Control of a XY Electromagnetic Positioning Stage

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Abstract: In this paper there is presented a new planar positioning system which is electromagnetically actuated. The movement along each direction is provided by a pair of variable reluctance electromagnetic actuators. The displacement of the mobile part is linear and guided by leaf spring supports on both axes. The position control and acquisition program was designed in LabVIEW. This control is a PWM closed-loop one, using as feedback sensors two foil strain gauges which are glued to the guide springs. The control algorithm uses an offline FEM model designed in the Finite Element Program FEMM software. The design of the XY stage embodies a new approach to the control of planar motion.

Keywords: closed-loop control, electromagnetic actuator, XY positioning stage gas measurement, controlling software.

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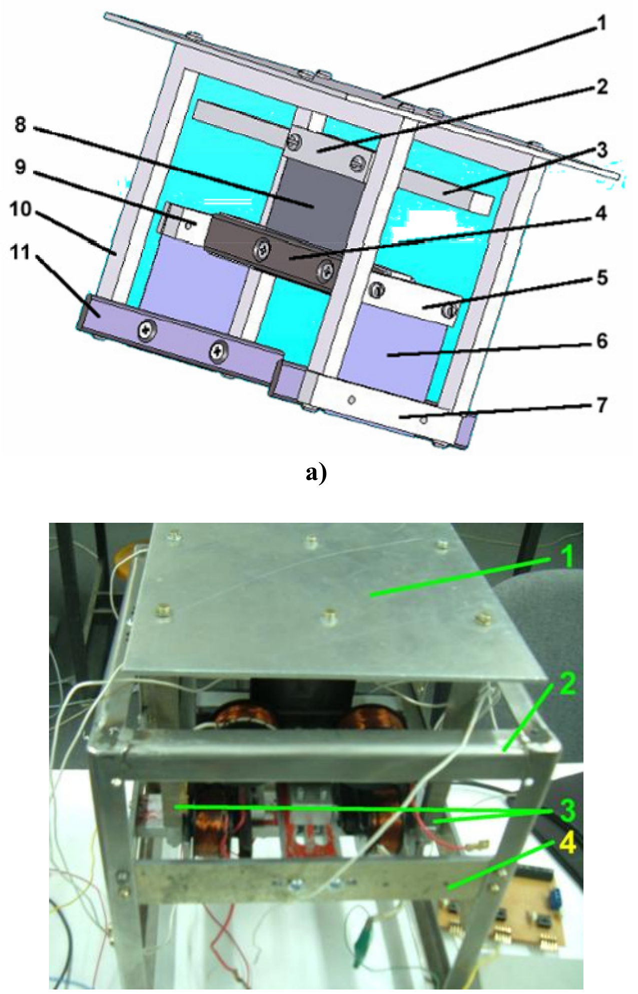
1. Introduction

Variable reluctance electromagnetic actuators are used as switching actuators, because they are simple in construction, small, and relatively cheap to produce. For these reasons they can be found in many industrial and domestic appliances in which limited stroke, on/off mechanical movements are required.

In the area of variable reluctance electromagnetic actuators, the focus of most researches has been on: the increase of the switching operation, speed [3], stroke length [6], the design of driving circuits [4], and the prediction of position by FEM analysis [9]. One notable exception is Tang [8], which couples two solenoids back to back, and makes the structure perform as a positioning device. However, the research lacks a detailed study on the complex electromagnetic characteristics, and as a result, the variable reluctance electromagnetic actuators can only be controlled around a limited set point range.



a)

b)

Figure 1. Bi-directional electromagnetic actuator: a) 3D model of the mobile part of a bi-directional electromagnetic actuator (1- upper table, 2, 5,9- part for fastening the leaf spring, 3- part for fastening the mobile system, 4- intermediary table, 6,8-leaf spring , 7- part for fastening the U part, 10- U part; 11- mobile armature for an electromagnet); b) Bi-directional electromagnetic actuator (1- upper stage , 2- seating frame, 3- mobile frame, 4- fastening part for electromagnets)

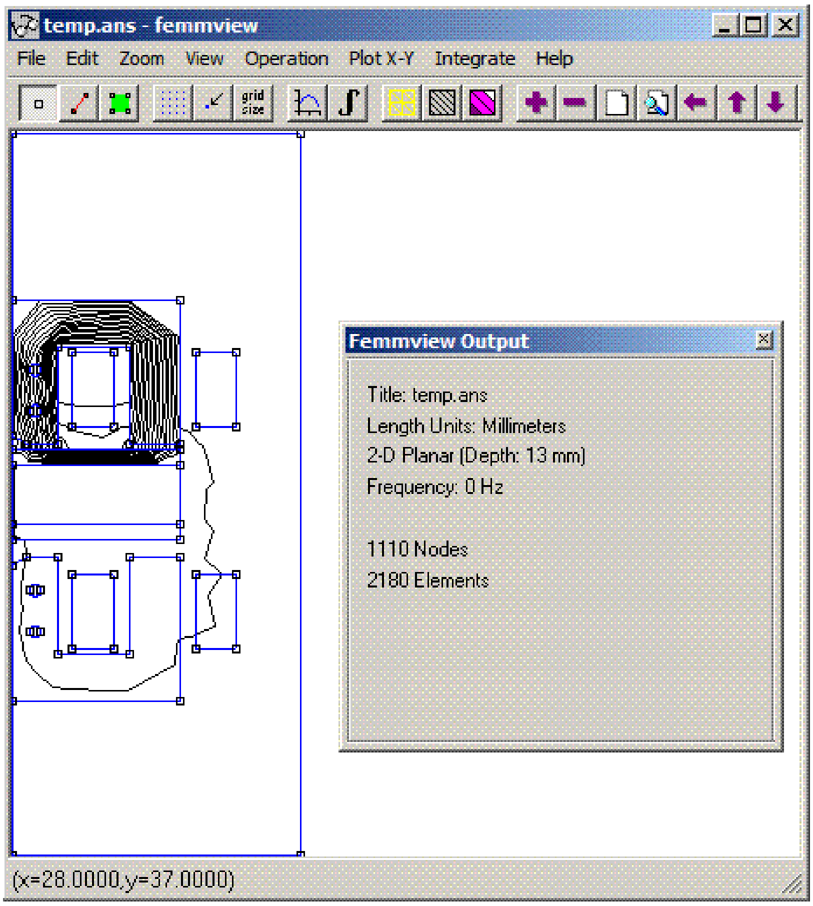
The new planar positioning system (Figure 1) presented in this paper, consists of:

- Two actuation pairs of electromagnets, each one allowing motion displacement along a parallel plan to the seating frame. The electromagnets permit the implementation of a complex control for precision positioning;
- An upper mobile stage sustained by two guiding springs;
- An intermediary stage used as support between the upper table and the basis. This stage is sustained by guiding springs;
- Four spring leafs structured in two guiding springs, perpendicularly oriented for the two directions.

The mechanical assembly was designed having in mind two frames: a fixed frame for fastening the other parts and a mobile frame which sustains and guides the upper table. The electromagnets align ahead affront for one of the direction of movement and back to back for the other perpendicular direction, allowing for the interposition of the mobile intermediary table. The guides for the intermediary stage are fastened to the fixed frame at one end and on this stage at the other ends. The guides for the upper table are fixed to the intermediary stage and to the frame of the upper table. The stage sustains the mobile armatures of the electromagnets for moving in one direction. The frame of the upper stage sustains the mobile armatures of the electromagnets for moving in the other direction. The intermediary stage is made of a central rectangular element and two end parts for fastening the spring guides.

2. The Control Algorithm of the Stage

The offline control algorithm has been applied considering a FEM electromagnetic model of half of the electromagnetic actuator. Through a dynamic simulation of a pair of actuators, a PWM voltage control signal is applied to the four electromagnets; every direction of movement is individually controlled. The PWM signals working frequencies were varied both operating under a voltage of 7.5V. The model (Figure 2) was obtained with the Finite Element Program FEMM (2D electric and magnetic simulation software), considering different gaps between the mobile armature and the fixed armature (yoke).



Title: temp.ans
Length Units: Millimeters
2-D Planar (Depth: 13 mm)
Frequency: 0 Hz

1110 Nodes
2180 Elements

(x=28.0000,y=37.0000)

Figure 2. The FEM model used in the simulation

The electromagnet model has an inductive and a resistive structure, which can be described as:

$$U = Ri + U_L = Ri + L\frac{di}{dt} + i\frac{dL}{dt} \tag{1}$$

Where:

U – supply voltage,
R – circuit resistance ,
i – circuit current,
U_L – electromagnet coil voltage,
L - electromagnet inductance.

Equation (1) has been rewritten as finite difference equation:

$$i_{k+1} = i_k + \frac{\Delta t}{L_k}(U - R \cdot i_k - i_k \frac{L_k - L_{k-1}}{L_k}) \tag{2}$$

Where:

i_{k+1} – next iteration current,
i_k – the current iteration current,
L_k – electromagnet inductance for the current iteration,
L_{k+1} - electromagnet inductance for the next iteration,
The mechanical equation is:

$$m_{am}\ddot{x} + kx + c\dot{x} = F_{elmg1} - F_{elmg2} \tag{3}$$

Where:

m_{am} – mobile armature mass,
k – spring guide elastic constant,
c – dumping constant,
F_{elmg1} – electromagnetic force of one electromagnet
F_{elmg2} – electromagnetic force of the other electromagnet

Equation 2 and 3 can be rewritten as concentrate parameters equations:

$$\begin{cases} \dot{x} = y \\ \dot{y} = \frac{1}{m}(F_{elmg1} - F_{elmg2} - cy - kx) \end{cases} \tag{4}$$

Using Runge-Kutta method of integration:

$$\begin{cases} x_{k+1} = x_k + \frac{\Delta t}{6}(a_1 + 2a_2 + 2a_3 + a_4) \\ y_{k+1} = y_k + \frac{\Delta t}{6}(b_1 + 2b_2 + 2b_3 + b_4) \end{cases} \tag{5}$$

and:

$$a_1 = y_k \text{, } b_1 = \frac{1}{m}[F_{elmg1k} - F_{elmg2k} - c(y_k - k(x_k + \frac{a_1 \Delta t}{2})]$$

$$a_2 = y_k + \frac{a_1 \Delta t}{2} \text{, } b_2 = \frac{1}{m}[F_{elmg1k} - F_{elmg2k} - c(y_k + \frac{b_1 \Delta t}{2}) - k(x_k + \frac{a_1 \Delta t}{2})] \tag{6}$$

$$a_3 = y_k + \frac{a_2 \Delta t}{2} \text{, } b_3 = \frac{1}{m}[F_{elmg1k} - F_{elmg2k} - c(y_k + \frac{b_2 \Delta t}{2}) - k(x_k + \frac{a_2 \Delta t}{2})]$$

$$a_4 = y_k + \frac{a_3 \Delta t}{2} \text{, } b_4 = \frac{1}{m}[F_{elmg1k} - F_{elmg2k} - c(y_k + \frac{b_3 \Delta t}{2}) - k(x_k + \frac{a_3 \Delta t}{2})]$$

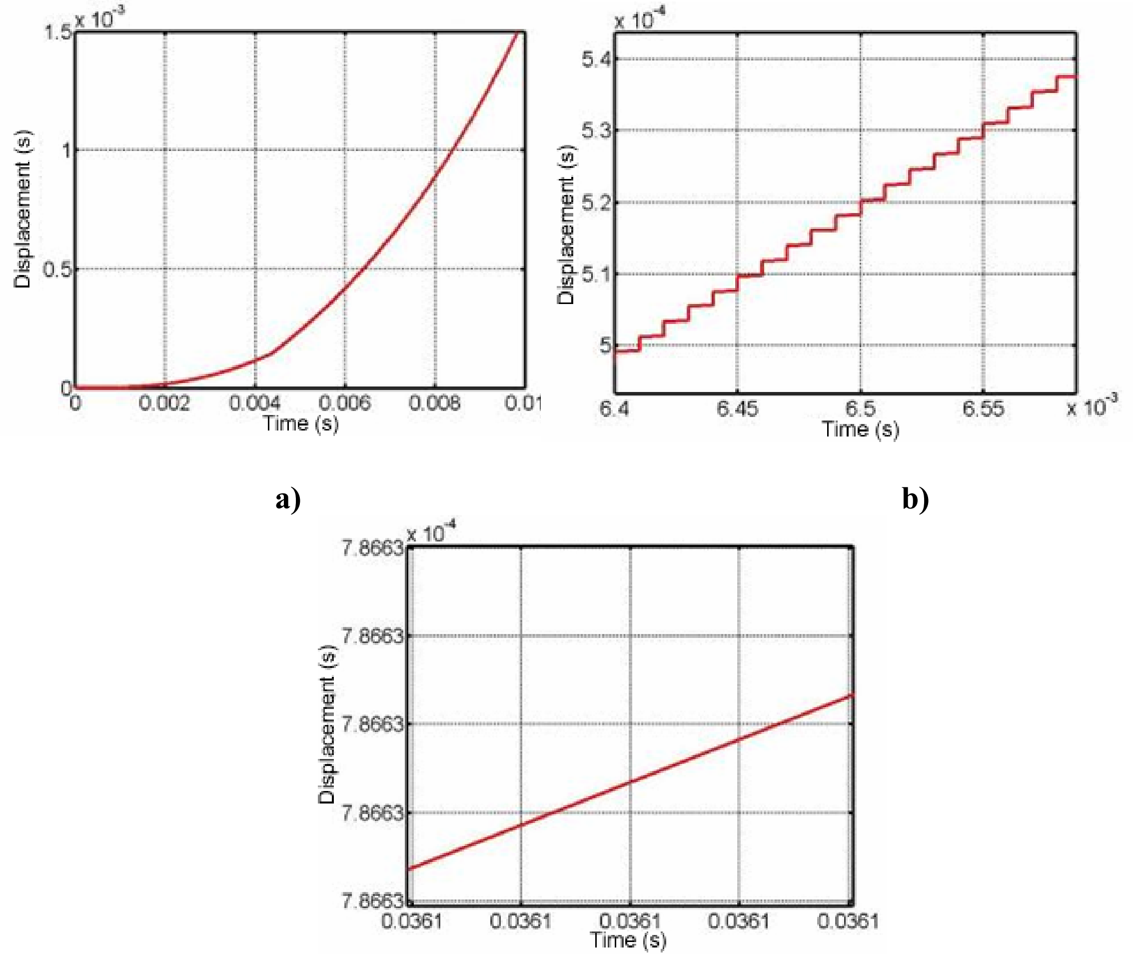
Where, k represents the step of the iteration.

The supply voltage is constant. The resistance and the iteration time Δt are also constants. The on-off ratio of the PWM signal and the position of the armature are input data for the simulation, the force and the inductance values are obtained from the finite element model, for each step of the iteration.

The displacement has two stages: initialization and positioning. The Finite Element Program FEMM has a LUA (V4.0) implementation for the modeling of the magnetic systems. LUA scripts were used to manipulate the program flow and automatically built models with preprocessing and post processing files. In the preprocessing file there have been defined the input data of the model, the form of the results files and the "calling" of the post processing file. A number of temporary files have been created for maintaining the parameters used during the pre and post processing file. In the post processing file of the current step there have been calculated or obtained from the FEM model the input parameters for preprocessing at the next step of simulation and for the results files.

In the initialization stage of the simulation just one electromagnet is working. The on-to-off ratio is modified from 0.1 to 0.9 (considering the shortest time) until the maximum position is achieved and the positioning algorithm starts.

In the positioning stage the on-to-off ratio of both electromagnets has been changed until the desired position has been obtained. After that, the mobile armature will be moved to another position, through the modification of the on-to-off ratio.

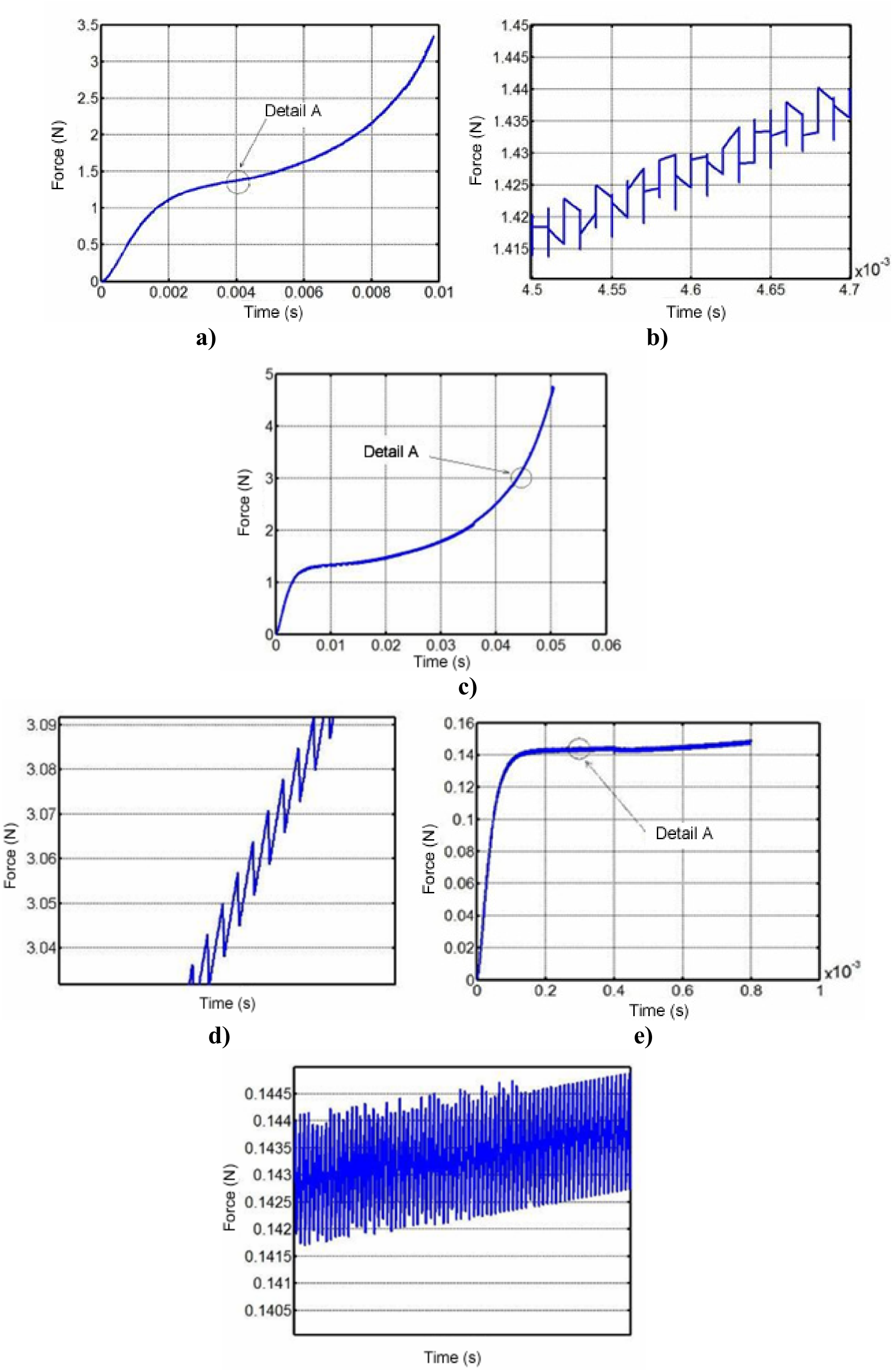


a) **b)**

c)

Figure 3. Mobile armature position in the initialization stage: a) armature mass 0.2 Kg and step period of 2 μs ; b) detail for armature mass 0.2 Kg and step period of 2 μs; c) detail for armature mass 0.2 Kg and step period of 0.1 μs

For finding the on-to-off ratio, a preliminary static simulation has been conducted offline. In all the considered cases, for the initialization stage, the profile of the position-time characteristic is almost the same (Figure 3); the only thing that changes is the time till the maximum position is achieved. When the mobile armature mass is small and the period of time for an iteration is long, rippling arises. When the period of time is long enough its position transition is smooth.



a) b)

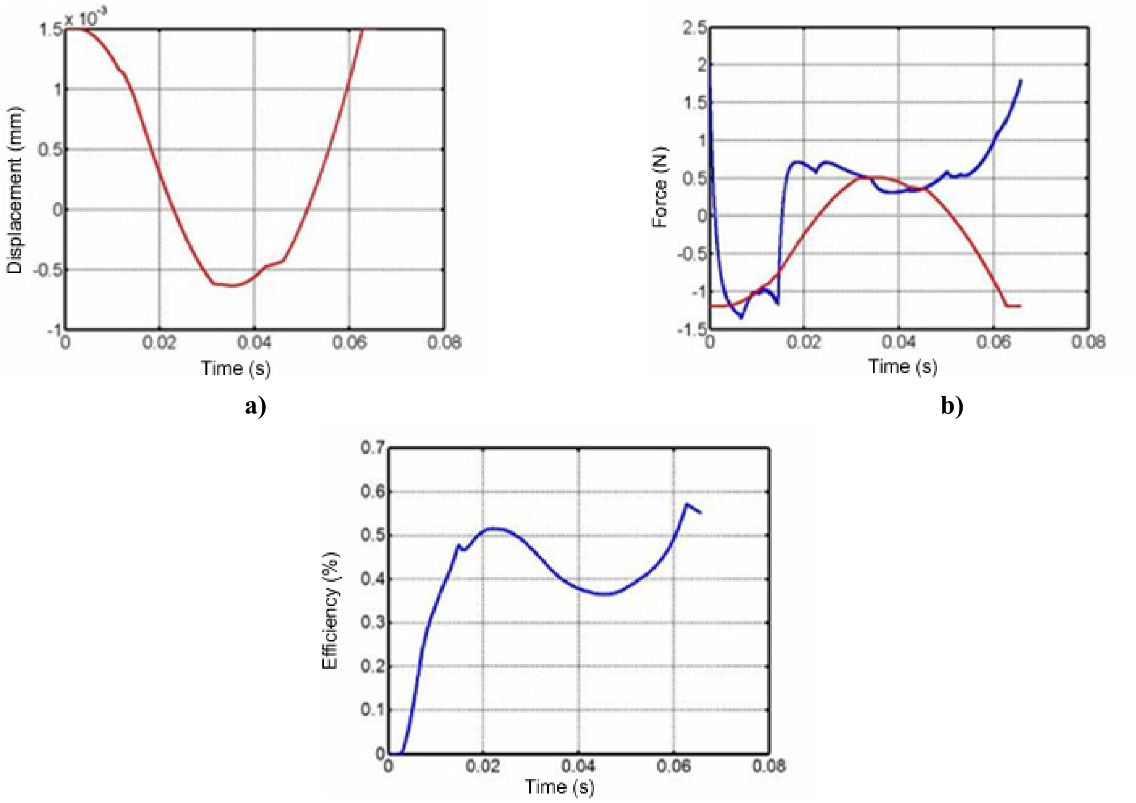
c)

d) e)

f)

Figure 4. Force-time diagrams in the initialization stage: a) armature mass 0.2 Kg and step period of 2 μs; b) detail, armature mass 0.2 Kg and step period of 2 μs; c) armature mass 1 Kg and step period of 2 μs; d) detail, armature mass 1 Kg and step period of 2 μs; e) armature mass 0.2 Kg and step period of 0.1 μs; f) detail, armature mass 0.2 Kg and step period of 0.1 μs.

The force profile (Figure 4) has two regions: a quasilinear zone where the resultant electromagnetic force is smaller than the elastic force of the spring guide, and a nonlinear zone where the displacement of the mobile armature appears. This characteristic was modified with the period of the iteration time and with the mass of the armature. When the period of iteration time is decreasing, the oscillations of the force are increasing. If the mass increased the quasilinear zone expanded and the nonlinear zone decreased, evolving into a saturation zone. In this zone the force has oscillations of hundreds of a Newton.



a) b)

c)

Figure 5. Mechanical parameters of the bi-directional electromagnetic actuator: a) displacement- time diagram; b) force- time diagram (blue- electromagnetic force, red-elastic force); c) efficiency-time diagram

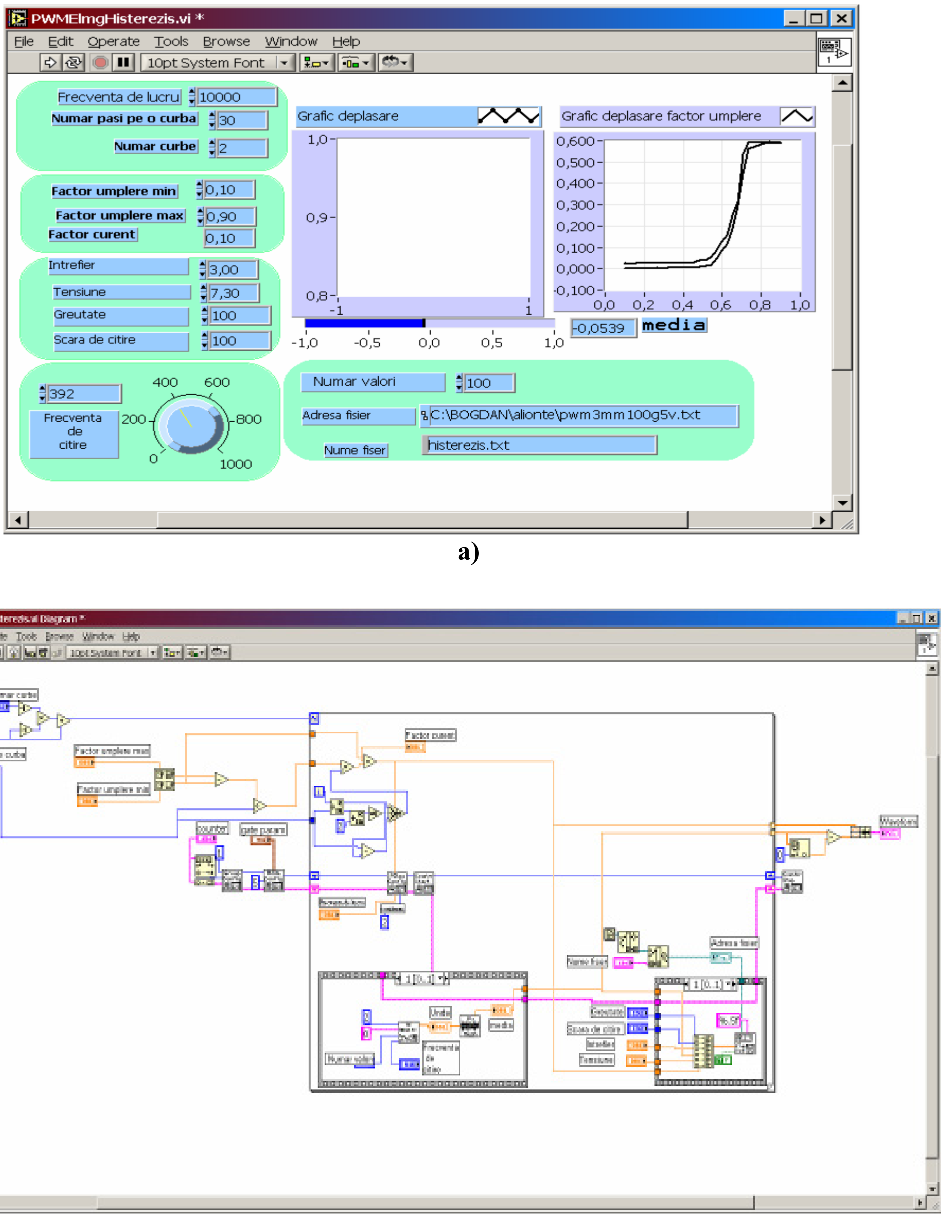
In the positioning stage, the simulation has been segregated in terms of different on-to-off ratio for the different positions obtained. In the simulation no reaction algorithm has been included and therefore, the position is not steady. In the diagram (Figure 4a), it can be noticed that the position achieved is just a modification of the curve downgrade. The force diagram shows how positioning is obtained where the resultant force of the electromagnetic actuators and the elastic force of the spring guide are equal. Another important factor for system stabilization is the speed of the mobile armature which is obtained from position derivation. The efficiency does not exceed 0.6% (Figure 5).

5. Control of the Bi-directional Electromagnetic Actuator

The testing system (presented in Figure 6) consists of: a bi-directional electromagnetic actuator, a PC for control and data acquisition, an acquisition board AT-MIO 16e10, a control board AT-DIO 96 (which can generate the PWM signal), strain gauges and a signal conditioning system (half bridge configuration), an electronic control circuit and a voltage excitation source.

Figure 6. Testing system

The position control and the acquisition program were designed in LabVIEW, the industry-leading software tool for designing, testing, and measuring and controlling systems. The control programs allow for changes in the on-to-off ratio, the frequency of the PWM signal, the acquisition interval and the sampling frequency (Figure 7). Also, the user can get the hysteresis loops using "for" loops and a uniform variation of the on-to-off ratio from 0.1 to 0.9 (Figure 8).



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Frecventa de lucru 10000
Numar pasi pe o curba 30
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a)

b)

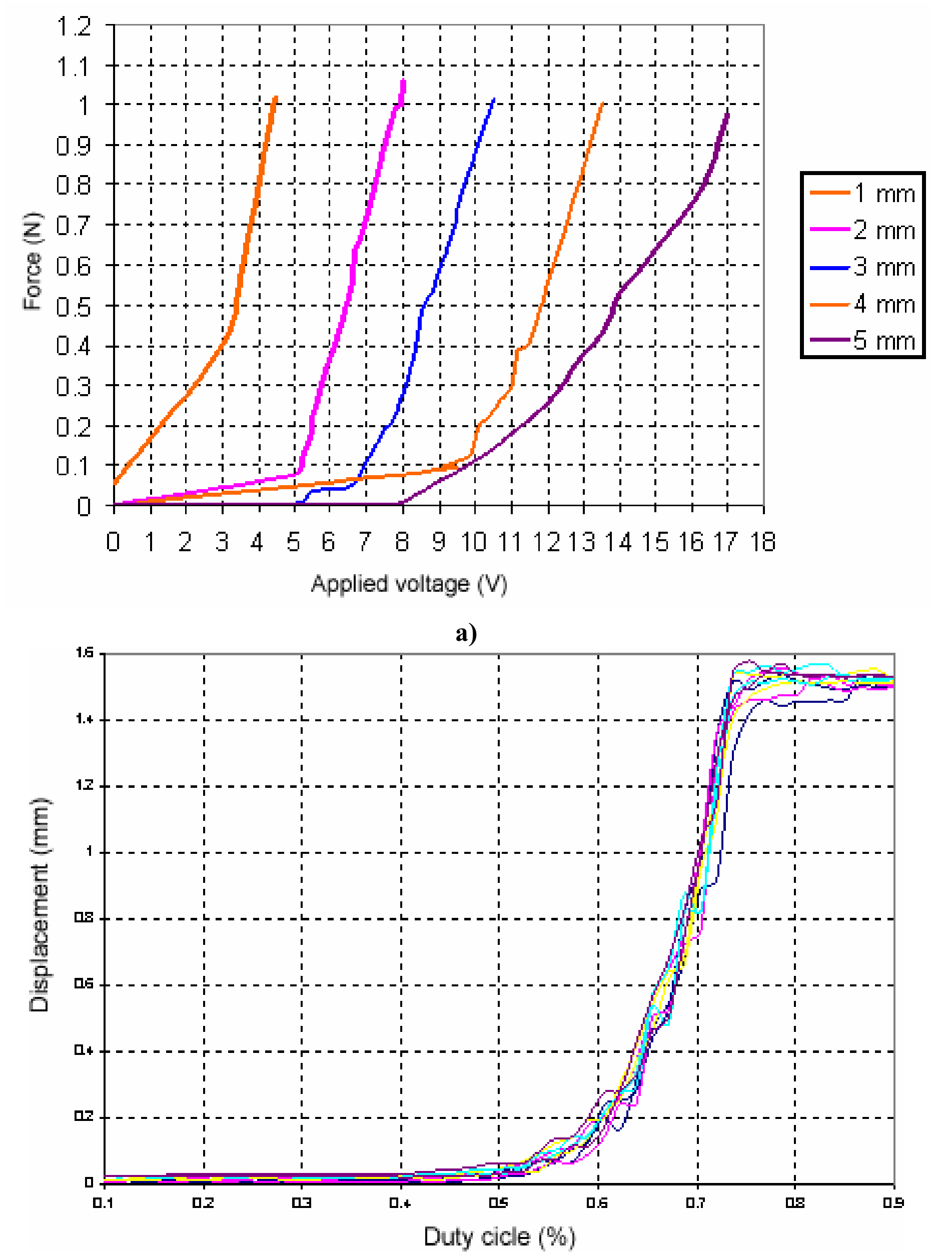
Figure 7. „ControlPWM" program. Program interface

The positioning sensors used are two strain gauges RS 308-102 N11-FA8-120-11 for each direction of displacement. The analogue signals provided by the strain gauges are filtered and amplified by an electronic bridge with 8 channels (two of them are used).The signal is converted into a digital signal with an A/D converter of the acquisition board AT-MIO 16e10.

The four electromagnets can be fed with two circuits based on L298 amplifier circuit, produced by SGS Thompson. The PWM signal is generated by a counter (4 digital lines D0...D7) of the control board PC-DIO 96. The counter configuration can be done for an individual counter or for a group of counters. The Counter Start subroutine permits to start the counter and to identify the execution thread. The counter can be stopped with Counter Stop with the execution thread associated, and the subroutine will generate an error message. Neither Counter Start nor Counter Stop can modify execution thread attributes.

Data acquisition is multipoint; acquisition can be controlled by two parameters: values number and reading frequency. The user can modify these parameters on the central panel. The signal is displayed on the PC screen, and a mean value is calculated and also displayed. This value is saved in a result file.

6. Results and Conclusions



a)

b)

Figure 8. Parameters diagrams for a bidirectional electromagnetic actuator: a) force-voltage diagram for an electromagnet; b) position-on-to-off ratio of the bidirectional electromagnetic actuator for 3 mm and for a PWM signal of 25 kHz

Analyzing the results obtained for an electromagnetic actuator (Figure 9a), one can observe the nonlinear characteristic force-voltage for different gaps. In general, a close correspondence between the simulation and the experimental results can be observed, with minor deviations at some points. The experimental values have been used on the one hand to correct the simulation model and to design the control strategy for the bi-directional actuator on the other hand.

At the same time, one can see that the hysteresis is small and the characteristic has a long quasilinear zone (Figure 9b),. In this way, we have good control and good repeatability.

The target pursued was the linearity of a large zone of the displacement-voltage characteristic which has a great influence for the control implemented. Thus, the experimental results demonstrate a consistent performance of the control strategy based on the dynamic theoretical model, satisfactorily regulating the output of the electromagnetic actuator. Compensation of faster variations may be possible, but could not be experimentally verified due to limitations in implementing the sampling and control rates of instruments used for measurement and control.

Although the research work has demonstrated that an electromagnet bidirectional actuator solenoid can have a precise positioning, additional work is required to turn this research work into a real development. This includes the simplification of hardware circuitry, the porting of the software to the embedded processor, and the conduction of extensive reliability and performance tests.

For further research we intend to upgrade the present position control structure to use force/position or stiffness control. Such a controller requires an additional feedback loop and a force transducer to implement control based on force feedback. We also can use neural networks to describe the nonlinear magnetic characteristics of the solenoid, including hysteresis, eddy current, and leakage flux into the magnetic model. The development of a neural network based controller to control the solenoid may be carried out. Finally, the performance of the neural network based controller on current-voltage linearization (current control), force compensation (nonlinear force function), and control of the mechanical movements (trajectory control) may be studied.

BIBLIOGRAPHY

1. ALIONTE, C.G., **Bidirectional Smart Electromagnetic Actuator**, PhD Thesis, Politehnica University Bucharest, 2006
2. CHEUNG, N.C., PAN, J.F., **Using Variable Reluctance Actuators in Automated Manufacturing Machines**, Industrial Robot: an International Journal, Vol. 30, No. 4, July 2003, pp. 355-362.
3. KAJIMA, T., **Development of a High-Speed Solenoid Valve - Investigation of the Energizing Circuits**, IEEE Transactions on Industrial Electronics, August, Vol. 40, No. 4, 1993, pp 428-435.
4. KAJIMA, T. and KAWAMURA, Y., **Development of a High Speed Solenoid Valve: Investigation of Solenoids**, IEEE Transactions on Industrial Electronics, February, Vol. 42, No. 1, 1995, pp 1-8.
5. Lab VIEW help, www.ni.com
6. LEQUESNE, B., **Fast Acting Long Stroke Solenoids with Two Springs**, IEEE Proceedings on Industry Applications Society annual general meeting, Vol. 1, 1989, pp 195-202.
7. RAHMAN, M.F., CHEUNG, N.C. and LIM, K.W., **Position Estimation in Solenoid Actuators**, IEEE Transactions on Industry Applications, Vol. 32, No. 3, May/Jun 1996, pp 552-559.
8. TANG, Y.W., **Short-stroke Position-Controlled Electromagnetic Actuators**, Ph.D. Thesis, Department of Electrical and Electronics Engineering, University of Leeds, January, 1994.
9. WANG, S.M., MIYANO, T. and HUBBARD, M., **Electromagnetic Field Analysis and Dynamic Simulation of a Two Valve Solenoid Actuator**, IEEE Transactions on Magnetics, March, Vol. 29, No. 2, 1993, pp 1741-1746.