621.316.72
621.3.024

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POSSIBILITIES OF OBTAINING FLAT STATIC CHARACTERISTIC OF DC FERROMAGNETIC ACTUATOR*)

ABSTRACT *DC ferromagnetic actuators enter generally into the composition of electric systems, used e.g. in electric apparatus, numerically controlled machines, in various automatons, robots, as well as in nuclear engineering where such kind of equipment, often combined with permanent magnets constitute important elements, of control and safety protection of nuclear reactors. In many applications they should have flat static characteristics, ensuring practically constant force, independently of armature position with respect to the stationary parts of the servo.*

The paper considers two possibilities of achieving flat characteristics by:
a) a special design of the magnetic core, ensuring its constant magnetic resistance at any armature position, and b) excitation current control ensuring a constant magnetic flux in the magnetic core of the servo.

*) This work was financially supported from project LN 00B34 (Ministry of Education of the Czech Republic) and Research Plan MSM 212300016.

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In the first case the desired result can be achieved by into the suitable slanting of armature or by placing nonmagnetic inserts moving parts because the excitation current will then remain constant without any control.

In the second case the actuator is simple and the practically flat characteristic is achieved by controlling the current according to the instantaneous position of the armature. However, this method requires a highly precise sensor and a sufficiently fast control circuitry.

The device can be properly designed only in the way of mathematical and computer-aided modelling. The existing professional programs are usually of no use for solving the problem fully, thus it becomes often necessary to combine a suitable professional tool with a user procedure developed especially for a determined class of tasks.

On the basis of a numerical analysis of the problem the following conclusions can be drawn:

- *Suitable design modifications of selected parts of the actuator can ensure accurately or approximately flat static characteristic.*
- *A good method is slanting the front part of the armature. The higher the slanting the flatter is the static characteristic. However this method may be limited by various technological considerations.*
- *Building the armature of several magnetic and nonmagnetic parts may lead to relatively flat characteristics however there appeare here often sharp minima and maxima which cannot be accepted in some applications.*
- *A perfectly flat characteristic can be achieved by direct control of the excitation current, depending on the position of the device moving parts. However this method requires a very precise sensor and an adequately fast control system.*

1. INTRODUCTION

DC ferromagnetic actuators – no matter whether they work as fast linear motors or switching electromagnets – represent widely used parts of heavy current systems that find application, for instance, in electric apparatus, numerically controlled machines, various automats, robots, and also in the nuclear engineering where special devices of this kind, often combined with permanent magnets, are used as an important parts of regulation and protective circuits of nuclear reactors. They have to satisfy various requirements that depend on the role they play in the given system. In a lot of applications, for example, they should exhibit a sufficiently flat static characteristic providing practically constant mechanical force of the actuator, independent of position of the armature with respect to its unmovable parts.

The paper deals with numerical analysis of two basic possibilities of obtaining a flat characteristic by means of

- special construction of the magnetic circuit that secures approximately constant magnetic resistance of magnetic circuit for any position of the armature,
- controlled field current providing constant magnetic flux through magnetic circuit of the actuator.

In the first case, the required result may be achieved by suitable slanting of the armature or inserting a nonmagnetic element into the movable parts. The field current is considered constant, without any regulation.

In the second case the arrangement of the actuator may remain simple and practically constant static characteristic may be obtained by control of the current that is regulated according to the instantaneous position of the armature. This way necessitates, however, highly accurate sensor and sufficiently fast control circuitry.

The only way how to correctly design the device is its mathematical and computer modeling. The complete mathematical model of the system consists of one nonlinear and nonstationary partial differential equation describing the distribution of electromagnetic field and one ordinary differential equation describing the movement of the armature. Specific cases may also require solution of another equation describing the time evolution of field current in the feeding circuit.

As the existing professional programs are usually not capable of providing complete solution of the problem, it is often necessary to combine suitable professional codes with single-purpose user procedures developed especially for certain classes of tasks.

Even when references on ferromagnetic actuators abound (see, for instance [1], [2], [3] and many others), they are prevailingly aimed at selected results (static and dynamic characteristics etc.). Optimization of their structural parts from various viewpoints is not such a frequent topic and, thus, the paper represents a contribution just in this domain.

2. FORMULATION OF THE TECHNICAL PROBLEM

Given is the basic arrangement of the actuator (Fig.1a) whose principal dimensions (with respect to the system it is built in) cannot change. The static characteristic of the actuator is required to be as flat as possible, and the force acting on the movable part at any position should be within a prescribed range.

The task is to

- Investigate and evaluate the static characteristic of the device for a series of field currents.
- Investigate the influence of slanting of the movable part of the armature (Fig.1b).
- Evaluate the influence of nonmagnetic element (part 11 in Fig.1c).
- Evaluate the possibilities of control of the field current.

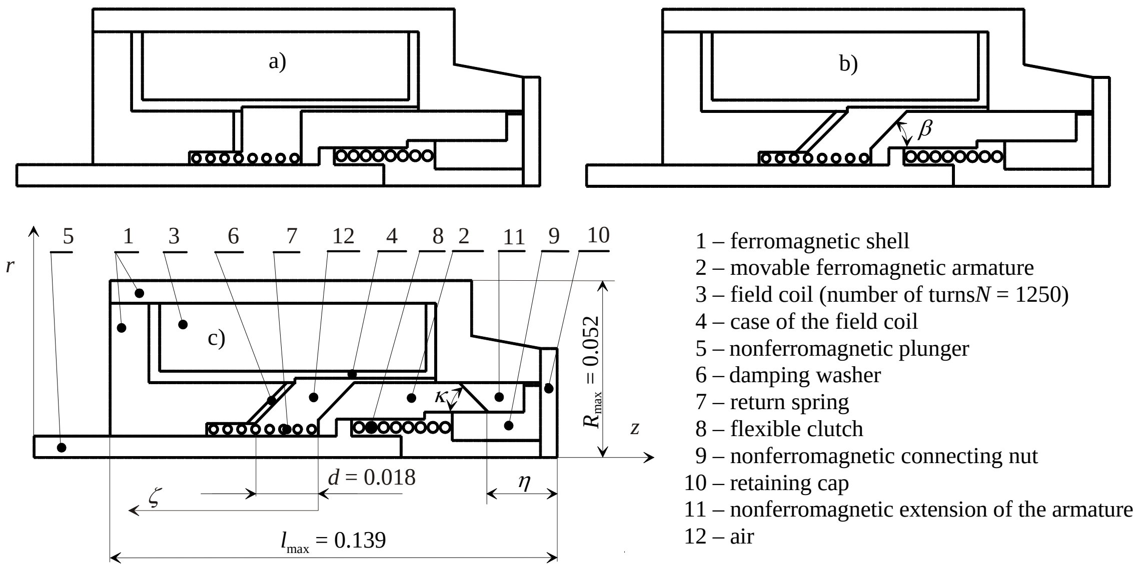

Fig.1. Investigated actuator

a) Basic arrangement, b) Conical modification of the armature front, c) Armature from magnetic and nonmagnetic parts

3. MATHEMATICAL MODEL AND ITS SOLUTION

The arrangement is considered axisymmetric and will be investigated in coordinates r, z. Distribution of the *electromagnetic field* in a definition area with boundary CDEFC depicted in Fig.2 is described in terms of magnetic vector potential $\boldsymbol{A}$ (of course, some elements of the definition area may change when solving various variants of the device, see Figs. 1a, b, c). The governing equation reads [4]

$$\mathrm{rot}\left(\frac{1}{\mu}\mathrm{rot}\,\boldsymbol{A}\right) = \boldsymbol{J}_{\mathrm{ext}} \qquad (1)$$

where $\boldsymbol{J}_{\text{ext}}$ denotes the density of external field current and μ permeability of the material. Both vector potential and external current density have only one component in the tangential direction A_φ and $J_{\text{ext},\varphi}$, respectively. Finally the boundary condition along line CDEFC reads $A_\varphi = 0$.

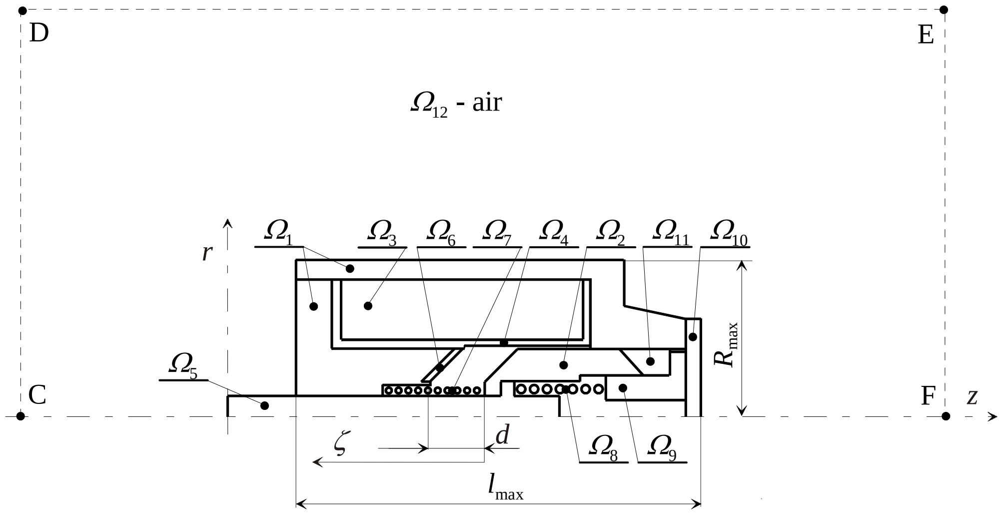

Fig.2. Definition area of the problem (particular elements are denoted in accordance with Fig.1c)

The force acting on movable parts (parts **2** and **11**, see Fig.1c) with boundary S_{m} may be calculated from well-known formula

$$\boldsymbol{F}_{\text{m}} = \frac{1}{2} \oint_{S_{\text{m}}} \left[\boldsymbol{H}\left(\boldsymbol{n} \cdot \boldsymbol{B}\right) + \boldsymbol{B}\left(\boldsymbol{n} \cdot \boldsymbol{H}\right) - \boldsymbol{n}\left(\boldsymbol{B} \cdot \boldsymbol{H}\right) \right] \mathrm{d}\boldsymbol{S} \tag{2}$$

where $\boldsymbol{B}$ and $\boldsymbol{H}$ are the field vectors and $\boldsymbol{n}$ is the unit vector of the outward normal to boundary S_{m}. Provided that the arrangement is axisymmetric, force $\boldsymbol{F}_{\text{m}}$ has only one component F_{m} in direction z.

This mathematical model was solved by combination of professional code QuickField [5] and several single-purpose user procedures written by the authors. Evaluated were many various arrangements in order to obtain the required static characteristic given by relation $F_{\text{m}}(\zeta)$ where $\zeta \in \langle 0, d \rangle$ denotes the shift of armature **2**.

4. ILLUSTRATIVE EXAMPLES

As the first case we investigated the basic disposition depicted in Fig.1a). The principal material parameters and properties of individual parts follow:

- Magnetic circuit **1** and armature **2**: carbon steel 12 040 whose magnetization characteristic is depicted in Fig.3.
- Plunger **5**, clutch **8,** spring **7** and parts **9**, **10**: nonmagnetic austenitic steel 17 335 with relative permeability $\mu_r = 1$.
- Coil insulation **4** and washer **6** are made from Teflon.
- Field coil **3**: Copper conductor, number of turns $N = 1250$.

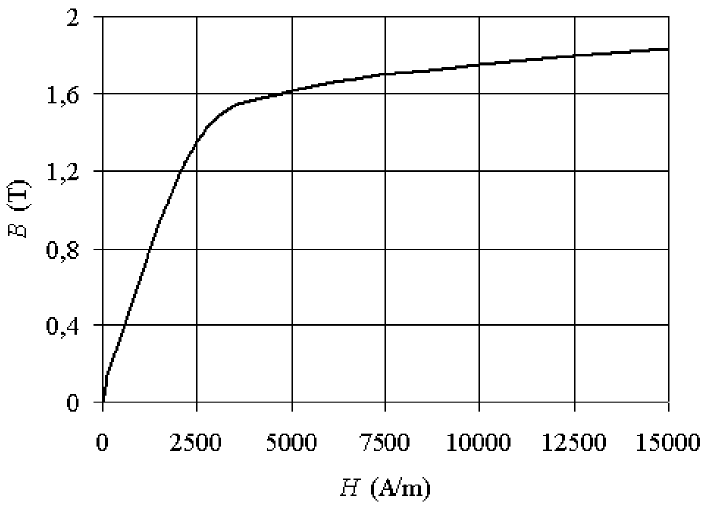

Fig.3. Magnetization characteristic of steel 12 040

Calculations of electromagnetic field were performed on a mesh with about 100000 elements, which provided sufficient accuracy of the results (tests on geometrical convergence confirmed accuracy to two valid digits). For an illustration, Fig.4 depicts distribution of magnetic field in the device for field current density 4 A/mm^2 and air gap between the movable and unmovable parts 2 mm

Fig.4. Magnetic field distribution for current density 4 A/mm^2 and air gap 2 mm

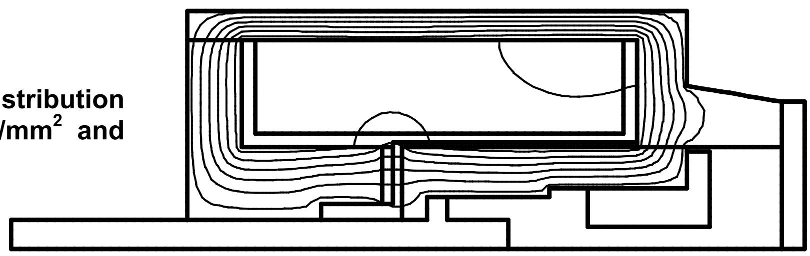

Figure 5 shows a series of static characteristics for various field currents $I_{\mathrm{ext}}(\zeta)$. These characteristics grow with increasing coordinate ζ and from the viewpoint of flatness are, unfortunately, unacceptable.

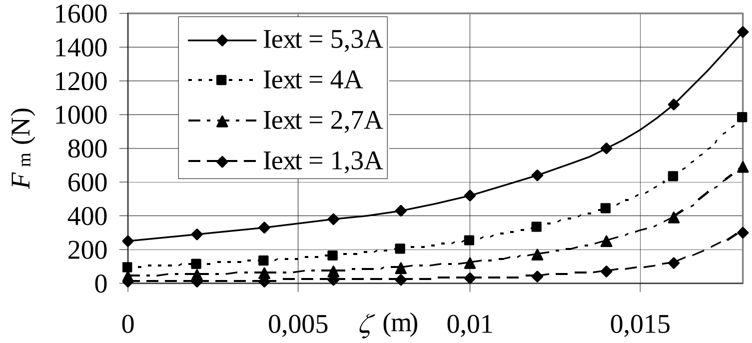

Fig.5. Static characteristics of the basic arrangement for selected field current densities

In the next step we investigated the influence of slanting the armature (see Fig.1b). Fig.6 shows the static characteristics for varying angle β.

It can be seen that for decreasing angle β the static characteristic becomes flatter and flatter. But from the viewpoint of technological aspects, further reduction of this angle is practically impossible. Several more computations confirmed that the shape of the above curves remained similar even for higher currents providing higher values of magnetic forces.

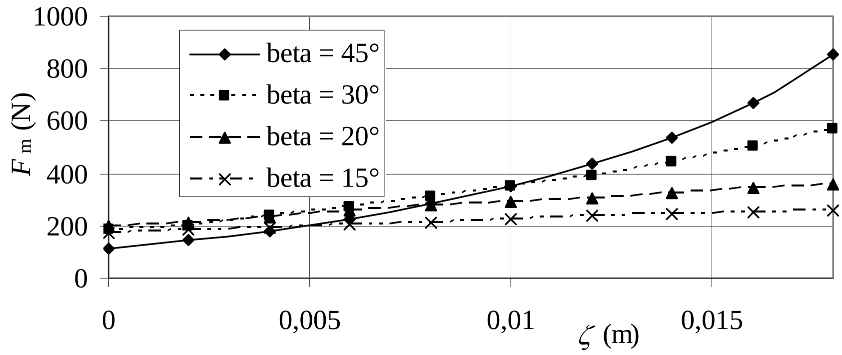

Fig.6. Static characteristic of the device for varying angle β of the armature ($J_{\mathrm{ext}} = 3 \cdot 10^6$ A/m^2)

Another possibility how to affect the static characteristic is to build the movable part from two elements (one of them being ferromagnetic – **2** and one nonferromagnetic – **11**). Geometry of both parts can vary in a wide range and optimization of their shapes is quite a complicated business. Figure 7 shows, for example the static characteristics of such arrangement.

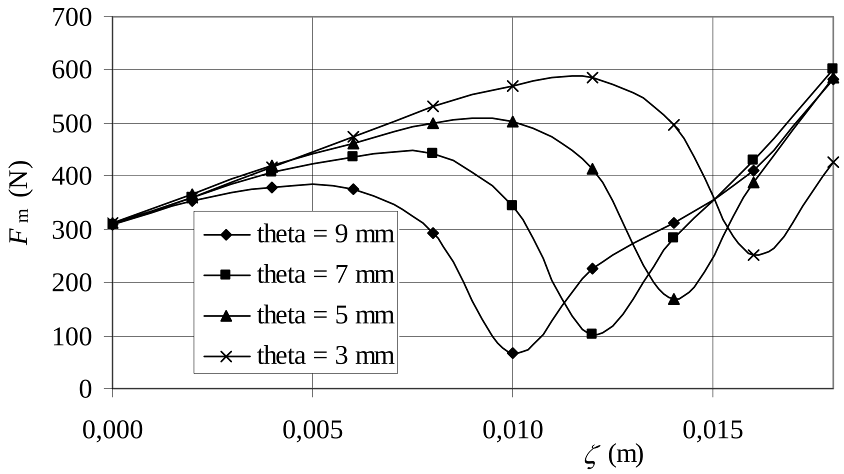

Fig.7. Static characteristics for alternative in Fig.1c for $J_{ext} = 5 \cdot 10^6$ A/m^2 and varying values of distance η (angles: $\beta = 90°$, $\kappa = 45°$)

Calculated families of these static characteristics are characterized by well expressed extremes. Even when a lot of various shapes of parts **2** and **11** were considered, we did not succeeded in obtaining sufficiently flat characteristics.

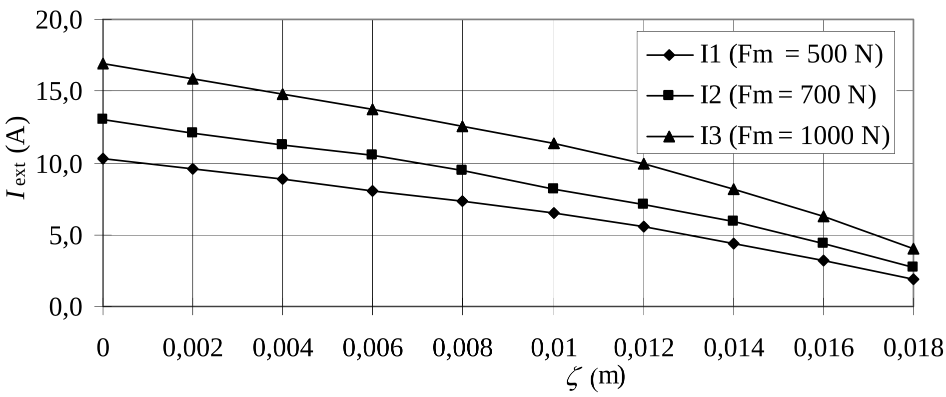

Fig.8. Function $I_{ext} = I_{ext}(\zeta)$ for reaching constant static characteristic ($F_m = 500, 700, 1000$ N), $\beta = 90°$

The final possibility is to regulate the field current in dependence on the instantaneous position ζ of the movable parts. In this way we can obtain a perfectly flat characteristic that we can iteratively construct for any prescribed magnetic force. Nevertheless, this technique requires an accurate position sensor and fast circuitry resulting in much higher financial costs necessary for building the system.

Figure 8 shows the position-dependent field currents necessary for reaching the prescribed forces at levels 500 N, 700 N and 1000 N.

5. CONCLUSION

A thorough numerical analysis of the problem led to the following conclusions:

- Specific construction modifications of selected part of the actuator can result in perfectly or approximately flat static characteristic.
- A good method consists in slanting the front of the armature. The higher degree of slanting, the flatter is the static characteristic. This way may be limited, however, by various technological aspects.
- Building of the armature from several magnetic and nonmagnetic parts may lead to relatively flat characteristic, but often with sharp minima and maxima, which is unacceptable in some applications.
- A perfectly flat static characteristic may be obtained by direct control of the field current whose value depends on the position of the movable parts of the device. This way requires, however, an extremely accurate sensor and sufficiently fast circuitry.

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Manuscript submitted 28.10.2004
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UZYSKIWANIE PŁASKICH CHARAKTERYSTYK STATYCZNYCH FERROMAGNETYCZNEGO SIŁOWNIKA PRĄDU STAŁEGO

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STRESZCZENIE *Ferromagnetyczne siłowniki (aktuatory) prądu stałego wchodzą powszechnie w skład systemów silnoprądowych, stosowanych np. w aparatach elektrycznych, maszynach sterowanych numerycznie, w różnych automatach, robotach, a także w inżynierii jądrowej, gdzie tego rodzaju przyrządy, często w kombinacji z magnesami trwałymi, są ważnymi elementami regulacji i zabezpieczeń reaktorów jądrowych. W wielu zastosowaniach powinny mieć płaskie charakterystyki statyczne, zapewniając praktycznie stałą siłę, niezależnie od położenia twornika względem części nieruchomych siłownika.*

W artykule rozważono dwie możliwości uzyskania płaskich charakterystyk poprzez:
a) specjalną konstrukcję magnetowodu, zapewniającą stałą jego rezystancję magnetyczną w każdej pozycji twornika, oraz b) regulację prądu wzbudzenia, zapewniając stały strumień magnetyczny w magnetowodzie siłownika.

W pierwszym przypadku pożądany wynik można osiągnąć poprzez odpowiednie skoszenie twornika lub umieszczenie niemagnetycznej wkładki w częściach ruchomych; prąd wzbudzenia będzie miał stałą wartość, bez regulacji.

W drugim przypadku siłownik jest prosty, a praktycznie stałą charakterystykę osiąga się regulując prąd stosownie do chwilowego położenia twornika. Ten sposób wymaga jednakże wysoce dokładnego czujnika i dostatecznie szybkiego obwodu sterowania.

Prawidłowo można zaprojektować przyrząd jedynie drogą matematycznego i komputerowego modelowania. Istniejące programy profesjonalne zazwyczaj są nieprzydatne do pełnego rozwiązania problemu, zachodzi zatem często potrzeba kombinacji odpowiedniego narzędzia profesjonalnego z procedurą użytkownika opracowaną specjalnie dla określonej klasy zadań.

Na podstawie analizy numerycznej problemu można wyciągnąć następujące wnioski:

- *Odpowiednie modyfikacje konstrukcyjne wybranych części siłownika mogą zaowocować dokładnie bądź przybliżeniu płaską charakterystyką statyczną.*
- *Dobrą metodą jest skoszenie czoła twornika. Im większy jest stopień skoszenia, tym bardziej płaska będzie charakterystyka statyczna. Sposób ten może być ograniczony jednakże różnymi względami technologicznymi.*

- *Budowa twornika z kilku części magnetycznych i niemagnetycznych może prowadzić do względnie płaskich charakterystyk, jednak częstokroć występują tu ostre minima i maksima, co jest nie do przyjęcia w niektórych zastosowaniach.*
- *Doskonale płaska charakterystykę statyczna uzyskuje się poprzez bezpośrednie sterowanie prądu wzbudzenia, zależnie od położenia części ruchomych przyrządu. Ten sposób wymaga jednakże bardzo dokładnego czujnika i odpowiednio szybkiego układu sterowania.*