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MOVING MAGNET TYPE ACTUATOR WITH RING MAGNETS

Ciprian Astratini-Enache* — Radu Olaru* — Camelia Petrescu*

In this paper a linear moving-magnet actuator with ring magnets is proposed and studied. The actuator has a proportional action because of the repulsive forces (elastomagnetic forces) developed between the two fixed magnets and the moving magnet(s). The experimental results obtained refer to: the distribution of magnetic flux density around of the movable element (with and without fixed magnets), the elastomagnetic stiffness for the repulsive interaction between the mobile element and a fixed magnet, static transfer characteristics (force *vs* current for different types of configuration) *etc*.

The magnetic field and the force acting on the mobile element are determined numerically using the software COMSOL Multiphysics, based on finite element method (FEM).

Keywords: magnetic field, electromagnetic actuator, moving magnet actuator, finite element method

1 INTRODUCTION

Electromagnetic actuators represent a very broad topic, covering a wide range of technologies, magnetic circuit topologies and performance characteristics imposed by the continuous growth of the spectrum of applications. These devices can be divided in three main categories: moving iron actuators, moving coil actuators and moving magnet actuators.

As a consequence of recent achievements in advanced magnetic materials and developments in the areas of power electronics, microprocessor and digital control strategies, and due to the continuous application of high performance motion control systems, currently there is a high research activity and development of electromagnetic actuators with permanent magnets for applications that include all economic sectors.

Moving magnet type actuators with linear motion have the mobile element (translator) constituted by a shaft and one or more permanent magnets having cylindrical shape [1, 2].

Commercial software based on FEM, designed to solve single or coupled physics problems described by partial differential equations (PDEs), is used to determine the distribution of the magnetic flux density around a movable element (with or without fixed magnets) and the force acting on the mobile element. Some experimental results compared with those obtained by performing the numerical field analysis, are reported [3, 4].

2 BASIC STRUCTURE OF MOVING MAGNET ACTUATOR

The linear moving magnet actuator (MMA) studied in this paper is shown in Fig. 1. It is composed of a coil with two identical opposing windings, moving magnet(s) or translator (which may consist of one or two annular shaped magnets), and two smaller ring magnets positioned at both ends. If the mobile magnets have the poles of the same name face to face, repulsive forces are typically generated. The opposing configuration allows for open loop control of position and stiffness. Actually, some innovative devices have been reported so far [5-7].

In order to improve the actuator performance *ie* the force generated by MMA, ferromagnetic disks are positioned on the faces of the mobile element. The proposed MMA has a minimum number of components and, depending on the size of the available neodymium permanent magnets, can be easily miniaturized.

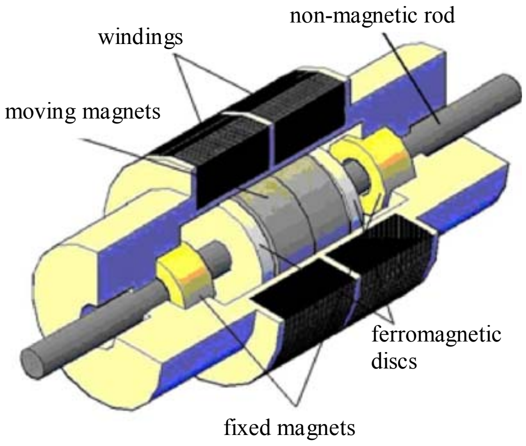

Fig. 1. MMA with repulsive magnetic forces

Ring magnets used in electromagnet actuators present a series of structural advantages. Replacement of mechanical spring systems, with a system consisting of permanent magnets positioned so as to generate repulsive forces, allows devices to increase operating cycle and to be easily miniaturized.

3 PHYSICAL MODEL OF THE MOVING MAGNET AND NUMERICAL ANALYSIS

3.1 Physical model

MMA performance according to design parameters can be predicted rapidly using numerical field analysis. The magnetic field and the transmitted force, F_z, acting on the mobile element can be determined numerically using the software COMSOL Multiphysics [8], [9], based on the finite element method, and capable of analyzing multiphysics problems.

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Two models of the moving magnetic part, were analysed each having two ring magnets, attractive (Fig. 2) and repulsive (Fig. 3) coupled, respectively. To realize a more accurate comparison between the force acting in axial direction in both cases, several factors must be taken into account, such as: the coils must have identical inner and outer radii, $R_{c\ int}$, $R_{c\ ext}$, and the total length of the coil system must be the same in all cases, $2L_c = 2L_1 + L_2$. The MMA types presented (Figs. 2 and 3) must have the permanent magnets identical in terms of length, l, exterior radius, r_m and remanent magnetic flux density, B_r.

In this case the equation solved by COMSOL is:

$$\nabla \times \left(\mu_0^{-1}\mu_r^{-1}\nabla \times \mathbf{A}\right) = J_\theta^{(ext)} \tag{1}$$

where $\boldsymbol{A} = A_\theta \boldsymbol{e}_\theta$ is the magnetic vector potential and $\mathbf{J} = J_\theta \mathbf{e}_\theta$ is the externally generated current density, with $J_\theta^{(ext)} = \pm \dfrac{N\,i}{(R_{cext} - R_{c\,int})\,L_c}$ in the coil. The formula applies for the first model. For the second model the externally generated current density is obtained by replacing the coil length L_c with L_1 or L_2.

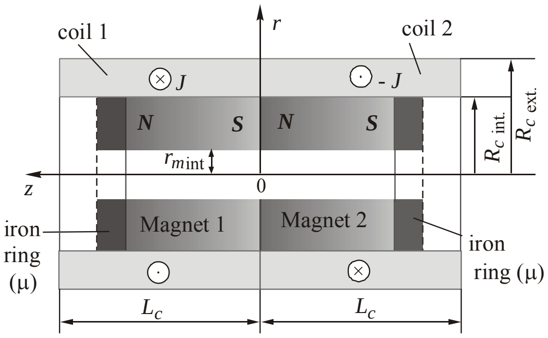

Fig 2. Moving magnet model

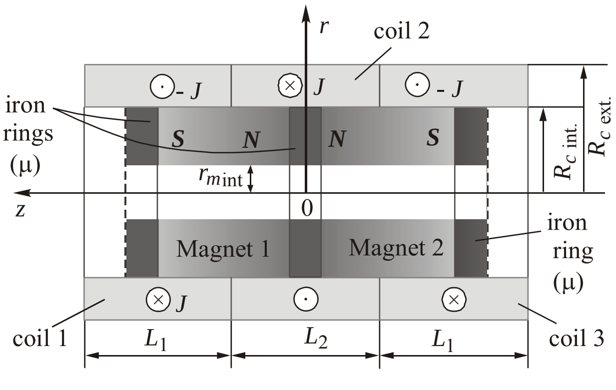

Fig. 3. Moving magnet model 2

The force acting in axial direction can be determined using Maxwell's magnetic surface stress tensor, T_{nmz}, and integrating on the surface of the mobile part:

$$F_z = \iint_{S_{ext}} \left[(\mathbf{n}\cdot\mathbf{H})\cdot\mathbf{B}^{\mathrm{T}} - \frac{1}{2}\mathbf{n}\cdot(\mathbf{H}\cdot\mathbf{B}) \right] \mathrm{d}A = \iint_{S_{ext}} T_{\mathrm{nmz}} \mathrm{d}A \tag{2}$$

where **n** is the normal pointing outwards from the permanent magnets and iron discs.

In the case of non-shielded devices, such as those analyzed in this chapter, the dimensions of the analyzed domain, a rectangle in the (r, z) plane must be chosen carefully so as to minimize the error due to space truncation.

Successive tests were carried out in order to establish the appropriate dimensions, taking into account that error minimization in field calculation requires a larger domain for analysis, but memory constraints impose a limitation. The domain extension in radial direction, r_{max} was 4.28 times the outer coil radius (r_{max}=4.28$R_{c\ ext}$) and that in axial direction, z_{max}, was 4.61 times that of the device height (z_{max}=4.61×2L_c).

The subdomain settings in the Azimuthal Induction Currents, Vector potential Mode concern the constitutive relation, $B = \mu_0\mu_r H + B_r$ in the permanent magnets, and $B = \mu_0\mu_r H$ elsewhere, with μ_r=1 in all subdomains, except the iron plates (where applicable). The current density is non-zero only in the subdomains corresponding to the coils. The force F_z is defined using the same name on all subdomains corresponding to the mobile part (magnets and iron plates). Lagrange quadratic shape functions (second order finite elements) were used in the field calculation.

3.2 Numerical results and analysis

The numerical values for the electric and geometric parameters were: J=1.6 A/mm^2, μ_r=200 (for the iron discs), B_r=1.29 T, l = 6mm (magnet length), L_c= 13mm (coil length), $R_{c\ int}$= 7.5mm, $R_{c\ ext}$= 14mm, $r_{m\ int}$= 3mm, L_1= 9mm, L_2= 8mm. The iron rings height was 2mm.

The numerical results for the axial force F_z, is considered for two cases: with and without ferromagnetic rings. For the first studied model (Fig. 2.) a 1.6395 N thrust force F_z is obtained without rigs and a 1.8381 N is obtained in the presence of rings. For the second model (Fig. 3.) the resultant force from simulations is 1.5294 N without rigs and 1.7795 N with ferromagnetic rigs.

The data show that the iron plates of high permeability placed on both ends of the magnets, and also between them (in models 2), increase the thrust force. The difference $\Delta F_z = F_z\big|_{\substack{with\\rings}} - F_z\big|_{\substack{without\\rings}}$ is depicted for both studied models. The absolute difference values, ΔF_z, for the first studied model is 0.1986 N and for second model is 0.2501 N.

A further increase of the thrust force F_z in the configurations with tubular magnets can be obtained for a smaller inner radius, $r_{m\ int}$.

The total magnetic energy for the 4 studied cases is presented in Table 1.

Table 1 Magnetic energy in the studied configurations

		W_m(J)
Model 1	Without iron rings	0.8247
	With iron rings	0.9074
Model 2	Without iron rings	0.5555
	With iron rings	0.6507

It is to be noted that the largest forces are not necessarily associated with the highest total magnetic field energy and that system 2, in which multiple differential couplings occur, have smaller energies than models 1. The presence of the iron plates always produces a slight increase in W_m.

4 EXPERIMENTAL AND SIMULATION RESULTS

4.1 Magnetic flux density study

Accurate calculation of the field distribution is essential for the design of the linear electromagnetic actuators. The magnetic field generated by the permanent magnets for different configurations is determined in two ways: experimentally and by simulation.

Determination of the magnetic flux density, *B*, by successive measurements was made at the same height, 4 mm, from the central magnet face, in the middle of coil turns interacting with the command current. The results are presented in Fig. 4.

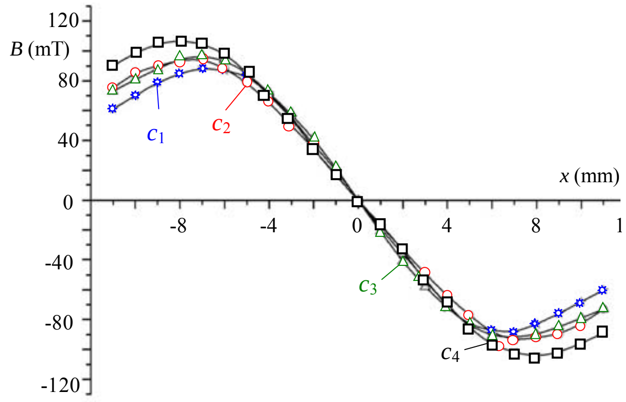

Fig. 4. B vs. x for different magnetic configurations of the MMA: c_1- without fixed magnets; c_2- with disks of 3 mm thickness; c_3- with fixed magnets, d= 9.5 mm; c_4- with disks of 3mm and fixed magnets, d= 9.5 mm.

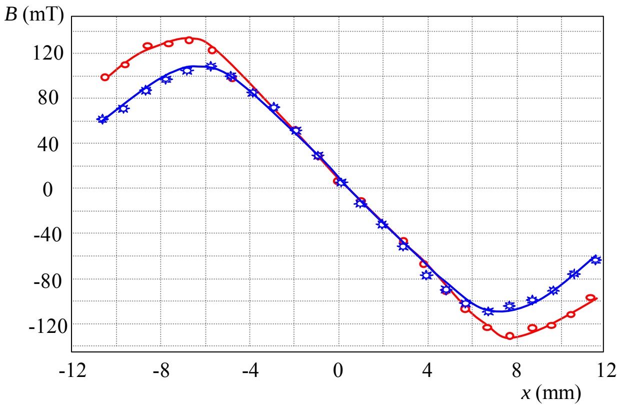

Fig. 5. Simulation of „c1” and „c4” magnetic flux density

From Fig. 4 it is clear that if a magnetic combination, denoted „c4”, of ferromagnetic ring disks having 3 mm thickness and a distance between the magnets d = 9.5 mm is used, a higher magnetic flux density is obtained than using the „c2” magnetic combination, with 3 mm ferromagnetic disks and without fixed magnets, or the „c3” magnetic combination, with fixed magnets and without ferromagnetic ring disks. Experimental results were compared with the initial configuration, consisting only of a mobile magnetic component (translator) „c1”.

In Fig. 5 a configuration identical to that in Fig. 4 is analyzed, the difference being the method of obtaining the data (these are results of simulation). The case when only the mobile component is used (star representation), and the case with 3 mm ferromagnetic disk and fixed magnets at 9.5 mm from the moving magnets (point representation) are presented. The characteristic is similar to that presented for measured values, but in this case larger values are obtained.

4.2 Force determination

The repulsive force generated between magnets allows the mobile component to return to the starting position. When the distance between magnets, *d*, becomes smaller, a higher repulsive strength is generated. The dependence on distance of the repulsive forces generated between the magnets is shown in Fig. 6. Because of the resultant repulsive force (elastomagnetic force) developed between the two fixed magnets and the moving magnet(s), the actuator has a proportional action (the displacement is proportional to the current).

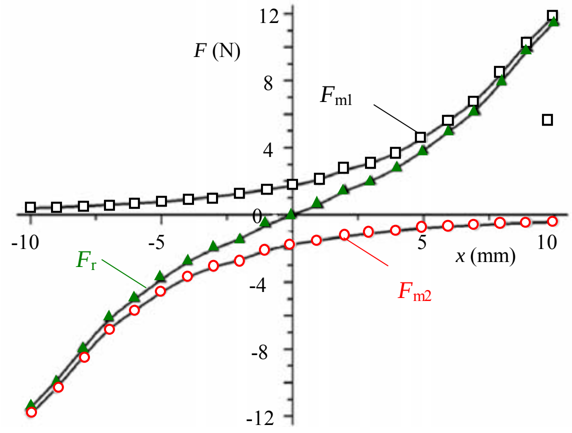

Fig. 6. Elasto-magnetic forces between the magnets

Knowing the elastomagnetic forces between the magnets, the elasto-magnetic constant, k_{em}, can be easily determinated, resulting in

$$k_{em} = \frac{\Delta F}{\Delta x} = 0.648 \text{ N/m} \qquad (3)$$

Thrust force determinations was made for real conditions when the distance between mobile magnets and stator coils is about 2.5 mm. Experimental values are noted with F_{exp}, and simulated values with F_{sim} (Fig. 7)

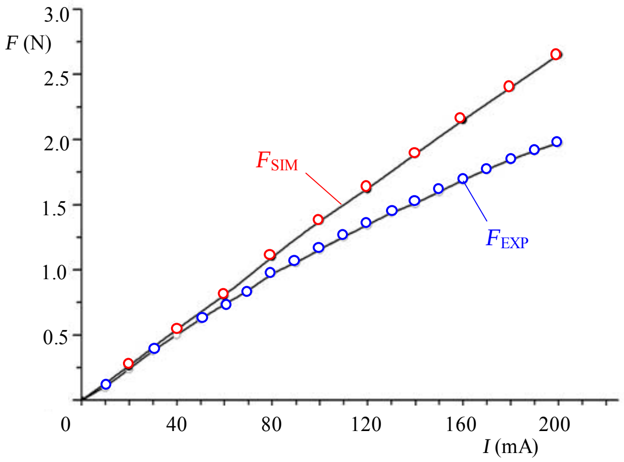

Fig. 7. Thrust force for different values of the current

5 CONCLUSIONS

Accurate calculation of the magnetic field distribution is essential for the design of the linear electromagnetic actuators. Magnetic field generated by permanent magnets for different configurations is determined in two ways: measured and simulated.

Using ferromagnetic disks leads to improved magnetic field, a higher force being obtained using the same permanent magnet material. The magnetic field is also improved when fixed magnets are used, and the highest value is obtained with a 3 mm thick ferromagnetic disk and fixed magnets set at 9.5 mm from the moving magnets.

Configurations with two or more permanent magnets, with poles of the same name face to face, can be used to create repulsive forces on the moving element without electric power and also to improve the distribution of the magnetic field.

Finite-element analysis using Comsol Multiphysics is an efficient method for obtaining information on the performance of a linear MMA. Different configurations can be easily analyzed in terms of influence parameters that occur, leading to system optimization.

Development of innovative multifunctional actuators, with a minimum number of components depends on the size of the available magnets. Using the presented configurations, a higher force is obtained with the same permanent magnet material, thus reducing the cost of production.

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