3D FINITE ELEMENT MODELLING OF A PERMANENT MAGNET ELECTROMAGNETIC VALVE ACTUATOR

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***Abstract* – The paper presents three-dimensional magnetic field modelling of a recently developed electromagnetic valve actuator with soft magnetic mover and stopper. The permanent magnet is employed in the actuator construction in order to reduce the energy consumption. Three-dimensional finite element method using magnetic vector potential formulation with edge elements is employed. Results are obtained for the magnetic field distribution and the static force of the actuator. Force-displacement characteristics for different values of the magnetomotive force and different lengths of the stopper are also obtained.**

***Keywords*: *linear actuators, permanent magnets, 3D finite element method, electromagnetic force, static force characteristics*.**

1. INTRODUCTION

In recent years, permanent magnets have been increasingly used in electromagnetic actuators for different applications [1-3]. One of these applications is the electromagnetic valve actuator in its varieties. The properties of rare earth magnets give opportunities for obtaining more suitable static and dynamic characteristics. An important advantage of permanent magnet actuators is also reduced energy consumption with respect to the neutral ones.

Finite element method has been employed as a key tool for the prediction of electromagnetic valve actuator characteristics [4-10]. In [5], three-dimensional magnetic field analysis is employed for the estimation of the effect and shielding of strong external magnetic field on the performance of an axisymmetric electromagnetic valve actuator. In [6], an electromechanical valve system using hybrid permanent magnet/electromagnet electromagnetic actuator is presented. In [7], two- and three-dimensional finite element modelling has been employed for obtaining proper static and dynamic characteristics of variable air-gap reluctance actuator. Significant interest is observed in the area of permanent magnet electromagnetic valve actuators for internal combustion engine valve actuation systems [8-10]. In [8], the topology of a permanent-magnet polarized reluctance actuator that enhances the performance of electromagnetic valve actuation systems is presented together with analysis of its static performance. In [9], permanent magnet linear actuator has been developed for variable valve timing in a combustion engine valve system. Dynamic performance of a new permanent magnet linear actuator for use in combustion engine systems is presented in [10]. In previous work [11], a construction of a permanent magnet linear actuator for electromagnetic valve for hydraulic applications is presented and its magnetic field is analysed using three-dimensional finite element method.

In the present work, the construction from [11] is modified by adding a stopper, the actuator is studied using three dimensional finite element magnetic field analysis and its static force characteristics are obtained for different stopper lengths and coil magnetomotive force.

2. ACTUATOR CONSTRUCTION

The principal construction of the actuator is shown in Fig. 1. The two coils are identical and supplied in a way to create flux in the same direction. The permanent magnet is block type and magnetized in transversal direction.

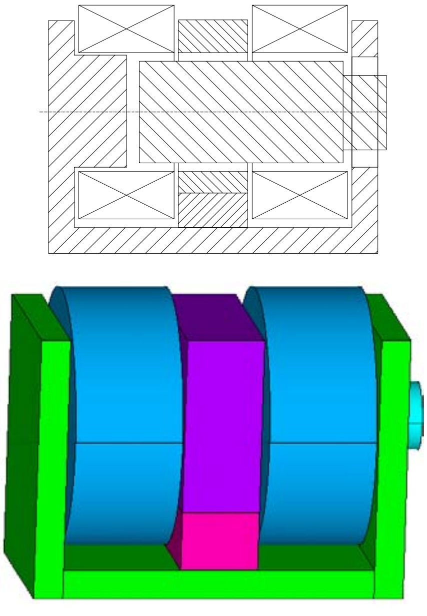

Figure 1: Principal construction of the actuator.

The total stroke of the mover is 2 mm. The overall dimensions of the actuator core are as follows: length: 38 mm; width: 22 mm; height: 27 mm.

Outer diameter of the coils can vary depending on the maximal magnetomotive force of the coils.

The permanent magnet is magnetized in transversal direction as shown in Fig. 1. It is NdFeB magnet with remanent flux density Br = 1.29T and coercive field Hc = 979 000 A/m. The principle of actuator operation is as follows. The two coils are connected in a way to create flux in the armature in the same direction. The permanent magnet creates flux in different directions in the two parts of the armature – from the pole ring to the side yokes. This means that when the coils are supplied in a way to create flux in positive z direction, the right coil and the permanent magnet will create flux in the same direction in the right part of the armature, while in its left part the left coil and the magnet will counteract each other. Thus, if suitable balance is obtained, the flux in the left armature part and in the stopper can be minimized. The same considerations apply when the coils are supplied in a way to create flux in left direction – the left coil and the magnet create coinciding flux in the left part of the armature and the right coil counteracts with the magnet in its right part. As the construction is magnetically non-symmetric (due to the presence of stopper) and at the left end the electromagnetic force is greater, the spring creates force in positive z-direction, i.e. to the right in Fig. 1.

The whole stroke of the armature is 1 mm.

When the armature is at left position (corresponding to air gap of 0.5 mm to the stopper) without current in the coils, the force created by the permanent magnet holds the armature in this position, overcoming the spring force. When coils are supplied in a way to create flux in positive z-direction (we will call it positive coil current), the armature moves to the right position. Without supply in the right position, the spring holds the armature at this position. When coils are supplied in a way to create flux in negative z-direction (negative coil current), the electromagnetic force dominates over the spring force and the armature is moved to the left position, where, after breaking the supply, the permanent magnets holds it.

3. FINITE ELEMENT MODELLING

Three-dimensional finite element method has been employed for magnetostatic field analysis and electromagnetic force computation of the actuator. ANSYS® program [12] was used for performing the analysis. Formulation with edge degrees of freedom for the edge magnetic flux was chosen.

The computations were automated using the Ansys Parametric Design Language included in the program package. Flux-parallel boundary conditions are imposed on the boundary of a buffer zone around the actuator.

An example of the finite element mesh of the actuator without the buffer zone is shown in Fig. 2. The mesh consists of tetrahedral finite elements. Typical number of equations is about 72 000.

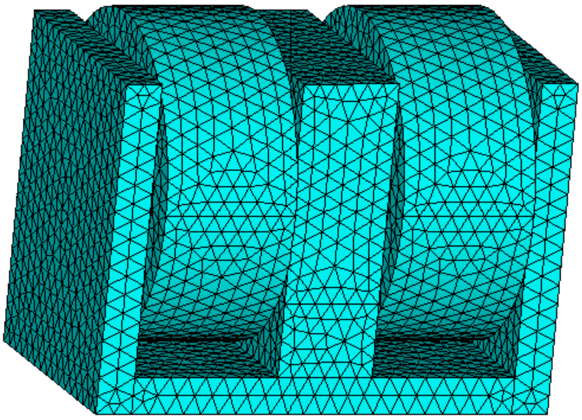

Figure 2: Finite element mesh.

As a result from finite element analysis the magnetic flux density distribution and the electromagnetic force acting on the armature are obtained.

The case of no power supply is also studied as at the two end position the armature should be fixed in a stable way. This is important for obtaining reduction of energy consumption as the power supply should be necessary only during the transition period of the motion of the armature between the end positions.

4. FLUX DENSITY DISTRIBUTION

The flux density distribution for the left position of the mover, m.m.f. of each coil of 400 A and positive coil current is shown in Fig. 3. Here the flux density and respectively the flux in the right part of the armature is greater than the one in its left part, but the latter is still not zero.

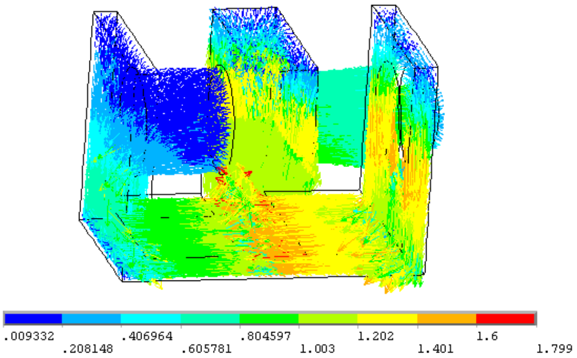

Figure 3: Flux density distribution for left armature position, positive coil current and 400 A mmf

The field created only by the permanent magnet is also studied and the magnetic flux density distribution in this case is given in Fig. 4. The result is for symmetry position of the armature. It is seen that due to the asymmetry of the magnetic circuit the fluxes in the two branches are not equal.

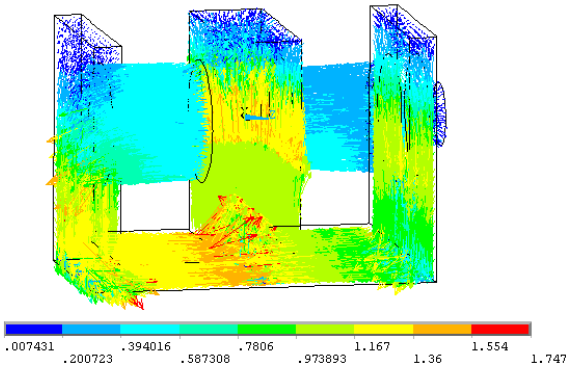

Figure 4: Flux density distribution for left armature position and no coil current (due to the permanent magnet only): a – vector plot; b – color map.

5. STATIC FORCE CHARACTERISTICS

The static force characteristics are obtained for value of the coil m.m.f. NI = 400 A for both positive and negative coil currents and for different lengths of the stopper.

As already mentioned, there is also a spring that acts in positive z-direction of Fig. 1. It is intended for keeping the armature at the right position as the magnet is able to hold it only at the left position.

The spring characteristic is shown in Fig. 5.

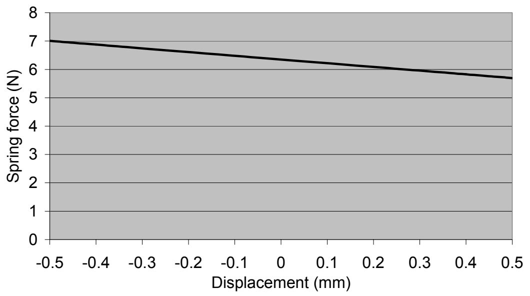

Figure 5: Spring characteristic.

In Fig. 6, the force-displacement characteristics for different stopper lengths are shown for positive coil current. In this case, the electromagnetic force acts together with the spring.

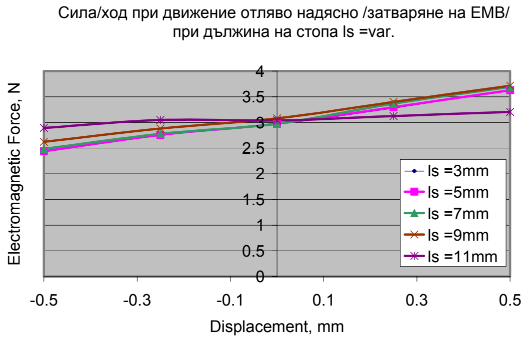

Figure 6: Force-stroke characteristic for positive coil current and different stopper lengths, NI=400A.

In Fig. 7, the force-displacement characteristics for different stopper lengths are shown for negative coil current.

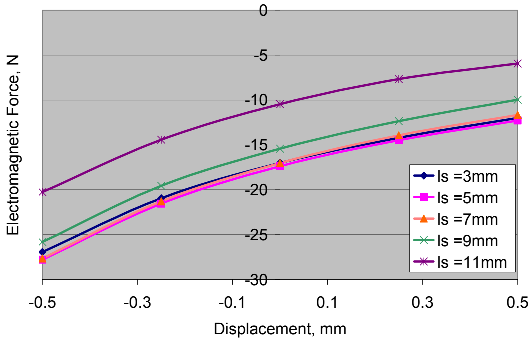

Figure 7: Force-stroke characteristic for negative coil current and different stopper lengths, NI=400A.

Due to the asymmetry in the magnetic circuit, the force created with negative current is much greater than the one with positive current.

6. CONCLUSIONS

The presented three-dimensional finite element modelling of permanent magnet electromagnetic valve actuator with soft magnetic mover and stopper demonstrates the ability of the actuator to act in both directions. The obtained results show that the actuator at negative coil supply acts similarly to a solenoid actuator and is able to overcome the spring force. In this way, good correspondence between the electromagnetic and spring force is obtained.

The stopper length also has been varied.

Acknowledgments

The present work was supported by the National Science Fund of Bulgarian Ministry of Education and Science, Project No. VU-EEC-306/2007.

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