Application of Neodymium-Iron-Boron Permanent Magnets on the Assembling of a Novel Planar Actuator

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***Abstract*—This paper depicts a new planar actuator, with novel structure and construction features. It includes a slotless stationary plane armature and a mover with two permanent magnets. By using NdFeB permanent magnets with high-energy product, it became possible to develop a planar motor with a novel topology. The planar actuator develops movement over a plane surface as a result of the interaction between the magnetic flux and current established through the orthogonal multiphase windings that comprehend the armature circuit. The actuator was analysed by means of the finite element method in order to compute the flux density distribution, the forces involved and improve its design. The results are presented in this paper.**

***Index Terms*—Planar actuator, xy motor, NdFeB permanent magnet, surface motor.**

I. INTRODUCTION

Planar motors, also named surface motors, x-y motors or two-dimensional linear motors, can be used in applications that require movement on a plane in two directions (x-y axes), e.g. semiconductor waffles and printed circuits movers, and pieces machined by numerically controlled (NC) machines. The use of electronic control systems allows motion of that sort of motor with accurate position detection and rapid response without the loss of steps or position deviation. Many research centres are involved in the development of surface motors usually based on the Sawyer motor topology [1]-[2]-[3]. The novel planar actuator analysed by this work has quite different characteristics in its structure: with a stationary slotless armature and a mover with two high-energy product NdFeB permanent magnets. The application of new materials with excellent magnetic characteristics, like NdFeB permanent magnets, propitiated the development of a planar motor with a novel topology.

II. BASIC STRUCTURE OF THE PLANAR ACTUATOR

Fig. 1 presents the perspective view of the planar actuator. The planar actuator has a stator with a plane surface and a mover with two permanent magnets. It has multiphase armature windings wound round an iron plate or armature core in such a way that two orthogonal windings are produced: one winding is assembled around the x-axis forming the x-coil sections, and the other around the y-axis forming the y-coil sections. The orthogonal windings have no electric connections one with the other and are assembled in intercalated layers, i. e. over one layer of the x-coil there will be a layer of the y-coil and so on. Owing to design considerations, each winding is divided into 12 independent coil sections or phases. There are 495 turns per coil section. The armature core is a soft iron slotless plate, measuring 400 mm x 400 mm x 8 mm. Between the mover and the stator there is a 1-mm thick acrylic plate that provides a regular plane surface for the mover. The mover has two NdFeB permanent magnets, placed in a truck structure with small bearings that enable bi-directional motion over the acrylic plate. This results in an actuator with two degrees of freedom. The moving direction is parallel to the plane surface. In the design presented here, the authors are using two NdFeB permanent magnets, having the following characteristics: $B_r = 1.24$ T, $H_c = 889.93$ kA/m and $BH_{max} = 295.87$ kJ/m^3. Each coil section has the same width as the permanent magnets. Fig. 2 presents a frontal view of the planar actuator. The permanent magnets are separated from the armature core by a 14-mm long airgap and are assembled in an opposition fashion to complete a closed magnet circuit. The coil arrangement allows the driving of as many coil sections as necessary at the same time.

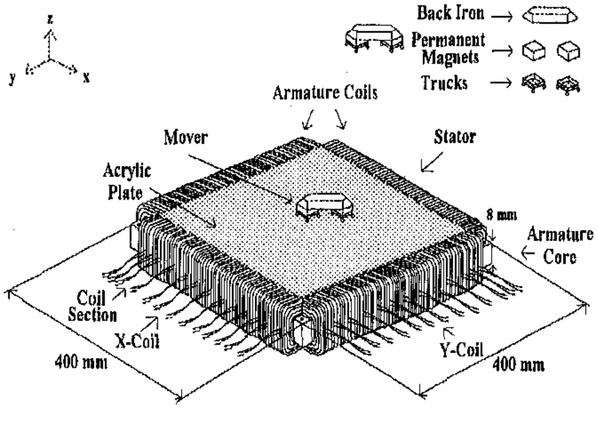

Fig. 1 – Perspective view of the planar actuator.

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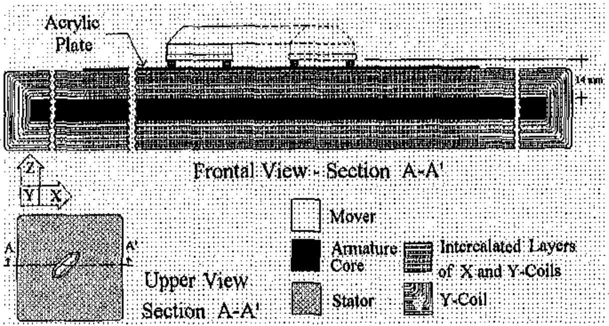


Fig. 2 - Frontal view of the planar actuator.

III. Analysis Methodology and Results

When one permanent magnet is located over a dc-excited coil section, a magnetic force will be created on the mover that pushes it accordingly. The moving direction is parallel to the plane surface. The intensity of magnetic force depends on the values of the active coil magnetomotive force and the airgap flux density established by the permanent magnets through the airgap. The movement will take place along the x and y-axis according to the electric current and flux density directions. The force can be computed theoretically by the Lorentz's law [4]. Its equation is derived from (1)

$$\vec{F}_n = \int_{V_n} \vec{B}_n \times \vec{J}_n dV_n \tag{1}$$

where $\vec{F}_n$ is electromagnetic force vector regarding permanent magnet n, with n=1 for permanent magnet 1 and 2 for permanent magnet 2, $\vec{B}_n$ is the correspondent airgap flux density, $\vec{J}_n$ is the armature current density vector, and V_n is the integration volume that surrounds the active coil sections. As far as the force is concerned, only the normal component of $\vec{B}_n$ will be taken into account. It gives

$$\vec{B}_n = B_n\vec{k} \tag{2}$$

The current density vector has two components to consider: J_{x_n} and J_{y_n}. The first is the current density through the x coil sections, while the second, through the y coil sections. Equation (3) defines $\vec{J}_n$.

$$\vec{J}_n = J_{x_n}\vec{i} + J_{y_n}\vec{j} \tag{3}$$

By using (2) and (3) to work out the result of (1), one derives:

$$\begin{aligned}\vec{F}_n &= \int_{Vn} B_n\vec{k} \times (J_{x_n}\vec{i} + J_{y_n}\vec{j})dV_n = \\ &= \int_{Vn} B_n(J_{y_n}\vec{i} - J_{x_n}\vec{j})dV_n = F_{x_n}\vec{i} - F_{y_n}\vec{j}\end{aligned} \tag{4}$$

In (4), F_{x_n} is the electromagnetic force component produced by an x coil section while F_{y_n} is produced by an y coil section. When the effect of both permanent magnets is considered, this results in a total force $\vec{F}$ acting on the mover that produces a movement along the x or y-axis and is given by (5).

$$\vec{F} = \vec{F}_1 + \vec{F}_2 \tag{5}$$

A normal force is also present and represents an undesirable characteristic. Because it is an attraction force between the mover and the armature core of the actuator, it can have the effect of braking the mover owing to an increased friction. This force on the mover of the planar actuator can be obtained from the following expression:

$$F_N = \frac{w_m b_m}{\mu_o}\left(B_1{}^2 + B_2{}^2\right) \tag{6}$$

In (6), F_N is the magnetic attraction normal force, w_m is the permanent magnet width and b_m is the permanent magnetic breadth. Theoretical results confirmed the presence of a high normal force on the mover. Fig. 3 presents a schematic frontal view of the planar actuator, showing the magnetic flux path through its structure. The figure presents two layers per coil only, in order to simplify the picture. The planar actuator was studied with the aid of the Finite Element Analysis. By doing that, it became possible to assess the flux density distribution in the back iron, in the armature core and in the airgap. The use of numerical analysis aids to analyse the normal force and to obtain an optimum electromagnetic force. The forces were obtained by means of the Maxwell's Stress Tensor applied to the Finite Element Analysis, and the results are shown in Table 1. It was done by setting an integration surface around the mover of the actuator. In the analysis, two coil sections were excited. The map of magnetic flux density in the actuator with zero current density is presented in figure 4(a) and in 4(b), the corresponding graph of the absolute value of the magnetic flux density in the airgap vs. the airgap width. Fig. 5(a) presents the map of magnetic flux density in the actuator with current density applied to each coil section equals to 28 A/mm^2 and in 5(b), the corresponding graph of the absolute value of the magnetic flux density in the airgap vs. the airgap width. In Table 1, the values of F and F_N obtained by means of (1), (5) and (6) are presented together with the figures computed by the Finite Element Analysis, under the conditions correspondent to figures 4 and 5.

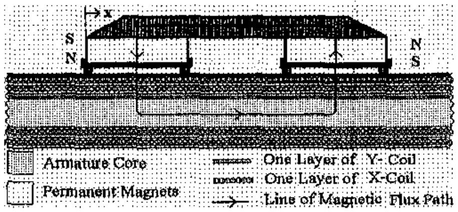
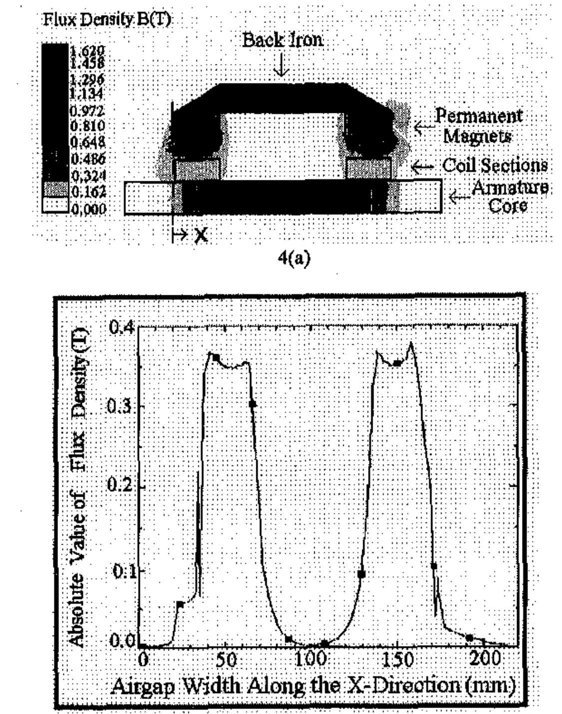


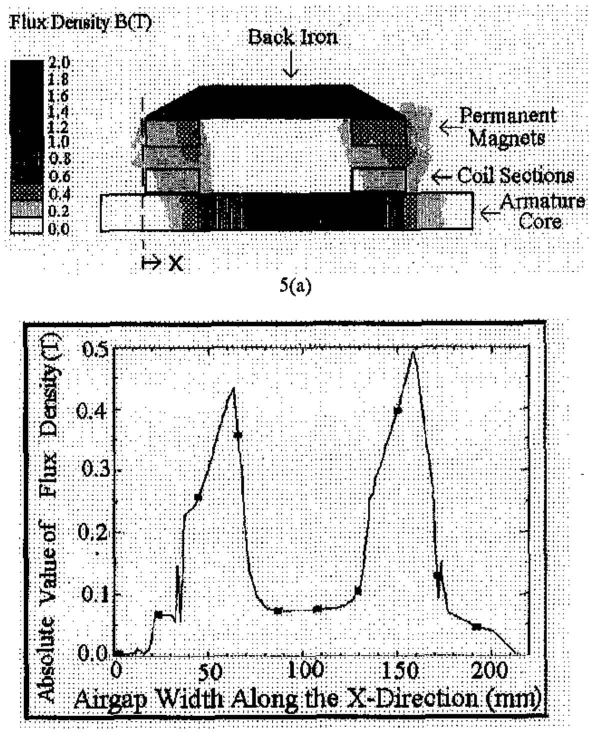
Fig. 3 - Schematic frontal view of the planar actuator



4(a)

4(b)

Fig. 4 - (a) Map of magnetic flux density in the actuator with zero current density and (b) corresponding graph of the absolute value of the magnetic flux density in the airgap vs. the airgap width.



5(a)

5(b)

Fig. 5 - (a) Map of magnetic flux density in the actuator with current density applied to each coil section equals to 28 A/mm^2 and (b) the corresponding graph of the absolute value of the magnetic flux density in the airgap vs. the airgap width.

TABLE I

FORCES ON THE MOVER OBTAINED ANALYTICALLY AND BY ELEMENT FINITE ANALYSIS

	Eletromagnetic Force, F (N)	Normal Force, F_N (N)	Total Force (N)
Analytical	61.3	61	86.48
Finite Element Analysis	48	51	70.04

IV. CONCLUSION

The planar actuator is on test. The authors observed a significant presence of end effects and normal force that reduced the actuator performance. The force that produces planar movement is 48 N and the normal force is 51 N, with two coil sections excited with a density current equal to 28 A/mm^2, applied to each section. By using permanent magnets with high-energy product, it became possible to compensate the demagnetisation behaviour of the 14-mm long airgap of the planar actuator. When current density is equal to zero, the magnetic flux density in the airgap is about 0.35 T. With current density applied to the coil sections it is observed a strong distortion of magnetic flux lines, and a non-uniform distribution of the magnetic flux in the airgap due to armature reaction. This affects the behaviour of the planar actuator. Due to the armature reaction, the contribution of each permanent magnet on the production of propulsion force must be considered separately. The presence of a high normal force produces an attraction force between the mover and the armature core of the actuator. The results produced by the Finite Element Analysis and Maxwell's Stress Tensor, in terms of force, Table 1, are reliable since they take into account the effect of fringing and leakage flux. It points out to the need of a elevated value of current density in the coil sections, in order to obtain a significant propulsion force. A PWM driver will be used to feed the coil sections in a switching mode fashion. This means that the coil sections will not be excited simultaneously and justifies the use of a high value of current density as well as long as the coils are not overheated. To carry on the work, the authors are considering the use of optical sensors in order to provide correct position tracking.

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