporting surfaces of poles has a significant impact on the thrust characteristics of the actuator and depending on the length of air gap this effect has a different character. The patterns of magnetic field of the studied actuators with an attracted armature are constructed, and the nature of magnetic field distribution and magnetic flux density distribution in operated gap are evaluated. The nature of the influence of cutting angle on static thrust characteristic for actuators with conical and cut-conical pole shapes is studied too. References 21, table 1, figures 7.
Keywords: electromagnetic DC actuator, static thrust characteristic, finite-element method, shape of supporting surfaces, poles of DC actuator.

Introduction. Direct current (DC) electromagnetic actuators are used as a source of mechanical displacements and creation of necessary forces in many technical objects. In contrast with AC actuators, DC actuators are more reliable due to the lesser number of parts in their construction. The actuators are simpler from the point of view of fabrication practice, do not require the operations of stamping, riveting, grinding of supporting surfaces, installation of short-circuited turns, etc., do not fail when the supporting surfaces of poles are contaminated or when short-circuited turns in the windings occur and have greater wear resistance. The listed advantages are the reason for the wide use of DC actuators in various industries including application as drive mechanisms of electrical devices.

The DC actuator (hereinafter referred to as actuator) as a part of any technical object almost always plays one of the main roles from the point of view of entire device reliability as a whole. Therefore the issue of improving the designs of actuators in order to improve their characteristics is a rather urgent task.

Review of publications. Problem definition. Many publications both among the domestic [1–3] and foreign scientists [4–17] are devoted to the problems of investigation and numerical modeling with further experimental verification of various actuator designs, but insufficient attention is paid to study on the influence of the shapes of the support surfaces of poles of forward-moving DC electromagnetic actuators on their static thrust characteristics. Therefore the further development of investigation in this area is relevant. It should be noted that in the vast majority of works the tool for conducting the numerical calculations is commercial licensed computer codes, which are currently practically inaccessible to most domestic researchers. This significantly limits the possibilities of domestic scientists. The FEMM code [18] among the codes with open access is the most widespread. This code is built on finite-element method and its computed results are verified experimentally by electrical engineers [19, 20]. Therefore the FEMM code is used in this work for study and modeling of electromagnetic processes in DC forward-moving actuator. The finite-element method is used along with FEMM program on open access [18] to carry out the numerical calculations of the static thrust characteristics of DC actuator.

It is known [8, 12, 16, 17] that the static thrust characteristic is one of the important characteristics of actuators. That is the dependence of thrust force F on the length of operated air gap δ between the poles of actuator at the constant magnetomotive force of winding F_m. The shape and dimensions of the supporting

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surfaces of actuator's poles have an effect on the shape of the thrust characteristics of actuator. The analysis of publications reveals that the question on the influence of DC actuator poles shape on the thrust characteristic of actuator does not sufficiently studied especially in the sense of improvement of design and technical characteristics.

The **aim of this work** is to determine the nature of the influence of the shape of poles supporting surfaces of DC electromagnetic actuator on its static thrust characteristic. The study is based on the determination of the magnetic field distribution in operated air gap between the poles of the actuator.

The well-known approach is used for **numerical modeling** of magnetic field of the actuator. According to this approach the magnetic field is determined in the subdomains, within which the magnetic permeability of ferromagnetic materials generally depends on the magnetic field strength in accordance with the main magnetization curve of corresponding material [21]. This allows to carry out the numerical solving of the nonlinear Poisson equation for given regions in terms of magnetic vector potential $\boldsymbol{A}(x, y, z)$ [21] for the known current density vector $\boldsymbol{j}(x, y, z)$ of external source specified by initial data. Here the boundary conditions for magnetic vector potential at subdomain boundaries are applied. The conditions are derived by the tangential components of magnetic field strength $\boldsymbol{H}$ and the normal components of magnetic flux density $\boldsymbol{B}$.

The Poisson equation in the general case of calculating the spatial distribution of 3D magnetic field in a ferromagnetic medium in the Cartesian coordinate system has the form [21]

$$\nabla\left[\frac{1}{\mu}\nabla\boldsymbol{A}(x,y,z)\right]=-\boldsymbol{j}(x,y,z)\,, \tag{1}$$

where $\boldsymbol{A}$ is the magnetic vector potential; $\boldsymbol{j}$ is the current density vector of external source; μ is the magnetic permeability of the material; ∇ is the Hamiltonian operator.

The finite-element method [21] allows to solve equation (1), that is to find the spatial magnetic field distribution in the structure under consideration by, for example, minimizing the corresponding functional (such a functional in FEMM code is the magnetic energy W accumulated in the field). The initial data supplemented by boundary conditions as well as energy dependencies lead to a system of nonlinear algebraic equations, the result of solving of which is the spatial distribution of magnetic vector potential $\boldsymbol{A}$. Knowing its values at each point of computational area allows to find magnetic flux density vector $\boldsymbol{B}$ and magnetic field strength vector $\boldsymbol{H}$ according to following expressions [21]:

$$\boldsymbol{B}=\mathrm{rot}\boldsymbol{A};\quad \boldsymbol{H}=\boldsymbol{B}/\mu\,. \tag{2}$$

Further, with known parameters of the magnetic field (2) at each point, the thrust force F of actuator can be found by:

$$F=\frac{1}{2}\oint_{S}\left[\boldsymbol{H}(\boldsymbol{nB})+\boldsymbol{B}(\boldsymbol{nH})-\boldsymbol{n}(\boldsymbol{HB})\right]\mathrm{d}S\,, \tag{3}$$

where $\boldsymbol{B}$ is the magnetic flux density vector on the outer surface of body; $\boldsymbol{n}$ is the unit normal vector; $\boldsymbol{S}$ is the surface over which the integration is carried out.

To perform the numerical modeling of magnetic field for axisymmetric actuator, equation (1) is written in the cylindrical coordinate system as

$$\frac{\partial}{\partial z}\left(\frac{1}{\mu(H)}\frac{\partial A_\varphi}{\partial z}\right)+\frac{\partial}{\partial r}\left(\frac{1}{\mu(H)r}\frac{\partial\left(rA_\varphi\right)}{\partial r}\right)=-j\left(r,z\right), \tag{4}$$

where A_φ is the magnetic vector potential (azimuthal component); r, z are the coordinates of the point of magnetic field region; $\mu(r, z)$ is the magnetic permeability of material at corresponding point in space with coordinates r, z (at corresponding node of finite-element mesh), the magnetic permeability depends on magnetic field strength H at point r, z; j is the given current density of external source at point with coordinates r, z.

The equation is solved in the domain as an open space:

$$r\in(0,\infty);\quad z\in(-\infty,\infty)\,, \tag{5}$$

with the boundary condition of symmetry on the axis:

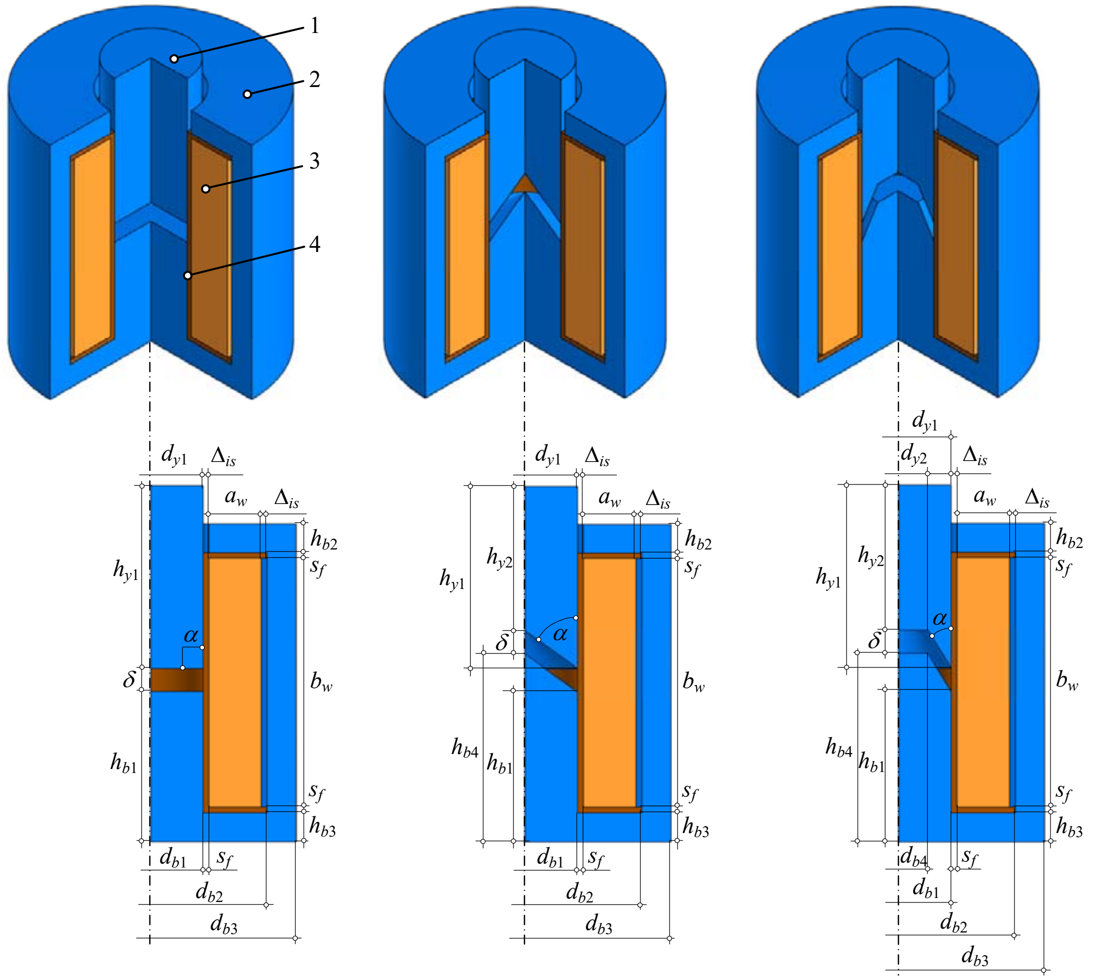
$$A_\varphi(0,z)=0\,. \tag{6}$$

That allows considering the field in r-z plane, that is, within only half of actuator design, and then the significantly reduced computational resources (running time, on-line storage, computer random access memory) is required for simulation.

Practically in order to limit the computational region, the zero boundary conditions for the azimuthal component of magnetic vector potential A_φ are set at the outer boundaries of the region sufficiently distant from actuator.

The non-linear equation (4) has no analytical solution for the complex configuration of boundaries, including the case under consideration; therefore the modern numerical methods are used to solve such equations, the most widespread of which is finite-element method [21].

The subject for investigation in this article consists in the three most common designs of cylindrical axisymmetric actuators with the same overall dimensions and winding data. The designs differ only in the shape of the supporting surfaces of poles, particularly – with flat (PL), conical (CON) and cut-conical (CUT) shapes according to Fig. 1 and Table (dimensions of the actuators are given in mm).



a *b* *c*

Fig. 1

The magnetization curve $B = f(H)$ of 10895 steel for the armature and actuator body is shown in Fig. 2.

The parameters of actuators' windings are assumed to be the same, specifically: supply voltage U_{dc} = 36 V; turn number w = 4500; winding wire diameter d_m = 0.5 mm; current in the winding I = 0.47 A.

	Armature – 10895 steel				Body – 10895 steel								Coil			Gaps		
Pole	d_{y1}	d_{y2}	h_{y1}	h_{y2}	d_{b1}	d_{b2}	d_{b3}	d_{b4}	h_{b1}	h_{b2}	h_{b3}	h_{b4}	a_w	b_w	s_f	Δ_{is}	δ_{min}	δ_{max}
Flat (α = 90°)		–		–				–				–						
Conical (α = 55°)		–		50				–				65						
Cut-conical (α = 30°)	36	20	63	50	36	80	100	20	52	10	10	65	18	86	2	2	0,2	8

In Table: Δ_{is} is the thickness of winding shrouding; δ_{mi} is the minimum gap between the armature and body when the armature is attracted, (the gap takes place due to surface roughness and anti-corrosion coating); δ_{max} is the maximum gap between the armature and body at released armature.

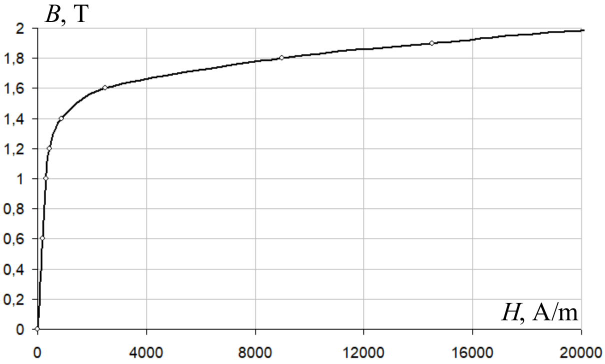


Fig. 2

Computed results. The static thrust characteristics of the actuators studied are obtained as a result of computations. The results along with opposing characteristic (P) are shown in Fig. 3. For better visualization Fig. 3 shows simultaneously the enlarged sections of thrust characteristics near gap with length δ = 2 mm and δ = 8 mm.

Analysis of the obtained results (Fig. 3) shows the following:

• the shape of pole supporting surfaces significantly affects the shape of actuator thrust characteristic, and depending on air gap length, this effect has a different character;

• *when the armature is attracted* (δ = 0.2 mm), the actuators with all shapes of pole supporting surfaces are operable, as they develop the thrust force greater than the opposing characteristic. The actuator with flat pole shape develops the largest thrust force (1175 N), which is 1.45 times greater than the thrust force of the actuator with conical pole shape (810 N) and 2.32 times greater than the thrust force of the actuator with cut-conical poles (507 N);

• *at* δ *= 2 mm* (the «jump» of opposing characteristic, associated with the need to create the additional pressure, for example, in order to compress the contact spring of electrical device and to ensure the necessary force of contact pressure), the actuator with flat pole shape is already inoperative, since its thrust force (294 N) is less than the opposing characteristic (300 N). In this section of armature movement, the actuator with conical pole shape (338 N) develops the greatest thrust force, which is 1.1 times greater than the thrust force of the actuator with cut-conical pole shape (310 N) and 1.15 times greater than the thrust force of the actuator with flat pole shape (294 N);

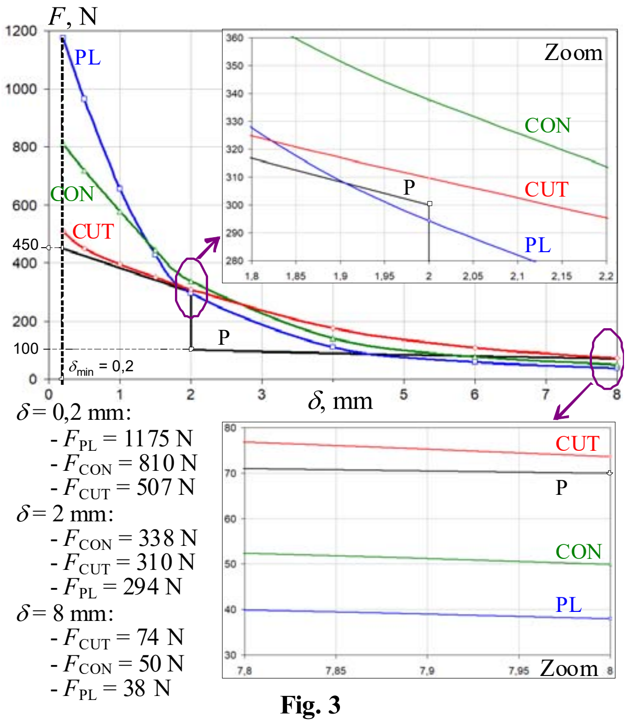
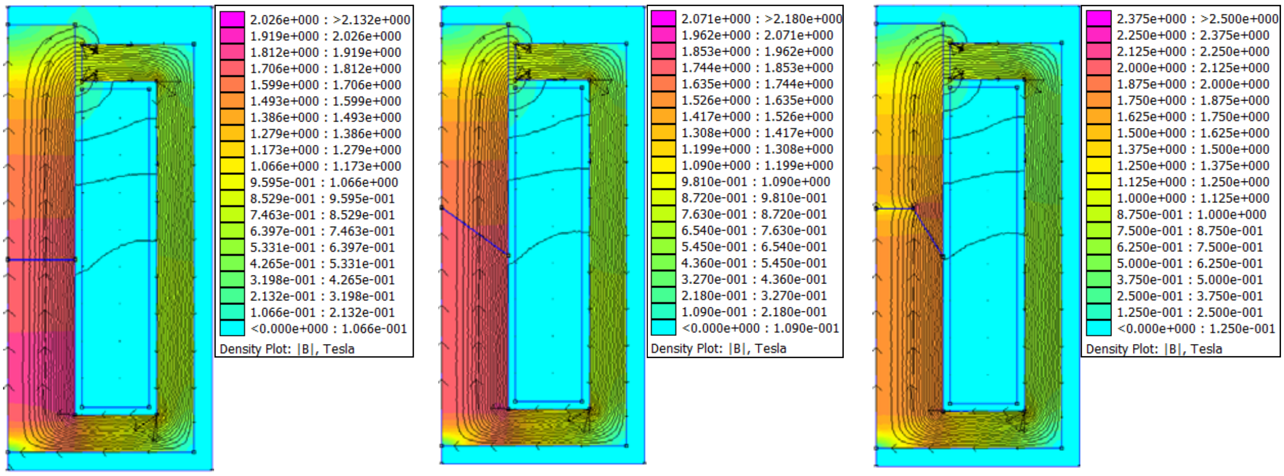


Fig. 3

• *when the armature is released* (δ = 8 mm), two actuators: with flat (38 N) and conical (50 N) pole shapes are incapable of start for movement and overcoming the opposing characteristic (70 N) and, accordingly, are inoperative. Thus the only actuator with cut-conical pole shape remains operable; the thrust force of such actuator at initial moment is the largest (74 N), the force is 1.48 times greater than the thrust force of the actuator with conical pole shape (50 N) and 1.95 times greater than the thrust force of the actuator with flat pole shape (38 N);

• only changing the shape of pole supporting surfaces provides the capacity of operation of actuator without changing either overall dimensions or the dimensions of magnetic core sections, or supply voltage and winding data. In order to reveal the nature of magnetic field distribution for the studied actuators, the computations are carried out using FEMM code. The magnetic flux density distributions at attracted armature are presented in Fig. 4. In this case the maximum saturation of the magnetic system takes place.

The plots of magnetic flux density in operated air gap at attracted armature are shown in Fig. 5.



a ***b*** ***c***

Fig. 4

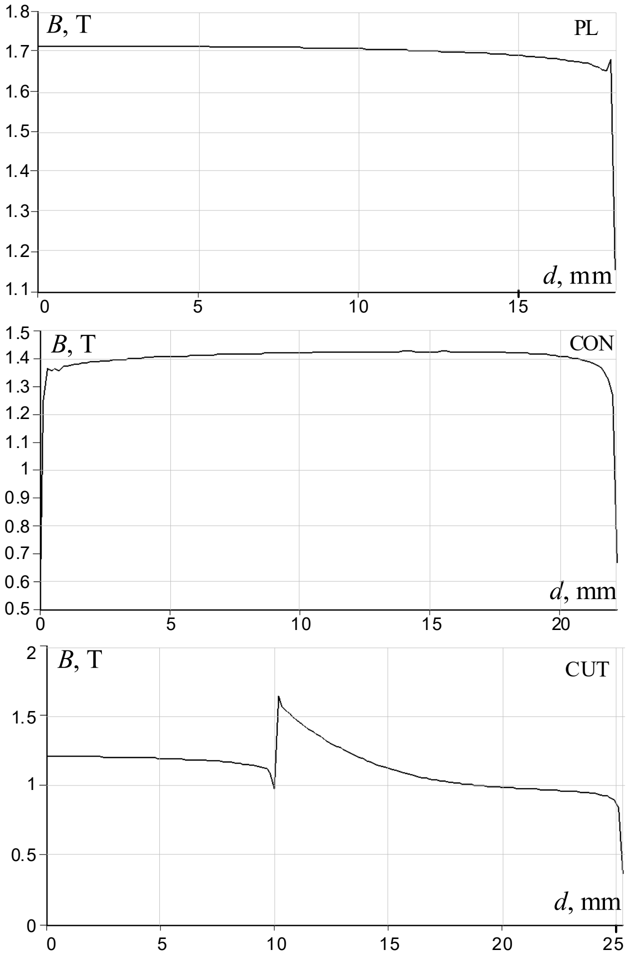


Fig. 5

The analysis of computed results in Fig. 5 shows the following:

• the plots of magnetic flux density in the area of operated gap of the actuators with flat and conical pole shapes have a monotonic character with average value of ~1.7 T for armature with flat pole shape and ~1.4 T for armature with conical pole shape. It is obvious that the lesser value of magnetic flux density is related to the larger area through which the magnetic flux passes in operated gap;

• the average value of the magnetic flux density of the actuator with cut-conical pole shape is the smallest among all considered actuators (~1.2 T), and the magnetic flux density variation is more complex and nonuniform, i.e. with sharp increase in the area of pole cut and further monotonous decrease.

The next stage is studying the influence of angle α (see Fig. 1) on the static thrust characteristics of the actuators with conical and cut-conical pole shapes. The results of computations are given in Fig. 6, *a* for actuator with conical pole shape and in Fig. 6, *b* for actuator with a cut-conical pole shape.

Fig. 7 presents the static thrust characteristics at different fixed values of angle α (*a* – 30°; *b* – 45°; *c* – 60°; *d* – 75°) for the actuators with conical and cut-conical shapes of pole supporting surfaces.

The results in Fig. 7 show the following:

• at attracted armature (δ = 0.2 mm) for all values of angle α, the actuator with cut-conical pole shape develops the greater thrust force than the actuator with conical pole shape, and as angle α increases the ratio of corresponding thrust forces (F_{CUT}/F_{CON}) for the two actuators decreases and has the following values:

- F_{CUT}/F_{CON} = 507.27 / 324.61 = 1.56 at α = 30°;
- F_{CUT}/F_{CON} = 711.5 / 628.9 = 1.13 at α = 45°;
- F_{CUT}/F_{CON} = 976.2 / 910.1 = 1.07 at α = 60°;
- F_{CUT}/F_{CON} = 1118.5 / 1106.7 = 1.01 at α = 75°;

• when the operated air gap increases from 0.2 to 8 mm, the degree of influence of angle α on static thrust characteristic for both actuators decreases. As seen from Fig. 7, the effect on static thrust characteristic is practically not detected at α = 75° and obviously at larger angles.

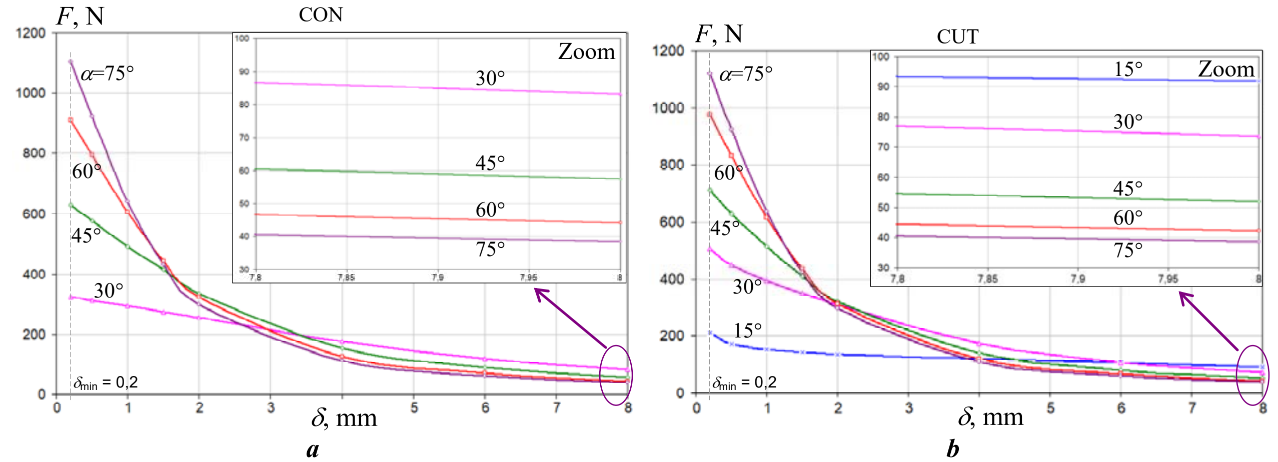


Fig. 6

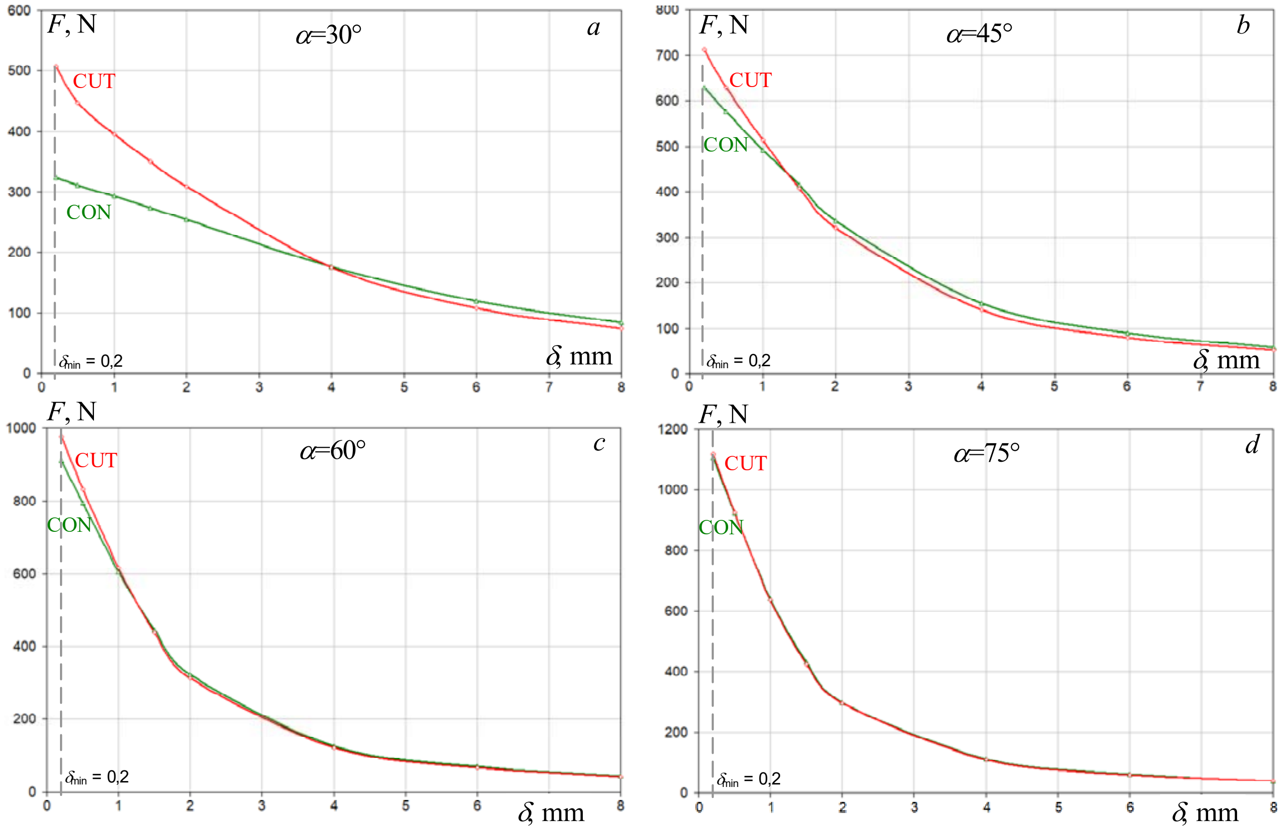


Fig. 7

Conclusion. It is revealed that the shape of actuator poles has a different effect on the shape of thrust characteristic depending on the length of air gap:

- when the armature is attracted, the actuator with a flat pole shape develops the largest thrust force, which is 1.45 times greater than the thrust force of the actuator with conical pole shape and 2.32 times greater than the thrust force of the actuator with cut-conical pole shape;
- when the air gap increases, the shape of the actuator poles has a lesser effect on the thrust characteristic, and when the armature is completely released at the initial moment of movement the thrust force of the actuator with cut-conical pole shape is the largest and 1.48 times greater than the thrust force of the actuator with conical pole shape and 1.95 times greater than the thrust force of the actuator with flat pole shape.

The nature of the effect of cutting angle on static thrust characteristic for actuators with conical and cut-conical pole shapes is determined:

• when the armature is attracted, the actuator with cut-conical pole shape develops the greater thrust force than the actuator with conical pole shape for all values of angle α, and as angle α increases, the ratio of corresponding thrust forces (F_{CUT}/F_{CON}) of the two actuators decreases;

• when the operated gap increases, the degree of influence of angle α on static thrust characteristic for the both actuators decreases, and when angle $\alpha \geq 75°$, the influence on the static thrust characteristic is practically not available.

The obtained results may form the basis for the development of recommendations on the design of actuators with improved technical characteristics.

Conflict of interest. The author of the article declares no conflict of interest.

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ВПЛИВ ФОРМИ ПОЛЮСІВ ЕЛЕКТРОМАГНІТНОГО АКТУАТОРА ПОСТІЙНОГО СТРУМУ НА ЙОГО ТЯГОВУ ХАРАКТЕРИСТИКУ

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Вступ. *У багатьох технічних об'єктах застосовуються електромагнітні актуатори постійного струму, які, на відміну від актуаторів змінного струму, відрізняються більшою надійністю, є простішими з точки зору технології виготовлення та мають більшу механічну зносостійкість. Перелічені переваги є причиною значного застосування саме актуаторів постійного струму в різних галузях промисловості, в тому числі у якості привідних механізмів електричних апаратів. У складі будь-якого технічного об'єкту актуатор постійного струму майже завжди відіграє одну з головних ролей з точки зору надійності функціонування усього пристрою цілком. Тому питання удосконалення конструкцій актуаторів з метою покращення їхніх характеристик є доволі актуальним завданням.* ***Мета.*** *Встановлення характеру впливу форми опорних поверхонь полюсів прямоходового електромагнітного актуатора постійного струму на його статичну тягову характеристику.* ***Методологія.*** *Характер впливу форми опорних поверхонь актуаторів на їхню тягову характеристику досліджено на основі визначення розподілу магнітного поля у їх повітряних робочих проміжках за допомогою методу скінченних елементів із використанням програми FEMM.* ***Оригінальність.*** *Отримали подальший розвиток дослідження циліндричних прямоходових електромагнітних актуаторів постійного струму щодо встановлення характеру впливу форми опорних поверхонь полюсів на їх статичну тягову характеристику.* ***Результати.*** *Досліджено три найбільш поширені конструкції прямоходових електромагнітних актуаторів постійного струму із однаковими габаритними розмірами та обмотковими даними, які відрізняються між собою формами опорних поверхонь полюсів – із пласкою, конічною та зрізано-конічною формами. Встановлено, що форма опорних поверхонь полюсів суттєво впливає на форму тягової характеристики актуатора і в залежності від значення повітряного проміжку цей вплив має різний характер. Побудовано картини магнітного поля досліджуваних актуаторів при притягнутому якорі, проведена оцінка характеру розподілу магнітного поля та розподілу магнітної індукції у повітряному робочому проміжку. Досліджено характер впливу кута зрізу на статичну тягову характеристику для актуаторів із конічною та зрізано-конічною формами полюсів.* Бібл. 21, табл. 1, рис. 7.

Ключові слова: електромагнітний актуатор постійного струму, статична тягова характеристика, метод скінченних елементів, форма опорних поверхонь полюсів актуатора постійного струму.

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