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# DECOUPLED DYNAMICS MODELLING OF AN ELECTROMAGNETIC VALVE ACTUATOR

Ivan Yatchev, Krastio Hinov and Vultchan Gueorgiev

Technical University of Sofia, Faculty of Electrical Engineering  
[yatchev@tu-sofia.bg](mailto:yatchev@tu-sofia.bg), [k\\_hinov@tu-sofia.bg](mailto:k_hinov@tu-sofia.bg), [vulchy@tu-sofia.bg](mailto:vulchy@tu-sofia.bg)

## ABSTRACT

The paper presents numerical modeling of the dynamics of recently developed electromagnetic valve actuator. The decoupled modelling approach is employed consisting of three-dimensional finite element analysis of the magnetic field of the actuator and solution of the dynamics equations on the basis of functions obtained from the magnetic field analysis. For the finite element analysis ANSYS program is employed, while the approximation of the functions using bicubic splines and for the solution of the dynamics is carried out in Matlab environment.

**Index Terms** – Dynamic models, decoupled approach, three-dimensional finite element method, magnetostatic field, linear actuators, and electromagnetic valves

## 1. INTRODUCTION

Permanent magnets have been increasingly used in electromagnetic actuators for different applications [1-3] in recent years. The properties of rare earth magnets give opportunities for obtaining more suitable static and dynamic characteristics, as well as the advantage of reduced energy consumption with respect to the neutral actuators.

For the modelling of the actuator characteristics, mainly the finite element method is employed [4-11]. Static characteristics of newly developed permanent magnet linear actuator for electromagnetic valve have been reported in [11]. In the present paper, dynamic model of the same actuator is presented based on decoupled approach and three-dimensional modeling of the magnetic field of the actuator.

## 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.

The total possible stroke of the mover is 1.5 mm. The overall dimensions of the actuator core are as follows: length: 38 mm; width: 22 mm; height: 27 mm

The permanent magnet is magnetized in transversal direction as shown in Fig. 1. It is NdFeB magnet with remanent flux density  $B_r = 1.29\text{T}$  and coercive field  $H_c = 979\,000\text{ A/m}$ . 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.

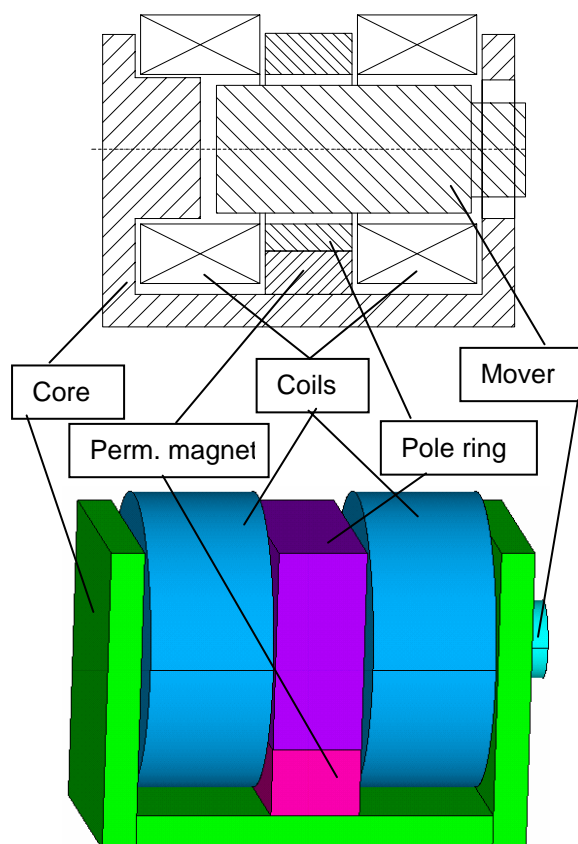


Figure 1 Principal construction of the actuator

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 working stroke of the armature is 0.5 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. DECOUPLED DYNAMICS MODELLING

Decoupled approach for the modeling of the actuator dynamics has been employed. An idea of similar approach is given in [10]. It consists of 3D finite element modelling of the magnetic field of the actuator and solution of the electric circuit – mechanical motion problem based on the functions obtained from the magnetic field modelling. These functions are the coil flux linkage, its derivatives with respect to the current and the displacement and the electromagnetic force. For the 3D magnetic field modelling, the finite element method and ANSYS® program [12] are used.

An example of the finite element mesh is given in Fig. 2

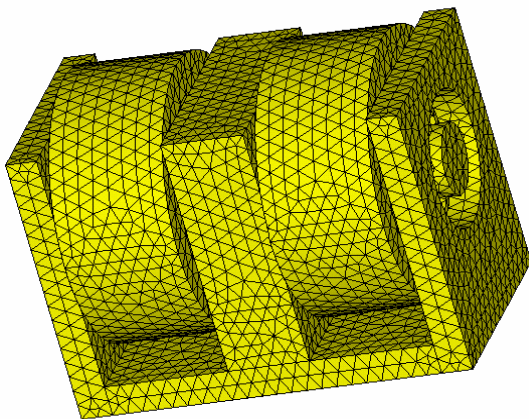


Figure 2 Finite element mesh

The three-dimensional finite element modeling is carried out using edge flux formulation and tetrahedral finite elements. The studied domain consists of the actuator and a buffer zone around it, on the boundaries of which flux-parallel boundary conditions are imposed. The total number of nodes of the mesh is about 100 000.

For both current in the coil and for the stroke minimal and maximal values are defined. Then a grid of points current-stroke is generated by setting values of the current and of the stroke to be uniformly distributed within the defined ranges. For each point of this grid (each point corresponds to a combination of the values of the current and the stroke) the magnetic field of the actuator is analyzed and the electromagnetic force and the flux linkage of the coil is obtained. Thus for both items two-dimensional arrays are formed.

The rest of the analysis is carried out in Matlab® environment.

First, bicubic spline approximations of the electromagnetic force and of the flux linkage are obtained. Using such approximations both functions and their derivatives could be obtained at arbitrary point.

Next, the system of ordinary equations is formed and solved.

The mathematical model in this case consists of the equation of the electric circuit

$$(1) \quad U = Ri + \frac{d\Psi}{dt},$$

where

$U$  is the supplied voltage;

$R$  is the coil resistance;

$i$  is the coil current;

$\Psi$  is the coil flux linkage,

and the equation of the force balance (equation of motion)

$$(2) \quad m \frac{d^2x}{dt^2} = F_{em} - \beta \frac{dx}{dt},$$

where

$m$  is mass of the mover;

$x$  is the stroke (displacement);

$F_{em}$  is the electromagnetic force;

$t$  is time;

$\beta$  is damping coefficient.

Having in mind that the flux linkage is a function of two variables, the current and the displacement, its derivative with respect to the time can be presented as

$$(3) \quad \frac{d\Psi}{dt} = \frac{\partial\Psi}{\partial i} \frac{di}{dt} + \frac{\partial\Psi}{\partial x} \frac{dx}{dt}.$$

In order to reduce the order of the force equation, a new unknown function is introduced – the velocity  $v$ . Thus, the system to be solved becomes of the following form

$$(4) \quad \frac{di}{dt} = \frac{1}{\frac{\partial \Psi}{\partial i}} \left[ U - Ri - \frac{\partial \Psi}{\partial x} v \right]$$

$$(5) \quad \frac{dx}{dt} = v$$

$$(6) \quad \frac{dv}{dt} = \frac{1}{m} (F_{em} - \beta v).$$

The required functions  $F_{em}(x, i)$ ,  $\Psi(x, i)$ ,  $\frac{\partial \Psi}{\partial i}(x, i)$  and  $\frac{\partial \Psi}{\partial x}(x, i)$  are obtained from the above mentioned bicubic spline approximations.

The system (4)-(6) is solved numerically using standard routines in Matlab (ode45).

#### 4. RESULTS

The above described decoupled approach is applied to the solution of the dynamics of the actuator. The dynamics is simulated when the mover is moving to the right in Fig. 1. This movement is more problematic as there is no normal working air gap at the right end of the mover.

The time evolutions of the current, displacement, velocity and electromagnetic force are shown in Fig. 3, Fig. 4, Fig. 5 and Fig. 6, respectively.

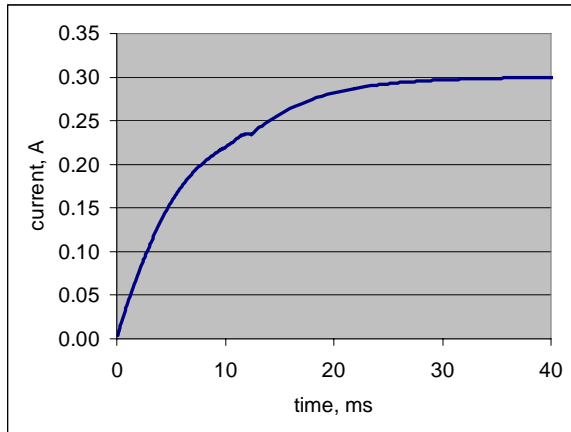


Figure 3 Coil current

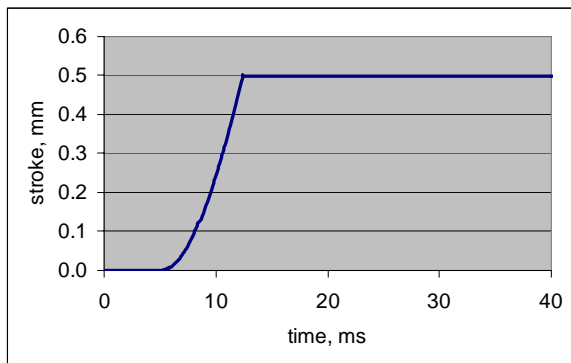


Figure 4 Mover stroke

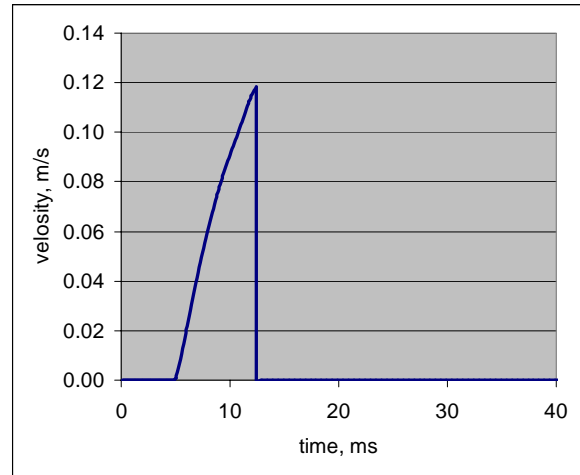


Figure 5 Mover velocity

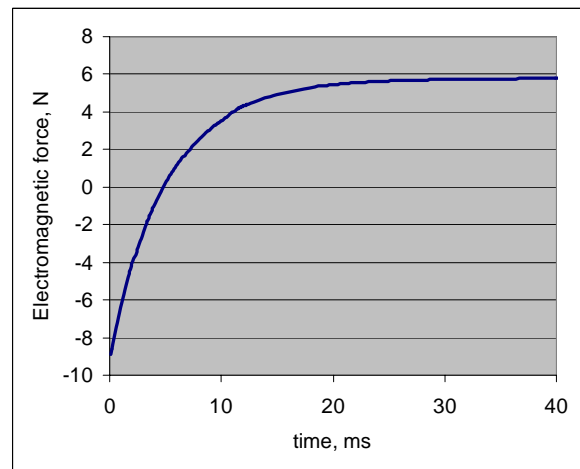


Figure 6 Electromagnetic force

As seen, the dynamic characteristics are more or less similar to those of neutral actuators. Here, instead of spring, the holding force is created by the permanent magnet.

The mover starts to move at about 5ms and the motion time is about 7.5 ms.

#### 5. CONCLUSIONS

The presented decoupled approach gives the opportunity to carry out multiple dynamic modeling for different supply conditions and external circuit parameters without necessity of additional magnetic field modeling.

This modeling can be considered as a step for the creation of the complete dynamic model, which will also include the valve itself and modeling of the hydraulic load.

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