

## Simulation of the Dynamic Behaviour of a Permanent Magnet Linear Actuator

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**Abstract:** The paper presents simulation of the dynamics of a permanent magnet linear actuator with soft magnetic mover and relatively long stroke 60 mm. The simulation is carried out using decoupled approach where the magnetic field problem is solved separately from the electric circuit and mechanical motion problems. The obtained results are compared with experiment.

**Keywords:** Linear actuators, permanent magnets, dynamic simulation, Finite Element Method.

### 1 Introduction

IN recent years, dynamic simulation of electromagnetic actuators has been the subject of continued interest to researchers. The variety of actuator constructions and their loads is a factor that stimulates this interest. Dynamic simulation requires the solution of a coupled problem consisting of electromagnetic field, electric/electronic circuit and mechanical motion problems.

The most widespread method for electromagnetic field modelling of linear actuators is the finite element method in its different formulations [1–6].

Two principal approaches are possible to solve the problem - coupled and decoupled. The coupled approach (for example [2]) requires solution of all the problems simultaneously. The decoupled model (e.g. [1]) involves separate solutions of the magnetostatic field problem (where a set of solutions is obtained for a wide range of current and displacement) and of the electric circuit and mechanical motion problems. The main drawback of the decoupled model is that the eddy currents are not taken into account.

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Manuscript received on November 19, 2009. An earlier version of this paper was presented at 9th International Conference on Applied Electromagnetics August 31–September 02, 2009, Niš, Serbia.

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In the present paper, decoupled modelling is applied to the simulation of the dynamic behaviour of a permanent magnet linear actuator for relatively long stroke - 60mm.

## 2 Actuator Construction

The principal construction of the actuator is shown in Fig. 1. It consists of core, coils, fixed permanent magnet, soft magnetic plunger and non-magnetic shafts. The permanent magnet is radially magnetized Barium ferrite magnet ( $H_c = 104 \text{ kA/m}$ ,  $B_r = 0.17 \text{ T}$ ).

The actuator operates as follows. Only one coil is energized at a time for motion in one direction e.g., for motion in the upper direction the upper coil is energized. The flux created by the permanent magnet is in the same direction with the flux created by the coil in the upper air gap and in opposite direction in the lower air gap.

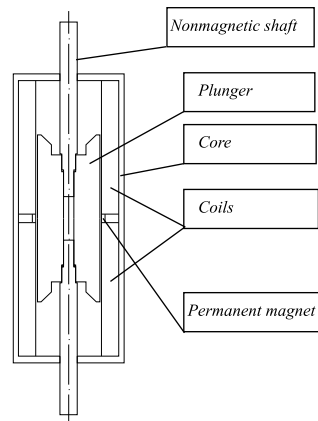


Fig. 1. Actuator construction.

In this way, the permanent magnet assists to the lowering of the opposite electromagnetic force due to the flux in the lower gap. The construction also prevents the permanent magnet from demagnetizing.

The same considerations are valid for the reverse motion.

The static force characteristics of similar actuator are presented in [6].

## 3 Dynamic Modelling

Decoupled approach for the dynamic modelling is applied, i.e., the magnetic field problem is solved separately from the rest of the problem (electric circuit - me-

chanical motion). The mathematical model for the latter consists of the following equations:

- Electric circuit equation:

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

where  $U$  is the supplied voltage,  $R$  is the coil resistance,  $i$  is the coil current,  $\Psi$  is the coil flux linkage and  $t$  is time.

- Mechanical motion (force balance) equation:

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

where  $m$  is mass of the mover,  $x$  is the stroke (displacement),  $F_{em}$  is the electromagnetic force,  $\beta$  is damping coefficient,  $F_s$  is spring force, defined by

$$F_s = F_{s0} + cx, \quad (3)$$

$F_{s0}$  is initial spring force and  $c$  is spring (stiffness) coefficient.

Horizontal position of the mover is assumed in Eqn. (2) and that is why the weight of the mover is not included in it.

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

$$\frac{d\Psi}{dt} = \frac{\partial \Psi}{\partial i} \frac{di}{dt} + \frac{\partial \Psi}{\partial x} \frac{dx}{dt}. \quad (4)$$

For reducing 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

$$\frac{di}{dt} = \frac{1}{\frac{\partial \Psi}{\partial i}} (U - Ri - \frac{\partial \Psi}{\partial x} v) \quad (5)$$

$$\frac{dx}{dt} = v \quad (6)$$

$$\frac{dv}{dt} = \frac{1}{m} (F_{em} - F_s - \beta v). \quad (7)$$

The following approach implementing decoupled modeling is employed for simulation of the actuator dynamics.

First, a range for the current and displacement of the mover is defined. Then a displacement-current grid is generated. At each point of this grid finite element analysis of the magnetic field is carried out. For this purpose, the program

FEMM [7] is used together with Lua Scripting<sup>®</sup> for automation of the computations. The field is solved as magnetostatic and axisymmetric. Homogeneous Dirichlet boundary conditions are imposed on a buffer zone around the actuator. As a result of each finite element analysis, the coil flux linkage and the electromagnetic force acting on the mover are obtained. All results are collected in suitable table form for successive handling.

The rest of the problem is solved in Matlab<sup>®</sup> environment [8]. Before solving the system (5)-(7), bicubic spline approximations for the flux linkage and the force as functions of the displacement and the current  $F_{em}(x, i)$  and  $\Psi(x, i)$  are obtained. This allows also the partial derivatives of the flux linkage to be available.

The system (5)-(7) is solved numerically using standard routines in Matlab (ode45). The required functions,  $F_{em}(x, i)$ ,  $\frac{\partial \Psi}{\partial i}(x, i)$  and  $\frac{\partial \Psi}{\partial i}(x, i)$  are obtained from the above mentioned bicubic spline approximation.

## 4 Results

The results are obtained for actuator of parameters given in Table 1.

Table 1. Main parameters of the studied actuator.

Parameter	Value
Overall length	203 mm
Overall diameter	60 mm
Plunger length	130 mm
Plunger outer diameter	32 mm
Working stroke	60 mm
Core thickness (top and bottom part)	4 mm
Core thickness (cylindrical part)	3 mm
Inner magnet diameter	34 mm
Outer magnet diameter	44 mm
Magnet length	15 mm
Supply voltage	15 V
Coil resistance	3.16 $\Omega$
Number of turns of the coil	770
Initial spring force	-21 N
Spring stiffness	0.7 N/mm
Mass of the mover	0.59 kg

The finite element analysis was carried out for a  $13 \times 13$  displacement-current grid (from 0 to 60 mm of the displacement and from 0 to 4800 A for the magnetomotive force, which corresponds to current of 6.23A). For improving the accuracy of the force computation, denser finite element mesh was created around the plunger. Typical total number of the nodes in the finite element mesh was about 10 000.

After performing the series of finite element analyses, the obtained results were used to create bicubic spline approximations of the functions  $F_{em}(x, i)$  and  $\Psi(x, i)$ . From the second function the partial derivatives  $\frac{\partial \Psi}{\partial x}(x, i)$  and  $\frac{\partial \Psi}{\partial i}(x, i)$  were also obtained.

The obtained four functions are shown in Fig. 2 - Fig. 5.

These functions were used for the solution of the system (5)-(7).

The time evolutions of the current, displacement and the electromagnetic force are shown in Fig. 6, Fig. 7 and Fig. 8, respectively.

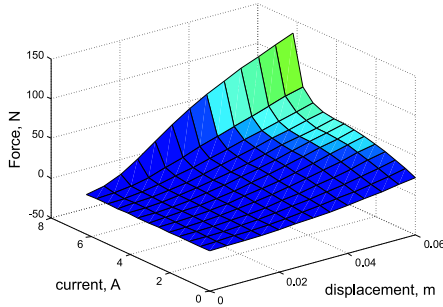


Fig. 2. Bicubic spline approximation  $F_{em}(x, i)$  of the electromagnetic force.

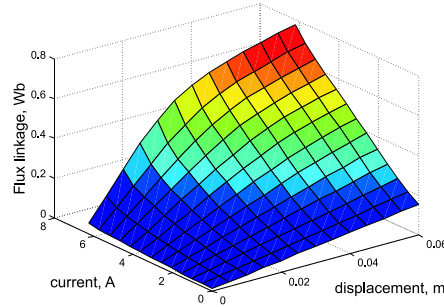


Fig. 3. Bicubic spline  $\Psi(x, i)$  approximation of the flux linkage of the coil.

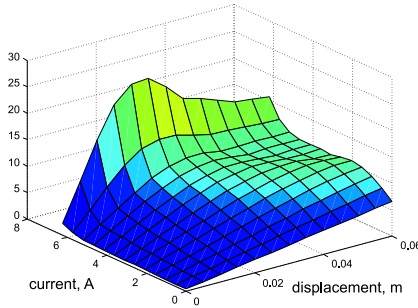


Fig. 4. Partial derivative  $\frac{\partial \Psi}{\partial x}(x, i)$  obtained from the bicubic spline approximation.

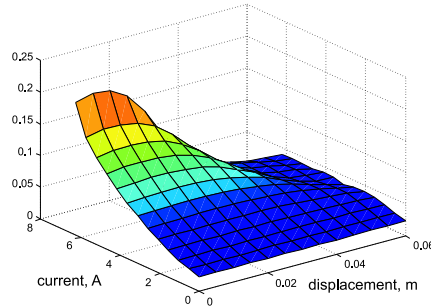


Fig. 5. Partial derivative  $\frac{\partial \Psi}{\partial i}(x, i)$  obtained from the bicubic spline approximation.

The results were verified experimentally, using sensors for the current and for the acceleration of the mover. The displacement is obtained using two successive integrations of the acceleration signal.

The experimental results for the current and displacement are shown in Fig. 9 and Fig. 10.

The difference in the shape of the current is due to the neglecting the eddy currents in the simulation.

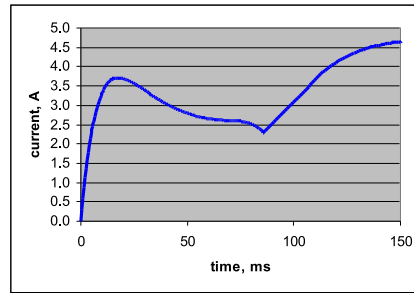


Fig. 6. Current in the coil vs. time.

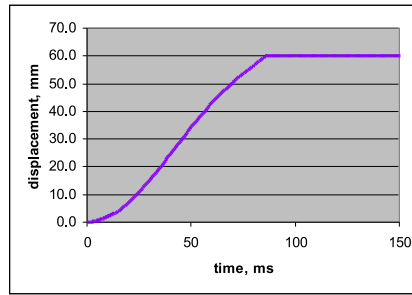


Fig. 7. Displacement vs. time.

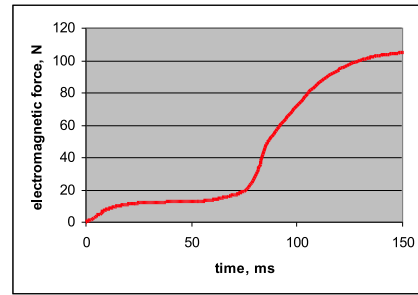


Fig. 8. Electromagnetic force vs. time.

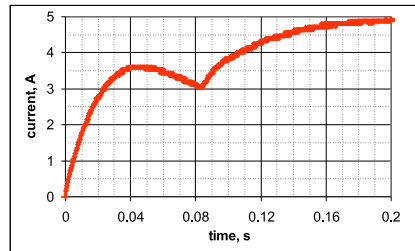


Fig. 9. Experimental results for the current.

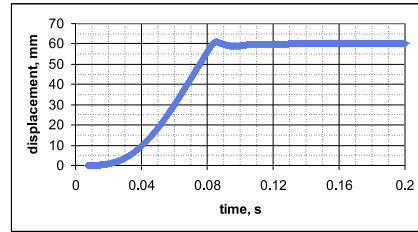


Fig. 10. Experimental results for the displacement.

## 5 Conclusion

The presented approach for simulation of the dynamics of a permanent magnet linear actuator gives the opportunity to simulate the actuator for different conditions and external circuit parameters. The approach was verified experimentally.

Further work can include simulation of the dynamics in reciprocating mode, i.e. when the two coils are supplied successively and the mover performs oscillating motion.

## 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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