Quadrature Field Oriented Control of a Linear Stepper Motor

Ioan-Adrian VIOREL – Loránd SZABÓ – Zoltán KOVÁCS
Technical University of Cluj-Napoca
Department of Electrical Engineering
Daicoviciu nr. 15
3400 CLUJ, Romania

Abstract: **The hybrid linear stepper motor allows precise linear incremental positioning at high speed. In open loop drive mode the operating frequency of the coil current pulses is given by an external source. If the frequency is not getting to accord to the variations of the load, the stability and step integrity of the motor can be affected. The dynamic performances of the motor can be improved by utilizing a quadrature field oriented control method. The authors propose and analyze by computer simulation a closed loop drive system using the presented quadrature field oriented control method.**

Cite as:
Viorel, I.A. – Szabó, L. – Kovács, Z.: *Quadrature Field Oriented Control of a Linear Stepper Motor*, Proceedings of the Power Conversion & Intelligent Motion Conference (PCIM '93), Nürnberg (Germany), vol. Intelligent Motion, pp. 64-73, 1993.

See attached the scan of the paper

References

1. VIOREL, I.A. – KOVACS, Z. – SZABO, L.: *Sawyer Type Linear Motor Modelling*, Proceedings of the International Conference on Electrical Machines (ICEM '92), Manchester (UK), pp. 697-701, 1992.
2. VIOREL, I.A. – ŢOPA, M. – KOVACS, Z.: *Variable Reluctance Linear Motor Air-Gap Permeance Calculations* (in Romanian), Scientific Bulletin of the Polytechnic Institute of Cluj-Napoca, vol. 27. (1984), pp. 27-32.
3. HAYT, W.H. Jr.: *Engineering Electromagnetics*, Third edition. Mc Graw Hill Book Company, New York, 1974.
4. SZABO, L. - VIOREL, I.A. - KOVACS, Z.: *Computer Simulation of a Closed-Loop Linear Positioning System*, Proceedings of the Power Conversion & Intelligent Motion Conference (PCIM '93), Nürnberg (Germany), vol. Intelligent Motion, pp. 142-151, 1993.

PCIM '93

EUROPE

OFFICIAL

PROCEEDINGS

OF THE TWENTYTHIRD

INTERNATIONAL

INTELLIGENT MOTION

CONFERENCE

JUNE 22 – 24, 1993
NÜRNBERG, GERMANY

This Book is the Property of

QUADRATURE FIELD-ORIENTED CONTROL OF A LINEAR STEPPER MOTOR

VIOREL. I.A. - SZABO L. - KOVACS Z.

Technical University of Cluj
Department of Electrical Engineering
Daicoviciu nr. 15.
3400-CLUJ, Romania

ABSTRACT

The hybrid linear stepper motor allows precise linear incremental positioning at high speed. In open-loop drive mode the operating frequency of the coil current pulses is given by an external source. If the frequency is not getting to accord to the variations of the load, the stability and step integrity of the motor can be affected. The dynamic performances of the motor can be improved by utilizing a quadrature field-oriented control method. The authors propose and analyze by computer simulation a closed-loop drive system using the presented quadrature field-oriented control method.

INTRODUCTION

Linear precise positioning systems are required in a variety of applications concerning high and low propulsion technology, computer peripherals, machine tools, robotics, etc. The interest for these systems has been witnessing a steady increase in requirements for positioning accuracy and repeatability, while at the same time placing ever tighter demands on the maximum speed and, moreimportantly, the constancy of speed.

The hybrid linear stepping motor is one of the best choices for the precision linear positioning systems. It is operated under the combined principles of the permanent magnet and variable reluctance motors. The motor consists of an equidistant toothed rectangular steel bar (the platen) of any length fabricated of cold-rolled steel and an assembly of a permanent magnet and two electromagnets called the mover. The toothed structure in both parts (slider and platen) have the same very fine teeth pitch. The flux of the permanent magnet from the mover passes through the cores of the two electromagnets with coils and toothed poles. By commuting the permanent magnet flux in a way to concentrate the magnetic flux into a single pole is resulting in a tangential force, which tends to align the teeth of that pole with the teeth of the platen, in a manner as to minimize the air-gap magnetic energy. The two-phase excitation mode firstly provides high resolution of the step size, one step corresponding to a quarter tooth pitch. Secondly there is always one strong and one weak pole at each magnetic circuit part, so the normal force, which is impossible to be eliminated, is better distributed on both sides of the magnet.

In the open-loop drive mode the phase excitation sequence is executed at a given constant frequency. However, if the load is varying the open-loop controller may demand acceleration rates which exceed the step capability of the motor, resulting in a loss of synchronism between the motor position and excitation changes, and in amplifying the vibrations of the mover. These vibrations cannot be suppressed completely because they are present anyway being caused by the modification of the large normal force attracting the mover to the platen, by the oscillations of the mover around the intermediate equilibrium positions and by the lack of harmonic purity in both the air-gap reluctance and the mover drive currents.

The dynamic performances of the motor can be improved by utilizing a quadrature field-oriented control method which will allow the motor speed to vary with the load. In this case the operating frequency will depend only on the capability of the motor to realize a step under given conditions as load and input power.

The proposed method is based on the fact that the flux linkage through the un-energized coil of the motor is only function of the mover position and is independent of the phase currents or of any other circuit parameters, such resistance and inductance. Monitoring the back EMF (electrical motive force) generated in this coils, the relative position of the mover can be directly detected. In constant-voltage operating mode when the mover had reached its equilibrium position for the last excitation change the absolute value of back EMF in the un- energized coil is minimum. In this moment the other coil must be energized in a manner as to execute the necessary excitation sequence. Without requiring any direct sensing of the mover position the control system avoids the use of expensive position sensors.

The authors propose and analyze by computer simulation a closed-loop drive system using a quadrature field-oriented control method using the sensing of the back EMF in the un- energized coil of the motor. The comparison of the results of the open-loop and of the described closed-loop control mode confirm the validity and demonstrates the advantages of the proposed quadrature field-oriented method. The digital simulation of the closed-loop dynamic behavior of the hybrid linear stepper motor offers the possibility to establish the correct command sequence of the supply source.

COIL EMF

The hybrid linear stepper motor mover contains, besides the permanent magnet, two electromagnets with coils, figure 1.

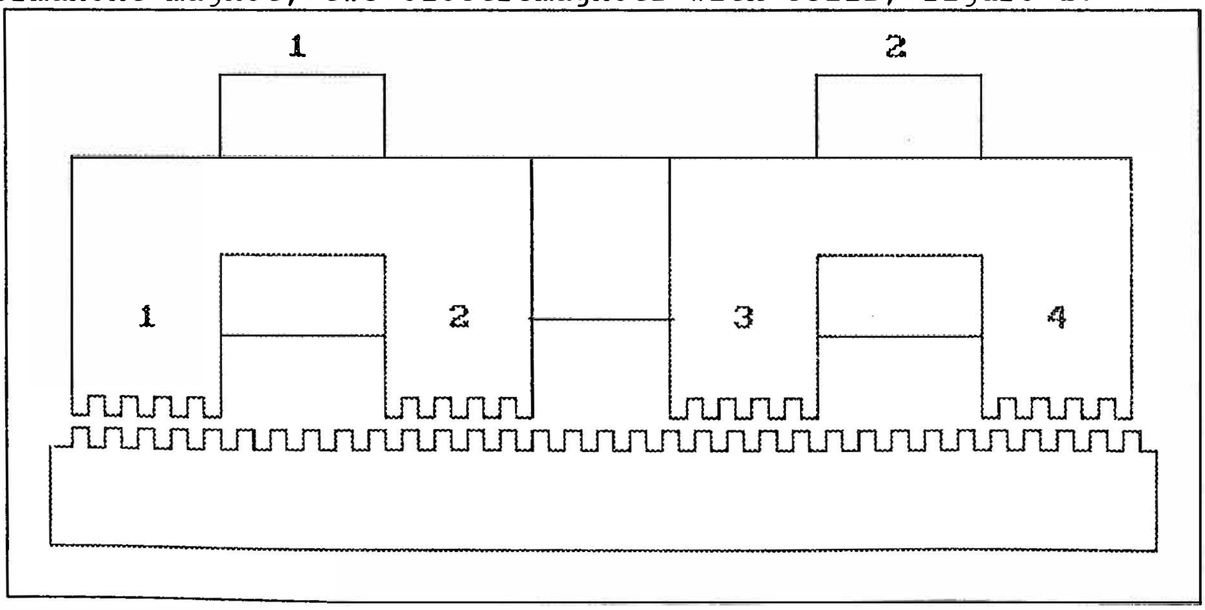

Figure 1

If the coils are not supplied and the mover changes its position related to the platen, the fluxes through the coils are not constant because of air-gap reluctance variation. Therefore, if the mover is moving with a certain speed, the flux variation will produce EMF in the coils.

In order to calculate number one coil EMF the magnetic equivalent circuit, given in figure 2., is considered; the flux through the coil being $\underline{\Phi}_1$. It is easy to see that only air-gap reluctances were taken into account, and really they are much more greater than all iron-core portion reluctances.

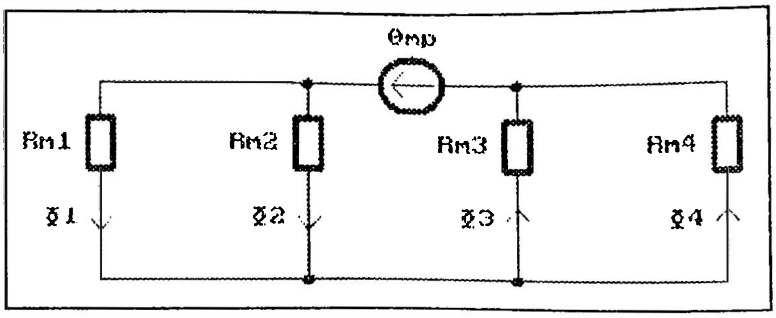

Figure 2

As only the flux $\underline{\Phi}_1$ is needed, an equivalent reluctance $\underline{R}_{me}$ can be calculated,

$$\frac{1}{R_{m_e}} = \frac{1}{R_{m_3}} + \frac{1}{R_{m_4}} = P_{m_e} \tag{1}$$

where

$$P_{m_e} = P_{m_3} + P_{m_4} \tag{2}$$

$\underline{P}_{m3}$, $\underline{P}_{m4}$ being the air-gap permeance under the poles number 3 and 4. The general formula for the air-gap pole permeance is:

$$P_{m_i} = \frac{\mu_0 S}{2Z\delta'}\left[\frac{\lambda}{2}\,[1+\lambda(2z-1)]\cos\alpha_i + 2Z + \lambda - 1\right], \quad i=1\div 4 \tag{3}$$

with:

$$\alpha_1 = \alpha;\ \ \alpha_2 = \alpha + \frac{t_d}{2}\frac{2\pi}{t_d};\ \ \alpha_3 = \alpha + \frac{t_d}{4}\frac{2\pi}{t_d};\ \ \alpha_4 = \alpha - \frac{t_d}{4}\frac{2\pi}{t_d} \tag{4}$$

$\underline{S}$ pole area and $\underline{Z}$ pole number of teeth,

$$\delta' = k_c\delta \tag{5}$$

is the equivalent air-gap length, with $\underline{\delta}$ real air-gap length and $\underline{k_c}$ Carter's factor.

Therefore it comes up that:

$$P_{m_e} = \frac{\mu_0 S}{Z\delta'}(2Z + \lambda - 1) \tag{6}$$

where λ is the coefficient of the air gap equivalent variable permeance [2], and

$$\alpha = x\frac{2\pi}{t_d} \tag{7}$$

is the mover displacement. It is easy to see that

$$P_{m_1} + P_{m_2} = P_{m_e} \tag{8}$$

because all the poles are identically, having the same area and number of teeth.

Then, considering the magnetic equivalent circuit given in figure 3., and applying Kirchhoff's theorems one can obtain the equations:

$$\begin{cases} \Phi = \Phi_1 + \Phi_2 \\ R_{m_1}\Phi_1 + R_{m_e}\Phi = \theta_{mp} \\ R_{m_2}\Phi_2 + R_{m_e}\Phi = \theta_{mp} \end{cases} \tag{9}$$

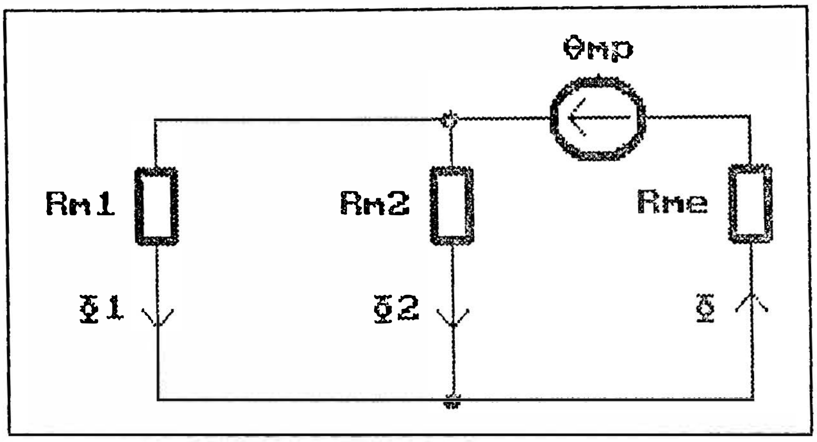

Figure 3

The flux $\underline{\Phi_1}$ through number one coil results:

$$\Phi_1 = \frac{\theta_{mp}}{2R_{m_1}} \tag{10}$$

and the resulting EMF is:

$$e_1 = -N\frac{d\Phi_1}{dt} = -\frac{N\theta_{mp}}{2}\frac{d(P_{m_1})}{dt} \tag{11}$$

where N is coil turns number.

After computing the time derivate of the magnetic permeance the EMF expression becomes:

$$e_1 = -\frac{N\theta_{mp}\mu_0 S\lambda}{8Z\delta'}[1+\lambda(2Z-1)]\sin\alpha\frac{dx}{dt}\frac{2\pi}{t_d} \tag{12}$$

where dx/dt is the mover's speed, and if the speed is constant like the permanent magnet MMF, θ_{mp}, the EMF varies sinusoidally, being function only of the mover displacement α.

Considering the initial value of the displacement zero, i.e. $\alpha=0$ for $t=0$, like in the figure 1., the EMF, e_1 minimum value will occur when the displacement is equal to a quarter of tooth pitch. In fact if

$$v = \frac{dx}{dt} \tag{13}$$

is the mover speed, the EMF's e_1 expression can be rewritten as:

$$e_1 = -K_E\theta_{mp}v\sin\alpha \tag{14}$$

all the constant terms from (12) being included in the EMF constant K_E. And, without any computation, because it is obviously clear, the EMF e_2 which occurs in the number two coil is expressed by

$$e_2 = -K_E\theta_{mp}v\sin(\alpha-\frac{\pi}{2}) \tag{15}$$

Two factors can affect the EMF sinusoidally variation: mover speed and permanent magnet MMF. Of course if the speed is not constant, the coil EMF will not be sinusoidal and only its zero value will occur when

$$x = k\frac{t_d}{2}; \qquad k=0;1;2... \tag{16}$$

for any kind of speed variation, except for zero.

The permanent magnet MMF changes together with its operating point due to air-gap variable reluctances and coils amperturns. As it was already proved, if the iron core is not saturated, the global air-gap reluctance is constant, even if the pole air-gap reluctance depends on the mover position. Also, when the saturation does not affect the iron core, the permanent magnet reluctance is much more bigger than the equivalent reluctance calculated on external magnetic circuit, including air-gaps. Therefore the coils amperturns will produce feeble or no change at all in permanent magnet MMF, which can be considered constant.

CONTROL STRATEGY

The total tangential force can be computed from magnetic energy:

$$F_t=\sum_{i=1}^{4}-\left(\frac{dW_{m_i}}{dx}\right)\Bigg|_{\Phi_i=ct.} \tag{17}$$

and, after some calculations it can be arranged as:

$$F_t=\sum_{i=1}^{4}-K_F\,(\Phi_i\delta_i)^2\,\sin\alpha_i \tag{18}$$

where $\underline{\delta_i}$ is the variable equivalent air-gap for the $\underline{i}$ pole of the mover, [2], and $\underline{K_F}$ is a constant.

The mover position presented in figure 1. is an equilibrium position. It has been obtained after supplying coil number one such in a way to keep the flux through second pole quite zero. If the mover has to continue its displacement to the right, coil number two has to be supplied with current to bring the flux through third pole to zero. So the tangential force developed under the fourth pole is maximum, while the tangential forces, developed under the other poles are zero ($\underline{\alpha_1=0,\ \alpha_2=\pi,\ \Phi_1\approx0}$). To the displacement zero value will correspond a maximum value for the EMF $\underline{e_2}$, which means that the flux $\underline{\Phi_4}$ and the EMF $\underline{e_2}$ has to be maximum at the same time.

If one goes further with this reasoning and looks on the next step, when coil number one has to be supplied in order to bring and keep to a zero value the flux through the first pole, will figure out that it will occur at the value $\underline{t_d/4}$ for $\underline{x}$. And at that value for $\underline{x}$, the coil number one EMF's will be minimum. It means that every time the current through the controlled coil, and the resulting flux under the poles will be in phase with EMF, if the mover speed is constant. Also it has to be pointed out that the control current changes from one coil to another has to be done such in a way as to be in quadrature with the EMF from the opposite coil, and at the un-energized coil EMF's peak value.

Concluding, one can say that EMF detection from the un-energized coil offers enough information to assure a correct quadrature field-oriented control, only if the mover speed is constant, or almost. The control strategy comes up entirely from the brief presentation given ahead.

The variable mover speed operating mode, which is quite a reality in the hybrid linear stepper motor case, because of its tangential force variation will bring coil's EMF out of the sinusoidal shape, and, of course the EMF will not contain the information which is necessary to assure the optimum control. It means that control signal can come earlier or late, depending on the mover speed variations and this fact will diminish the tangential force developed. Therefore it is quite clear that the peak EMF detection offers a better choice than open-loop operating mode of the constant frequency supplied hybrid linear stepper motor, but important variations of the mover speed will conduct to a decreasing of the control accuracy.

Even there are some possibilities to improve the processing of the detected EMF, not discussed in this paper, the best solution come from using the EMF detection coupled with a signal from an accelerometer which integrated will give the actual mover speed [4].

RESULTS AND CONCLUSIONS

The hybrid linear stepper motor with four poles, has 5 teeth on each pole; tooth pitch is .002 m and tooth length .001 m. The permanent magnet of the mover is of VACOMAX-145 type with residual flux density .9 T and coercive force 650 kA/m.

In this paper was considered, comparatively, open-loop and closed-loop operating modes. For the open-loop drive system the control coils were supplied with constant values current pulses at a given frequency. In the closed-loop operating mode the control coils were supplied also with constant values current pulses, but the frequency has been imposed by the control loop signal given by sensing the back EMF from the un-energized coil. The motor mathematical model is of coupled circuit-field type, taking fully into account the nonlinearities, [1].

In figure 4. and 6., respectively in figure 5. and 7. are shown the variations versus time of the currents in control coils, resulting tangential force, velocity and displacement in the case of a open-loop, respectively closed-loop drive system.

One can observe the great variations of the mover's speed during the movement in the open-loop operating mode, because the resulting tangential force has, from the mover's start, quite important negative values.

In the closed-loop operating mode at the beginning of the mover movement the total tangential force has small negative values, but with the speed increasing the negative values become much more important, and is quite clear that the control signal based on back EMF peak detection comes earlier or later.

It is very easy to see that, even not an ideal control method, the back EMF peak sensing closed-loop control assures better results, which means bigger speed and greater displacement, without increasing the drive control system cost.

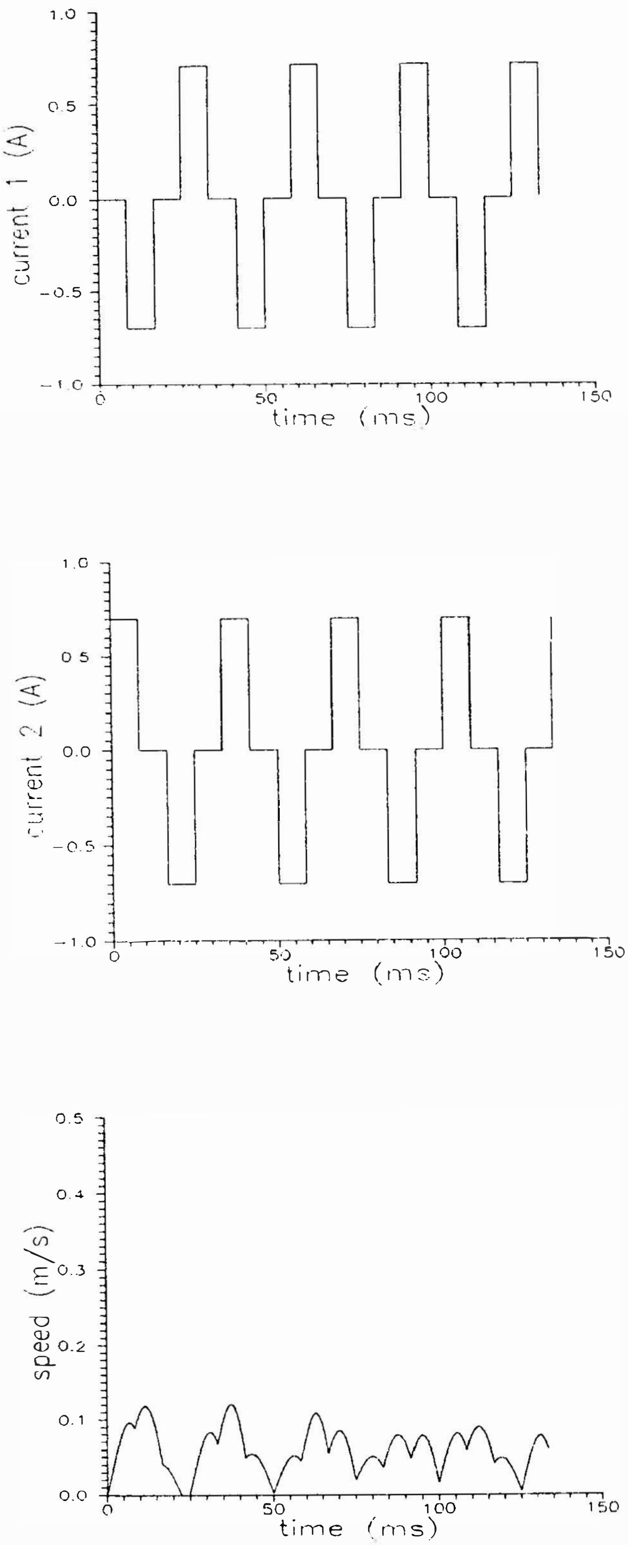

Figure 4.

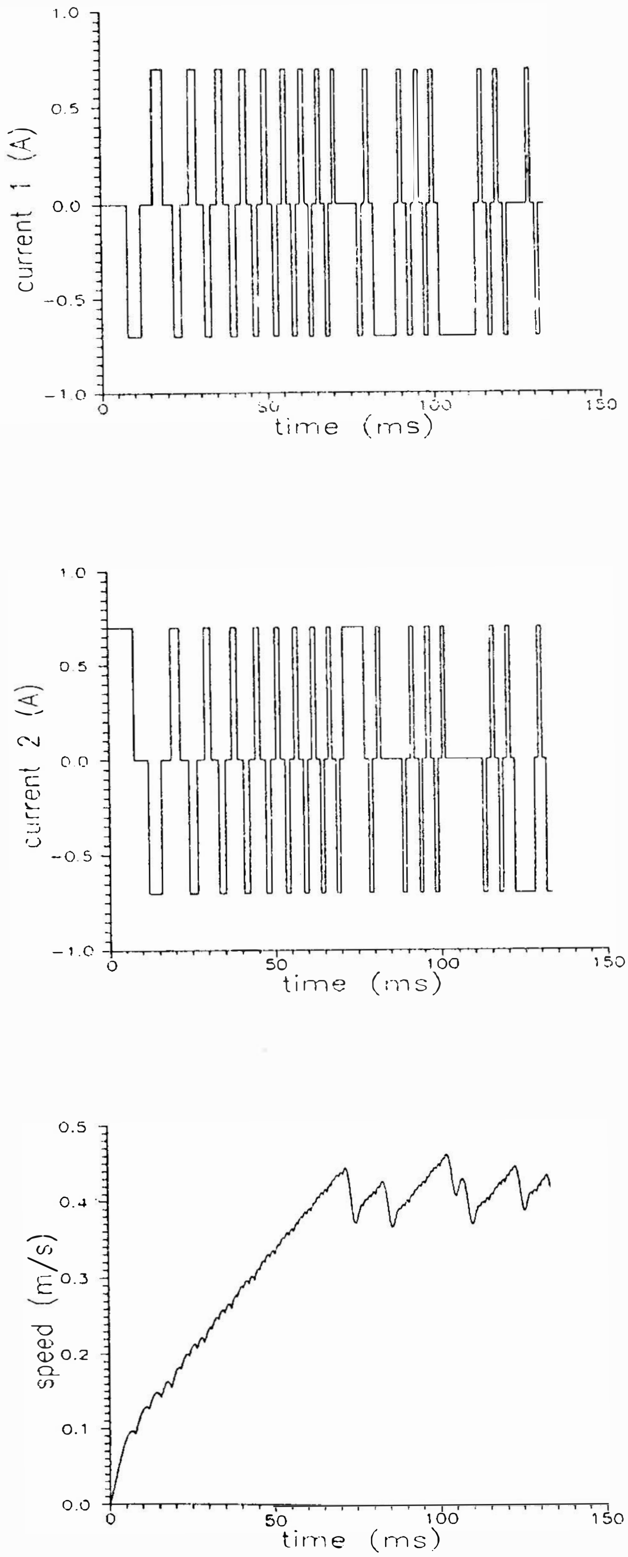

Figure 5.

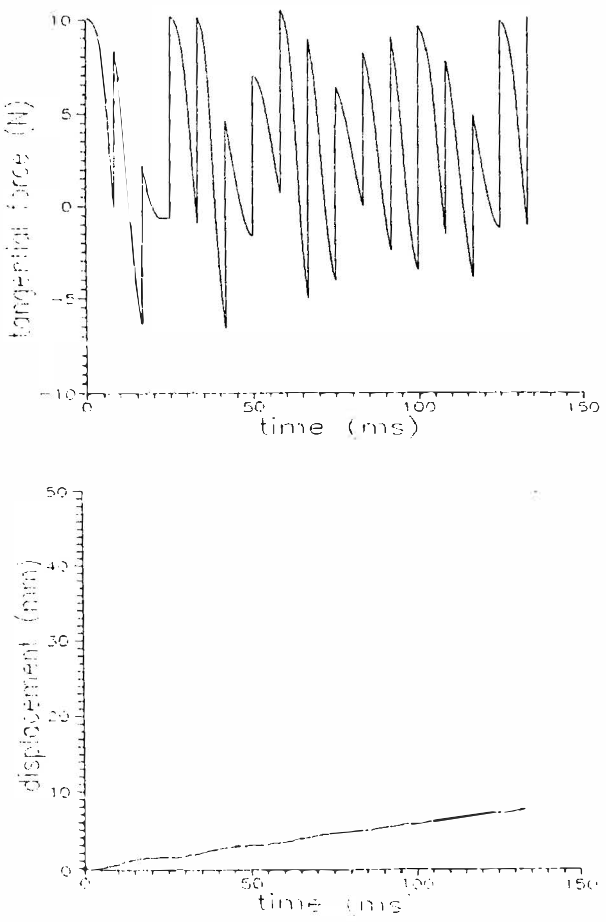

Figure 6.

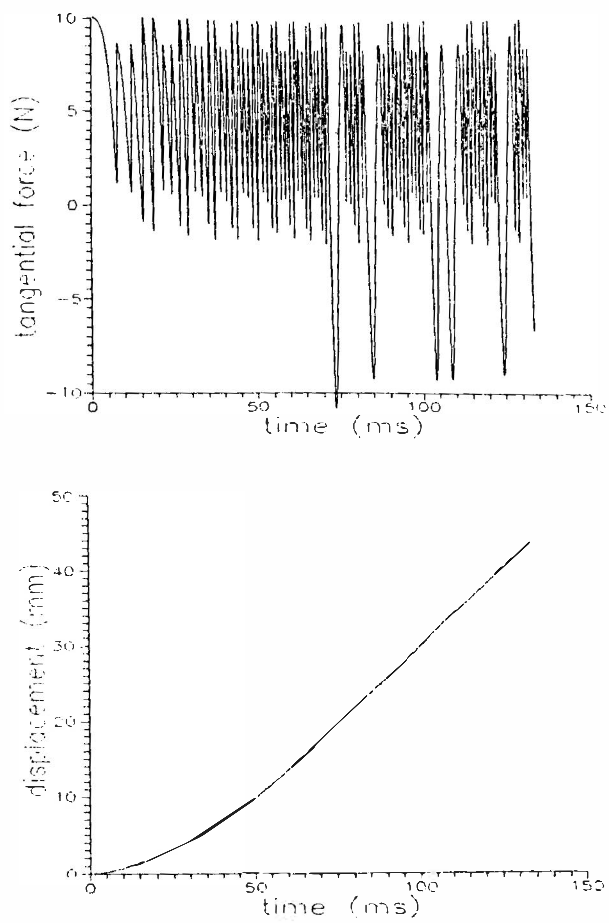

Figure 7.

REFERENCES

1. VIOREL I.A. - KOVACS Z. - SZABO L. : Sawyer Type Linear Motor Modelling, Proceedings of the International Conference on Electrical Machines 1992, pp. 697-701.
2. VIOREL I.A. - Topa M. - KOVACS Z.: Variable Reluctance Linear Motor Air-Gap Permeance Calculations (in Rumanian), Scientific Bulletin of the Polytechnic Institute of Cluj-Napoca, vol. 27. (1984)., pp. 27-32.
3. HAYT W.H. Jr.: Engineering Electromagnetics, Third edition. Mc Graw-Hill Book Company, New York, 1974.
4. SZABO L. - VIOREL I.A. - KOVACS Z.: Computer Simulation of a Closed-Loop Linear Positioning System, paper to be presented at PCIM '93 Conference.