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# Dynamic Characteristics of a Bistable Linear Actuator with Moving Permanent Magnet

**Ivan Yatchev[1], Krastio Hinov[2], Vultchan Gueorgiev[3]**

**Abstract**. The dynamic characteristics of an axisymmetrical linear actuator with axially magnetized moving permanent magnet are obtained using combined field and circuit approach. The magnetic field of the actuator has been analysed using the finite element method over a current-displacement sampling grid. Two field analyses are carried out for each point of the grid - one for the real system and one for the system where the permanent magnet is considered as a soft magnetic body. For each point of the grid, data for the total flux linkage, electromagnetic force and the coil inductance are extracted from the magnetic field analysis. These data are approximated by bicubic spline functions, which are employed in the solution of the system of ordinary differential equations of the electrical circuit and the mechanical motion. Results are obtained for the time variations of the coil current, mover displacement, mover velocity and electromagnetic force. The results for the current and displacement are verified experimentally.

**Keywords**: Linear actuators, Permanent magnets, Dynamic modelling, Finite element method, Bicubic spline approximation

## 1 Introduction

For adequate simulation of the dynamic behaviour of linear actuators, coupled problem has to be solved - electromagnetic field, electrical circuit and mechanical motion problem. This problem has been solved in a series of different ways and different models - from the magnetic circuit models to coupled field models [1 - 10].

Permanent magnet linear actuators become more intensively used devices for a wide range of industrial application. They offer lower energy consumption compared to the neutral electromagnetic actuators.

The present paper deals with a linear actuator with axially magnetised moving permanent magnet. In a previous paper [11], the static characteristics of the actuator were obtained. In the present paper, the dynamic characteristics of the actuator are studied.

[1] Dept. of Electrical Apparatus, Technical University of Sofia, 1156 Sofia, Bulgaria, E-mail: yatchev@tu-sofia.bg
[2] Dept. of Electrical Apparatus, Technical University of Sofia, 1156 Sofia, Bulgaria, E-mail: hinov@elap.tu-sofia.bg
[3] Dept. of Electrical Power Supply, Electrical Equipment and Electrical Transport, Technical University of Sofia, 1156 Sofia, Bulgaria, E-mail:vulchy@tu-sofia.bg

## 2 Studied actuator

The studied actuator is of axial symmetry - Fig. 1. It is a bistable linear actuator intended to interlock two mechanical systems. The stroke length of the actuator is 5 mm.

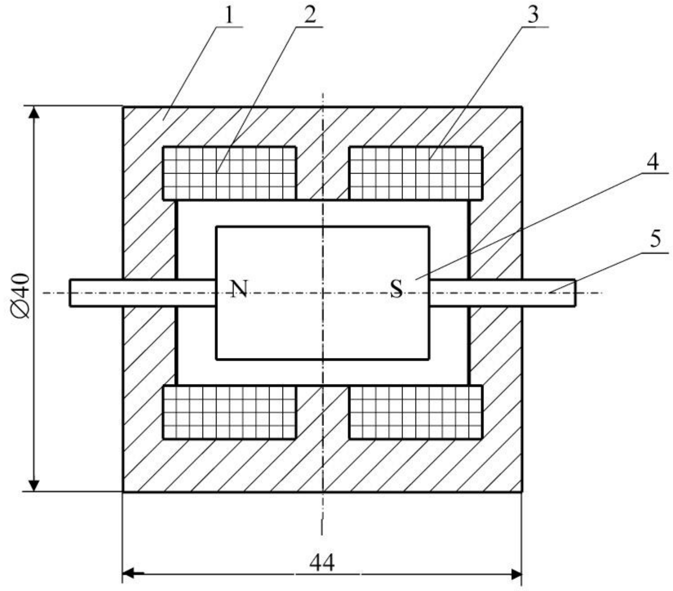



**Fig. 1** - *Principal construction of the studied actuator*
*1 - core; 2, 3 - coils; 4 - permanent magnet; 5 - non-magnetic shaft.*

The actuator consists of a core, two exciting coils and moving permanent magnet fixed on non-magnetic shaft. The permanent magnet is magnetised in axial direction. The two coils are connected in series in a way to create opposite m.m.f.-s. As a result axial electromagnetic force arises on the permanent magnet. The direction of the force depends on the direction of the current. The mover is held at the end positions by the permanent magnet, without current in the coils.

## 3 Dynamic model

The approach for obtaining the dynamic model starts from the standard set of circuit and force balance equations:

$$U = Ri + \frac{d\Psi}{dt} \tag{1}$$

$$m\frac{d^2x}{dt^2} + \beta\frac{dx}{dt} = F_e \pm mg\,, \tag{2}$$

where $U$ is the supplied voltage;

$R$ is the coil resistance;

$\Psi$ id the total flux linkage

$m$ is the mass of the mover;

$x$ is the displacement of the mover;

$F_e$ is the electromagnetic force;

$\beta$ is damping coefficient.

We will consider in more details Eqn. (1). The total flux linkage $\Psi$ can be presented as a sum of two components - the flux linkage $\Psi_m$ with the flux created by the permanent magnet and the flux linkage $\Psi_i$ with the flux created by the current in the coils:

$$\Psi = \Psi_m + \Psi_i \,. \tag{3}$$

The flux linkage $\Psi_m$ depends only on the position of the mover, i.e. $\Psi_m = \Psi_m(x)$, while the flux linkage $\Psi_i$ depends both on the displacement and on the coil current, i.e. $\Psi_i = \Psi_i(x,i)$. The time derivative in Eqn. (1) therefore can be presented in the form

$$\frac{d\Psi}{dt} = \frac{\partial \Psi}{\partial x}\frac{dx}{dt} + \frac{\partial \Psi}{\partial i}\frac{di}{dt} = \frac{\partial \Psi}{\partial x}\frac{dx}{dt} + \frac{\partial \Psi_i}{\partial i}\frac{di}{dt} \,. \tag{4}$$

Denoting the coil inductance by $L$, the flux linkage $\Psi_i$ can be presented as $\Psi_i = Li$ and

$$\frac{d\Psi_i}{di} = \frac{\partial L}{\partial i} i + L \,. \tag{5}$$

Taking into account (3), (4) and (5), Eqn. (1) takes the form

$$U = Ri + \frac{\partial \Psi}{\partial x}\frac{dx}{dt} + \left( L + i\frac{\partial L}{\partial i} \right)\frac{di}{dt} \,. \tag{6}$$

After introducing the velocity $v$ as an unknown and reducing the order of the force equation, the final set of equations becomes

$$\frac{di}{dt} = \frac{1}{L + i\dfrac{\partial L}{\partial i}}\left( U - Ri - \frac{\partial \Psi}{\partial x} v \right), \tag{7}$$

$$\frac{dx}{dt} = v \,, \tag{8}$$

$$\frac{dv}{dt} = \frac{1}{m}\left( F_e - \beta v \pm mg \right) \cdot \tag{9}$$

The following functions have to be determined for solving the system (7)-(9): $\frac{\partial \Psi}{\partial x}(x,i)$, $L(x,i)$, $\frac{\partial L}{\partial i}(x,i)$, $F_e(x,i)$. For obtaining all these functions finite element analysis of the magnetic field is carried out.

The program FEMM [13] is used for finite element analysis. In order to obtain the desired function both current and displacement should be varied. A grid displacement-current is defined and at each point of this grid two magnetic field analyses are performed. The first one is with all real data. From this analysis the total flux linkage and the electromagnetic force are obtained. In the second analysis the permanent magnet is replaced with a ferromagnetic body of the same magnetic permeability, i.e. the coercive force of the magnet is set to zero. From this analysis the result for the coil inductance is obtained. All these results are stored in an intermediate data file. For automatic generating of the coil-displacement grid and obtaining the desired results, a program is written in Lua scripting language.

The rest of the analysis is carried out using the Matlab® package [13]. First, the data from the intermediate file are used for creating bicubic spline approximations of the functions $\Psi(x,i)$, $L(x,i)$ and $F_e(x,i)$. After that, the set of ordinary differential equations (7)-(9) is solved numerically. The necessary derivatives $\frac{\partial \Psi}{\partial x}(x,i)$ and $\frac{\partial L}{\partial i}(x,i)$ are obtained from the bicubic spline approximations. The approach is illustrated in Fig. 2.

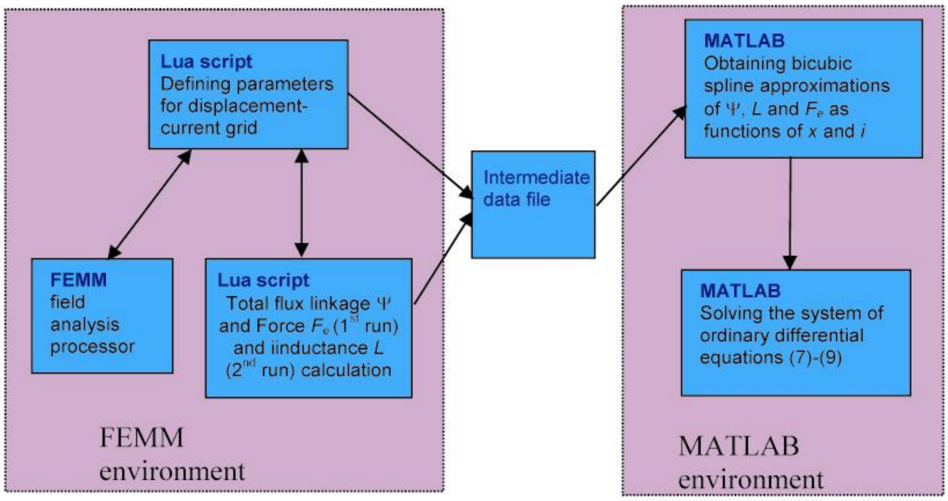
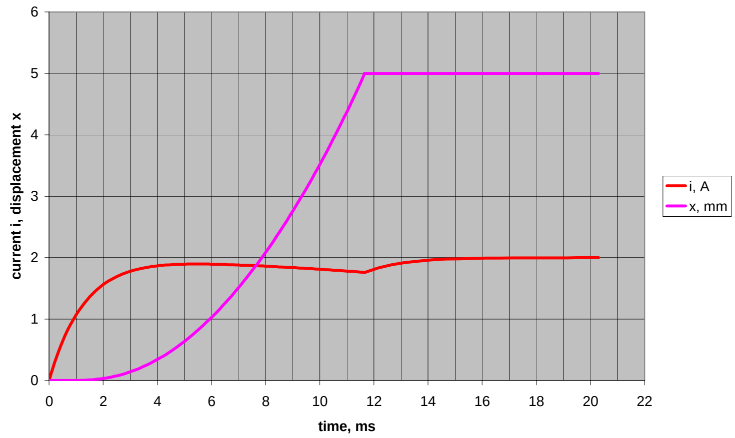



**Fig. 2** - *The approach for dynamic analysis.*

The approach allows fast multiple solutions for different supply voltages. In case of change the supply voltage or some external circuit parameters, only the Matlab solution of the system of ordinary differential equations is to be performed.

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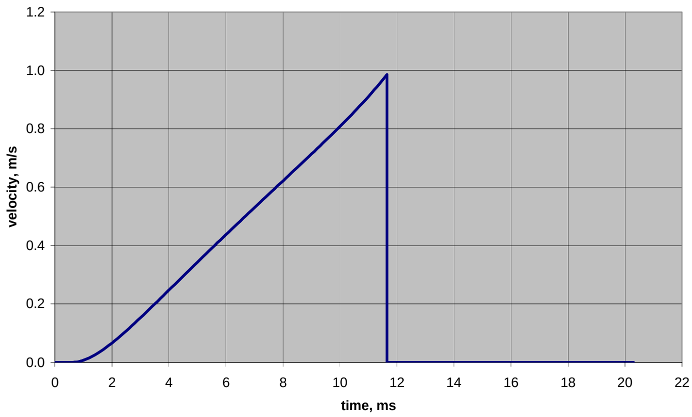


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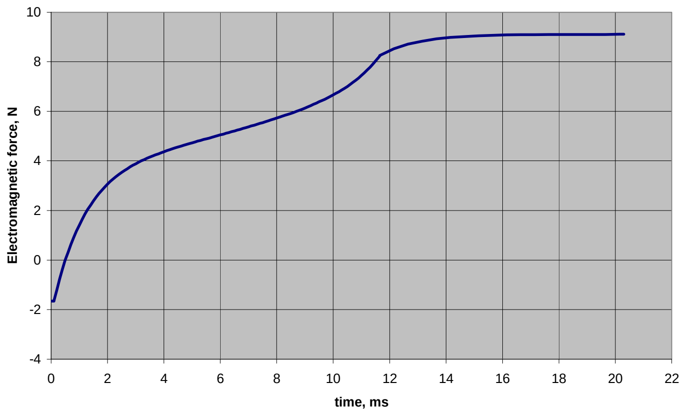


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**Fig. 3 -** *Computed results for motion up.*

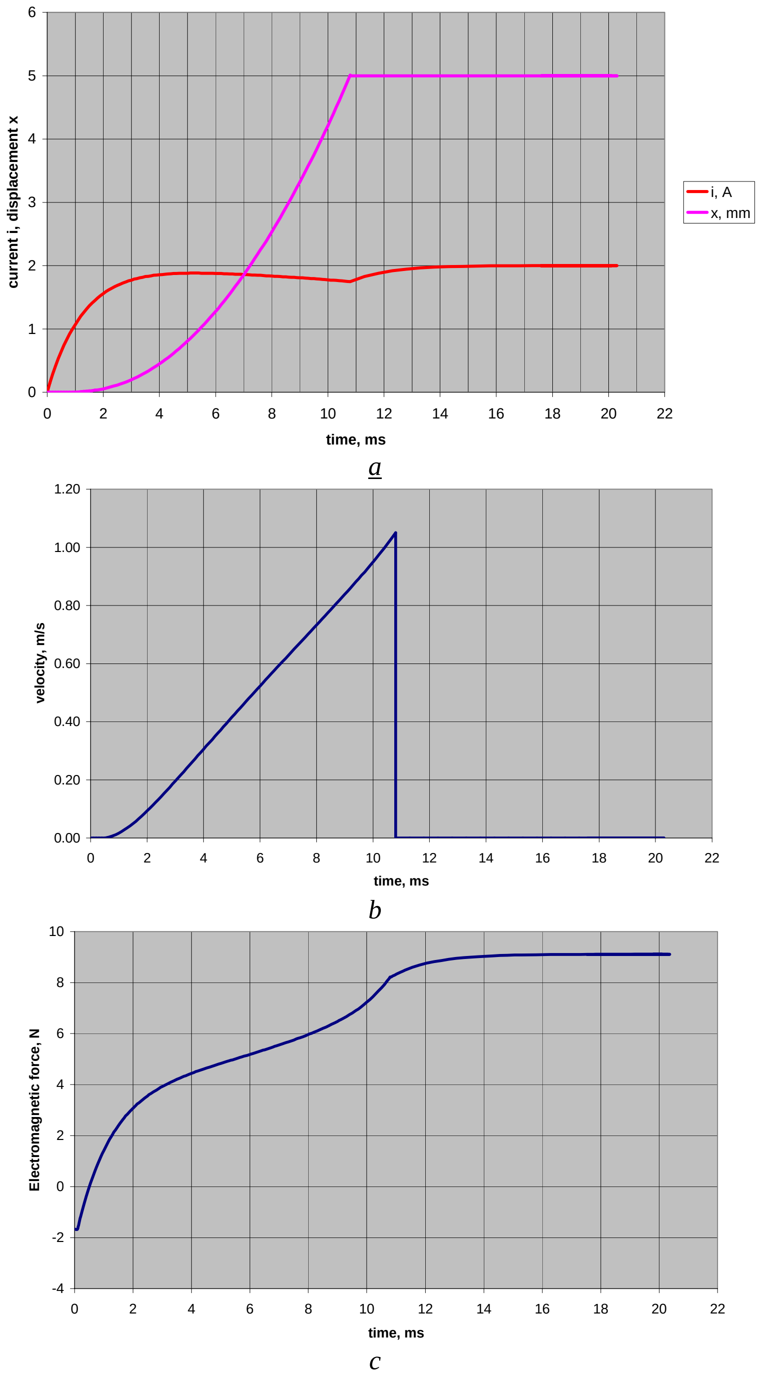


**Fig. 4** - *Computed results for motion down.*

## 4 Results

The results are obtained for the actuator from Fig. 1 with the following data: supply voltage U = 24 V DC; coil resistance R = 12 Ω; number of turns: 700; mass of the mover $m$ = 32 g. The axially magnetised permanent magnet (Ba ferrite, $H_c$ = 104 kA/m, $B_r$ = 0.17 T) is of dimensions ∅20/∅5×15 mm.

The actuator is analysed in vertical position. Two groups of results are obtained - one for motion up and one for motion down. In Fig. 3 the results for current, displacement, velocity and electromagnetic force are shown for motion up. In Fig. 4 the same items are shown for motion down.

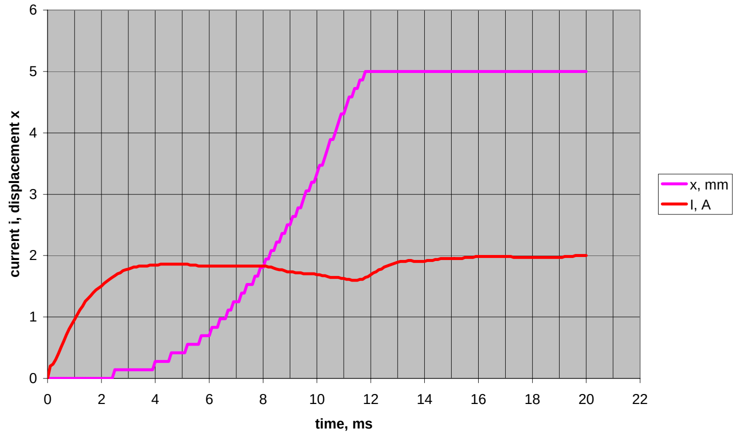


**Fig. 5** - *Measured results for motion up.*

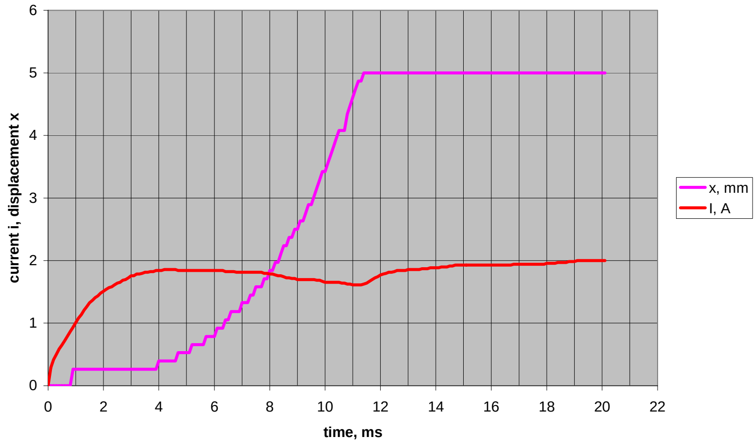


**Fig. 6** - *Measured results for motion down.*

Experimental verification has been carried out using the approach emplyed in [14]. In Fig. 5 and Fig. 6, the experimental results for the current and displacement are shown, respectively for motion up and down.

As seen, the agreement between the computed and measured results is satisfactory.

## 5 Conclusion

Dynamic characteristics of a bistable linear actuator with axially magnetised moving permanent magnet are obtained. The employed approach includes bicubic spline approximation of the total flux linkage, inductance and electromagnetic force, obtained using the finite element method over a displacement-current grid. This approach allows fast multiple analyses for different supply voltages and external circuit parameters, which can be especially useful at the stage of actuator design. The computed results have been verified experimentally.

## 6 References

[1] L. Erping, P. M. Mc Ewan: Analysis of a Circuit Breaker Solenoid Actuator System Uning the Decoupled CAD-FE-Integral Technique,. IEEE Trans. Magn., vol. 28, No. 2, 1992, pp. 1279 - 1282.

[2] Z. Ren, A. Razek: A Strong Coupled Model for Analysing Dinamic Behaviors of Non-linear Electromechanical Systems,. IEEE Trans. Magn., vol. 30, No. 5, 1994, pp. 3252 - 3255.

[3] L. Nowak: Dynamic FE Analysis of Quasi-Axisymmetrical Electromechanical Converters,. IEEE Trans. Magn., vol. 30, No. 5, 1994, pp. 3268 - 3261.

[4] N. Sadowski et al.: Dynamic modeling of a newly designed linear actuator using 3D edge element analysis, IEEE Trans. Magn., vol. 32, No. 3, 1996, pp. 1633 - 1636.

[5] L. Nowak: Simulation of Dynamics of Electromagnetic Driving Device for Comet Ground Penetrator, IEEE Trans. Magn., vol. 34, No. 5, 1998, pp. 3146 - 3149.

[6] C.S. Biddlecombe, J. Simkin, A.P. Jay, J.K.Sykulski, S. Lepaul: Transient Electromagnetic Analysis Coupled to Electric Circuits and Motion, IEEE Trans. Magn., vol. 34, No. 5, 1998, pp. 3182 - 3185.

[7] K. Tani, T. Yamada, Y. Kawase: A New Technique for 3-D Dynamic Finite Element Analysis of Electromagnetic Problems with Relative Movement, IEEE Trans. Magn., vol. 34, No. 5, 1998, pp. 3371 - 3374.

[8] K. Srairi, M. Feliachi: Numerical Coupling Models for Analyzing Dynamic Behaviors of Electromagnetic Actuators, IEEE Trans. Magn., vol. 34, No. 5, 1998, pp. 3608 - 3611.

[9] K. Tani, T. Yamada, Y. Kawase: Dynamic Analysis of Linear Actuator Taking into Account Eddy Currents Using Finite Element Method and 3-D Mesh Coupling Method, IEEE Trans. Magn., vol. 35, No. 3, 1999, pp. 1785 - 1788.

[10] I. Yatchev, E. Ritchie: Dynamic model of a linear actuator with moving permanent magnet, Proceedings of the 9th Int. IGTE Symp. 2000, Graz, 2000, pp. 148 - 151.

[11] K. Hinov, I. Yatchev, N. Trifonov: Study of a linear actuator with axially magnetized moving permanent magnet, Proc. of XIII-th Int. Symp. on Electrical Apparatus and Technologies SIELA 2003, Plovdiv, Volume II, pp. 124 - 130.

[12] D. Meeker: Finite element method magnetics version 3.3, User’s Manual, 2003.

[13] The Math Works, Inc.: Using MATLAB, Version 6, 2002.

[14] V. Gueorgiev, I. Yatchev, A. Alexandrov: Experimental Study of Dynamics of Solenoid Electromagnet with Ferromagnetic Disc in the Coil, Proc. of XIII-th Int. Symp. on Electrical Apparatus and Technologies SIELA 2003, Plovdiv, Volume II, pp. 112 - 117.