

Numerical And Experimental Aspects Concerning The Static and Dynamic Regime Of A Linear Actuator

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Abstract – In this paper the dynamic behavior of a D.C. linear actuator is analyzed. A finite element numerical model was used. A coupled system of electrical and mechanical differential equations was solved by coupled simulation among magnetic field transitory regime, electric circuit and mechanical translation with variable speed. The time variations of the current, of the magnetic force and of the moving part speed were determined. The current variation was validated by experimental measurements.

Keywords- linear actuator;dynamic regime; finite element method;coupled problem

I. INTRODUCTION

Linear actuators have many applications in digitally controlled compact pumps, electromagnetic valves, circuit breakers, micro machines and robotics.

In order to simulate the dynamic behavior of a linear actuator a coupled problem that comprises magnetic field, electrical circuit and mechanical motion, has to be solved.

In [1] certain finite element numerical models of electro mechanical systems are presented. In [2] the basics of the switching equipments are presented.

Paper [3] deals with a linear actuator that has an axially magnetized moving magnet. Paper [4] focuses on modeling and simulation of the electromagnetic actuators integrated in ABB's reclosers. Paper [5] presents an accurate model for optimization of design and supply control for linear actuators.

In [6-8] the application of finite element method to actuators study is presented. In the literature there are coupled and decoupled approaches. The decoupled solves the problems sequentially: magneto-static, electric circuit and mechanical movement.

In [9] a decoupled dynamic model that employs bi-cubic spline approximations of the results from the magnetostatic field analysis and compare it with the

coupled model. In the coupled approach [10], all the problems should be solved simultaneously.

In this paper the analysis of the dynamic behavior of a D.C. linear actuator is performed by finite method. It is a coupled simulation among magnetic field transitory regime, electric circuit and mechanical translation with variable speed.

The numerical model was validated by experimental measurements.

II. THEORETICAL ASPECTS

A. Mathematical model

In order to determine the time variations of the moving part speed $v(t)$, of the current $i(t)$ and of the magnetic force $F_m(t)$ the following system of coupled electromagnetic, electric circuit and mechanical motion equations have to be solved, considering that the movement is performed along the Oz axis [9] :

- the electromagnetic field equation

$$\nabla \cdot (\nu \nabla \times \bar{A}) - \bar{J}_e + \sigma \frac{\partial \bar{A}}{\partial t} - \sigma \bar{v} \times \bar{B} - \nabla \times (\nu \mu_0 \bar{M}) = 0 \quad (1)$$

where \bar{A} is the magnetic vector potential having only the azimuthally component A_φ , ν is the magnetic reluctivity, \bar{J}_e is the current density in the coil, σ is the electric conductivity, \bar{v} is the velocity of the plunger, \bar{B} is the magnetic flux density, μ_0 is the magnetic permeability for the free space and \bar{M} is the magnetization vector

- the electric circuit equation :

$$U_0 = R \cdot i + L(z) \cdot \frac{di}{dt} + i \cdot \frac{dL(z)}{dz} \cdot v \quad (2)$$

where U_0 is the supply voltage, R is the resistance of the coil, L is the variable inductivity of the coil i is the electric current and z is the discrete value of the air gap δ .

- the mechanical motion equation :

$$m \cdot \ddot{a} = F_m - F_{load} - F_r \quad (3)$$

where F_m is the magnetic force, F_{load} is the load force and $F_r(x)$ is another resistant force that can depend on the speed.

To calculate the force exerted on the plunger, the Maxwell stresses or the virtual work method can be used.

The volume density of the magnetic force $\overline{f_{Vm}}$, within a certain volume V_Σ can be reduced to a system of fictitious stresses acting on the surface Σ that bounds the considered volume.

Equivalent condition is that the resultant force must be the same:

$$\overline{F}_m = \int_{V_\Sigma} \overline{f_{Vm}} dV = \int_{\Sigma} \overline{T}_n dA \quad (4)$$

where T_n is magnetic Maxwell stress tensor.

The virtual work method for computing force and torques is derived from magnetic energy W_m or co energy W_m' changes against space displacement.

The magnetic force F_m is obtained from the generalized magnetic force theorem, when the current is constant:

$$F_m = -\left(\frac{\partial W_m}{\partial z}\right)_{i=ct.} \quad (5)$$

Rewriting equation (3), using (5) we obtain equation (6) that describes the motion of the plunger:

$$m \frac{d^2 z}{dt^2} = \frac{1}{2} i^2 \frac{dL(z)}{dz} - F_{load} - F_r(z) \quad (6)$$

In the case of high magnetic permeability (ferromagnetic material), a simplified expression for the force can be obtained [11]:

$$F = -\frac{1}{2} \cdot \mu_0 \frac{N^2 I^2 A_0}{\delta^2} \quad (7)$$

From relation (6), some observations can be drawn:

- the magnetic force is directly proportional to cross section of the plunger;
- force is reverse proportional to the square air gap length, and it tends to reduce the air gap;
- being an attraction force between two magnetic parts, the mobile and fixed ones, a steady state is

obtained only for a minimum value of magnetic energy.

III. NUMERICAL SIMULATIONS

Numerical calculation of the magnetic field was done using Flux 2D software package developed by the Cedrat company.

A dc linear actuator (with plunger), produced by INTERTEC Components GmbH, was studied.

It has the following characteristics: power supply 12 V dc, number of turns $N = 288$ and the connection current $I=0.33$ A.

In this electromagnet with limiter type, the air gap is between two truncated cone surfaces, and the force exerted is pulling.



Figure 1. The studied linear actuator

A. The geometry

The axial cross section through the electromagnet is described in Fig., where 1 is the fixed part (the case), 2 is the plunger (made of massive steel) and 3 is the coil.

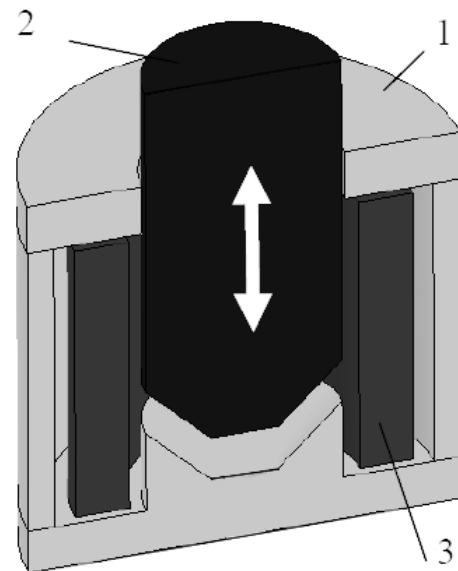


Figure 2. Axial cross section in the dc actuator

Because of the geometric model only a half of the geometry was modeled. The gap is of conic shape.

The geometry dimensions of the actuator are presented in Fig.3

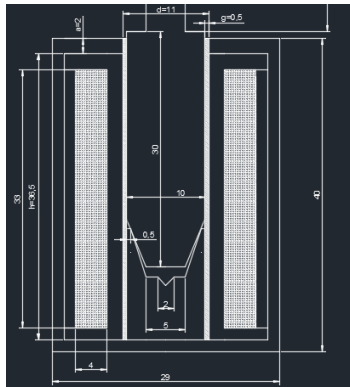


Figure 3. The model geometry

The elements of the geometry are : 2 is the case, 3 is the plunger, 4 is the coil and 5 is the aer (Fig.4)

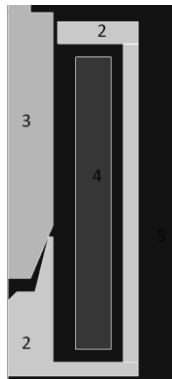


Figure 4. Model components

B. The material properties

The non linear characteristic B (H) of the steel from the plunger has the saturation flux density $B_s=1.9$ T and the initial relative magnetic permeability is $\mu_{ri} = 500$. It is represented in Fig.5. The other regions of the field domain are non magnetized. The steel electrical resistivity is $\rho = 0.2 \cdot 10^{-6} \Omega m$

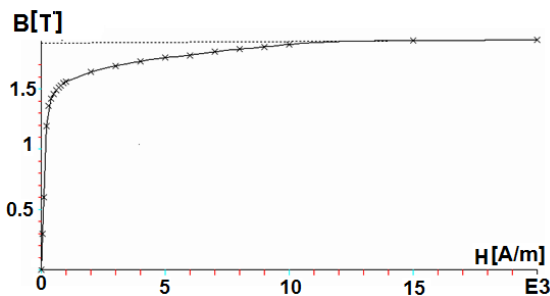


Figure 5. The B-H characteristic of the steel used for the plunger

C. The mesh

The mesh is composed of triangular finite elements and the areas of the translating region are devised in rectangles.

On the width of the translation strip there is only one triangular finite element. The mesh had 149285 nodes. (Fig.6)

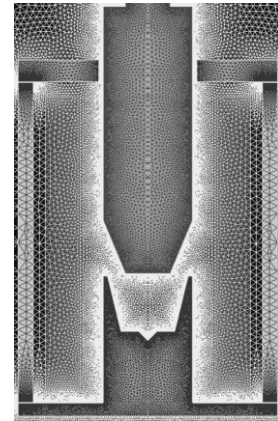


Figure 6. The mesh of the actuator

The mesh is concentrated in the plunger, in the coil and in the airgap. In Fig 7 the general mesh of the whole field domain is presented.

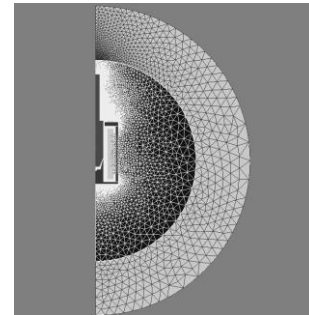


Figure 7. The whole mesh

The external light blue mesh area is a special region used to model problem with infinit boundary, by default non conductive and non magnetic.

D. The boundary conditions

The limit of the computation domain (which is the also the axis of the actuator) is a magnetic field line, where the Dirichlet boundary condition is imposed (the magnetic vector potential (MVP) $A = 0$).

The external light blue area indicates also that the magnetic field vanishes at infinity.

E. Anslsysis and results

Being a 2D axial symmetric model the electromagnet presents a rotation symmetry described by the cylindrical system of coordinates (r, ϕ , and z).

The source of the magnetic field, the current density J, has only an azimuthally component, as well as the magnetic vector potential A.

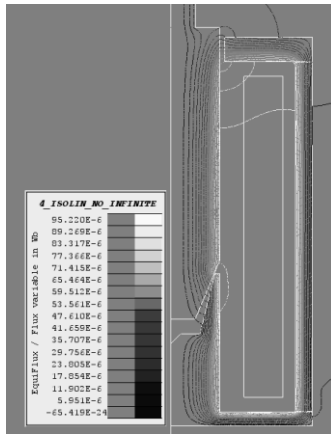
As a consequence the transitory regime is described by a time variable current source $J(t)$ and a MVP A , time and space dependent. The equation of the field model is:

$$\text{rot}\left[\left(\frac{1}{\mu}\right)\text{rot}(A)\right] + \frac{\partial A}{\partial t} / \rho = J \quad (8)$$

where ρ is the electric resistivity and μ is the magnetic permeability.

The second term from the left hand side of the equation represents the density of the induced currents, which is non zero in the conducting regions.

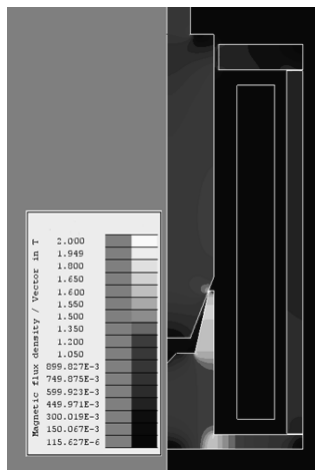
In Fig.8 the equipotential lines of the magnetic field are represented.



t = 10 ms

Figure 8. The equipotential lines distribution

In Fig.9 the flux density distribution is presented.



t = 10 ms

Figure 9. The flux density distribution

F. The coupled analysis

The 2D Transient Magnetic application is used. In order to describe the equivalent electric circuit of the electromagnet the Circuit Editor function has been used.

The simulated electric circuit is presented in Fig.10. It comprises the actuator coil inductivity, a dc power supply and an electric resistance of 0.1 Ohm, used for measurements.

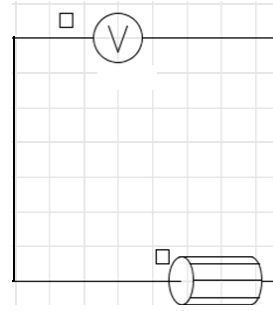


Figure 10. The electric circuit model of the actuator

The equation 7 is solved in time domain, step by step. The current source from this equation is initially unknown.

At any moment of time the current density J has a constant but unknown value. A certain link between the MVP and J is assured by the circuit model of the application.

The step by step method is used because a part of the computation field domain, the moving part, changes the position in time.

The non linear algebraic system of equations obtained by finite element method was solved by Newton Raphson method.

The transitory regime of the electric current from coil is dependent on its resistance R and inductivity L .

The inductivity L is time variable because of the moving part. In Fig.11 the time variation of the current is presented.

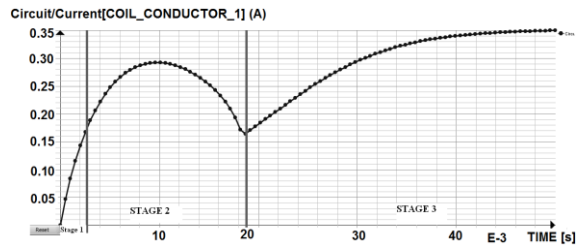


Figure 11. Coil current vs time

Three stages can be noticed.

The first one begins when we supply the electromagnet until the moment the plunger starts moving. In this stage the variation of the coil inductance is small and the current increases exponentially.

The second stage begins when the moving part begins to move, from the initial value of the air gap 6mm to the final value 0.5 mm. At the beginning the inductivity varies slowly but at the end of the interval the growing up is explosive such as, due to the self induction voltage, the absorbed current goes down, after it reaches a maximum value.

The last stage begins when the plunger has stopped up to the end of the electric transitory regime. Again the current increases exponentially but

slower than in the first stage, because the coil inductance is greater. In order to evaluate the simulation time and the time steps the problem was first solved in magneto static regime for the total current. Two magneto static problems were solved, each one corresponding to the initial and to the final value of the air gap, respectively. The time variation of the magnetic force is presented in Fig.12

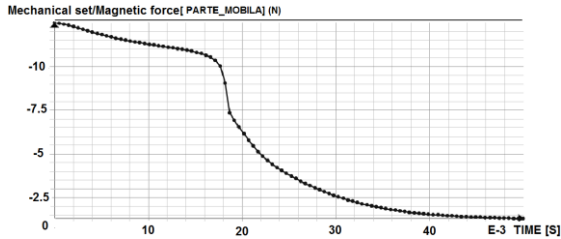


Figure 12. Magnetic force vs.time

It can be noticed that the force decreases as the air gap grows. This variation depends on the geometry of the plunger (the skewing angle) and on the material used. The time variation of the plunger speed is presented in Fig.13.

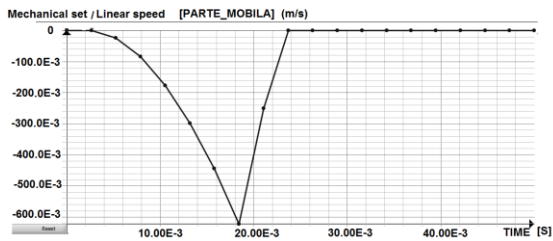


Figure 13. Plunger speed vs time

It can be noticed that the speed of the plunger increases rapidly until it reaches the end of the course and then instantaneously drops to zero at the end.

G. Experimental validation of the numerical model

The main elements of the experimental equipment are the variable voltage source Hameg and the electronic oscilloscope Scopix 7204 Metrix. In order to measure the time variation of the current a resistance of 0.1 ohm was connected with the actuator. The information obtained, the fast variable signal in Fig.14, was filtered and represented as the thicker curve in same figure.

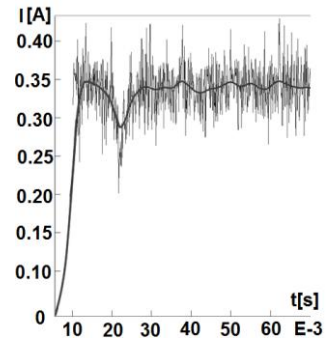


Figure 14. The current vs. time

A good agreement between the measured and the computed current time variation can be noticed. The stable value of the current 0.35 A is almost the same in both cases. Also the time interval to reach that value is about 10 ms in both cases. The time for the minimum value of the current is about 20 ms for numerical model and about 23 ms for the experimental one.

In order to determine the actuator force an electronic scale was used (Fig.15). The plunger was connected to it with a slide rod. The actuator was mounted on a slide fixed on the slide rod. The movement of the slide is performed by a step by step motor that allows a good adjustment .

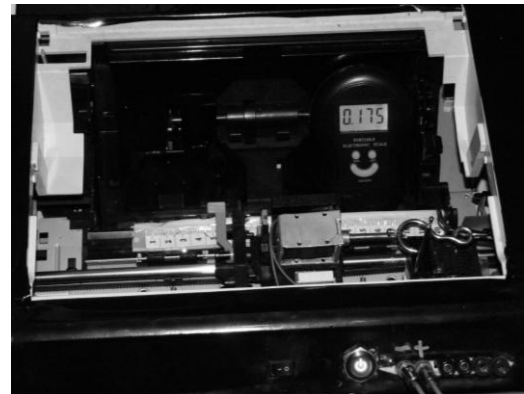


Figure 15. The experimental measuring equipment

In Fig.16 the experimental and the numerical static characteristic of the actuator for 9 V and 15 V are considered.

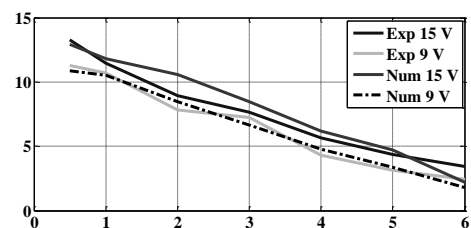


Figure 16. Numerical vs experimental static characteristics at different voltages

The first and the second curves (from the top) represents the numerical and the experimental static characteristic, respectively, at 15 V.

The third and the fourth upper curves (from the top) represent the numerical and the experimental static characteristic, respectively, at 9 V.

The magnetic forces have greater values as the voltage increases. It can be noticed that as the air gap increases the differences between the measured and the calculated values grow up.

In Fig.17 experimental static characteristics at different voltages are compared.

From the top, the first curve is at 15 V, the line dot curve is at 12 V and the last one is at 9 V.

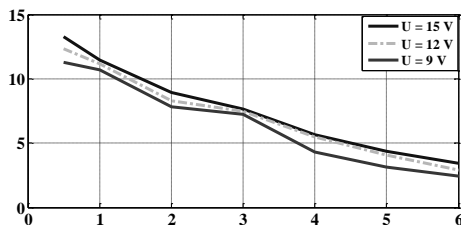


Figure 17. Experimental static characteristics at different voltages

In Fig.18 numerical static characteristics at different voltages are compared. From the top, the line dot curve is at 15 V, the second one is at 12 V and the third one is at 9 V.

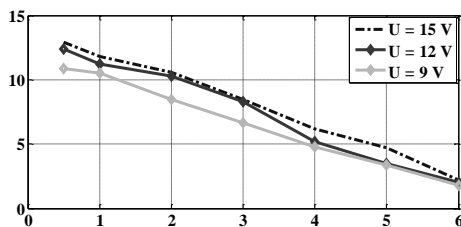


Figure 18. Numerical static characteristics at different voltages

In both figures 16 and 17 we can observe that the magnetic forces are mostly higher when the voltage increases.

IV. CONCLUSIONS

In this paper numerical (static and dynamic) simulations and experimental measurements of a linear actuator were performed. The static analysis was performed at different voltages: 9V, 12 V and 15 V.

It is a good agreement between the numerical and the experimental characteristics.

The differences between the experimental and numerical static characteristics are caused by the difference between the real B(H) characteristics and the used one.

The numerical time variation of the transitory current meets closely the experimental result.

Future work will analyse the influence of different ferromagnetic materials for the plunger on the duration of the transitory regime as well the influence of a plunger made of sheets.

The dynamics of the electromagnet, using the co-simulation between finite element analysis and a Simulink model, will be also a subject of a future work.

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