Computer Simulation of a Constant Velocity Contouring System Using x-y Surface Motor

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Abstract: **Two dimensional linear (surface) motors are in use for industrial applications that require positioning with more degrees of mechanical freedom. The x-y surface motor, obtained by combining two variable reluctance, permanent magnet excited synchronous (hybrid) linear motors, can travel in any direction of the x-y plane. The computer simulation of the constant velocity contouring system using such kind of motor is performed by a coupled circuit-field mathematic model. The utilized simulation method allows a wide range of design variables to be evaluated without prototyping the contouring system.**

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COMPUTER SIMULATION OF A CONSTANT VELOCITY CONTOURING SYSTEM USING X-Y SURFACE MOTOR

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ABSTRACT

Two dimensional linear (surface) motors are in use for industrial applications that require positioning with more degrees of mechanical freedom. The x-y surface motor, obtained by combining two variable reluctance, permanent magnet excited synchronous (hybrid) linear motors, can travel in any direction of the x-y plane. The computer simulation of the constant velocity contouring system using such kind of motor is performed by a coupled circuit-field mathematic model. The utilized simulation method allows a wide range of design variables to be evaluated without prototyping the contouring system.

1. INTRODUCTION

Modern mechanical systems require electrical drives based on motors with more degrees of mechanical freedom, particularly in industrial manipulation, robotics, precise positioning equipment and so on. Recently for such applications direct driven x-y surface motors had been introduced [1].

The x-y surface motor was patented by B. Sawyer. The basic construction of the x-y surface motor is obtained by combining two variable reluctance, permanent magnet excited synchronous (hybrid) motors, described in detail in several previous papers [2], [3]. It can travel in any direction of the x-y plane by turning on and off in a right sequence the current of the command coils on the four electromagnetic poles of the mover. The forcer body advances in a way to keep its teeth of the poles in alignment with the platen teeth.

The smooth continuous path of the movement is generated by the two axis contouring software. Complex motion profiles for point to point search of each axis are easily executed by using high order interpolation functions or analytical expressions.

Each axis movement of the contouring system is controlled by a separate motion controller. The two precisely synchronized motion controllers are based on the quadrature field-oriented control method. Monitoring the back EMF generated in the un-energized coil of each mover the command current is commuted at the optimum control angle. This way step integrity and small ripple of the tracking force is ensured. The stress and wear of the motor is minimized too. The prescribed trajectory is accurately followed with the imposed velocity, assuring high accuracy during contouring operations.

The constant velocity contouring systems using x-y surface motors provide high speed, repeatable constant velocity contouring motion for automated dispensing, routing, water jet and gas plasma cutting, scanning, welding, laser marking and machining and other similar profiling applications.

The dynamic behavior of the x-y surface motor can be studied via digital simulation performed using a coupled circuit-field mathematical model. The computer program based on this model offers the possibility to calculate all the motor characteristics, such as: forces, acceleration, velocity, displacement, control currents, back e.m.f. etc. It can be used by the designers to check the performances without prototyping system variants.

The simulated task for the x-y surface motor of the contouring system presented in this paper is an elliptic trajectory. The performed trajectory and velocities of the motor are presented. The current of one command coil and the tangential force developed of one mover are presented too. The given characteristics obtained via computer simulation stand by to sustain the theoretical results and to confirm that the proposed control strategy is one of the best for these purposes.

2. THE X-Y SURFACE MOTOR

An x-y surface motor can be obtained by combining two variable reluctance, permanent magnet excited synchronous (hybrid) linear motors (see figure 1).

The surface motor can travel in any direction of the x-y plane on a stationary base (the platen), cross-scored to form equidistant square islands (an array of square teeth) in waffle pattern. The grooves are filled with non-magnetic material and the entire platen is then grounded flat to provide a smooth travel surface so that the mover can float above or below the stationary base on a stable air-bearing. The air-bearing contains a pressurized film of air that separates the moving surface from the platen surface. The air is supplied from four holes to the surface. This virtually frictionless bearing eliminates motion errors due to mechanical hysteresis, vibrations and crookedness of travel. There are resilient mechanical stops that limit the travel in order to protect the mover.

The mover is suspended from the stationary base by the normal magnetic attracting force, but free to move in the

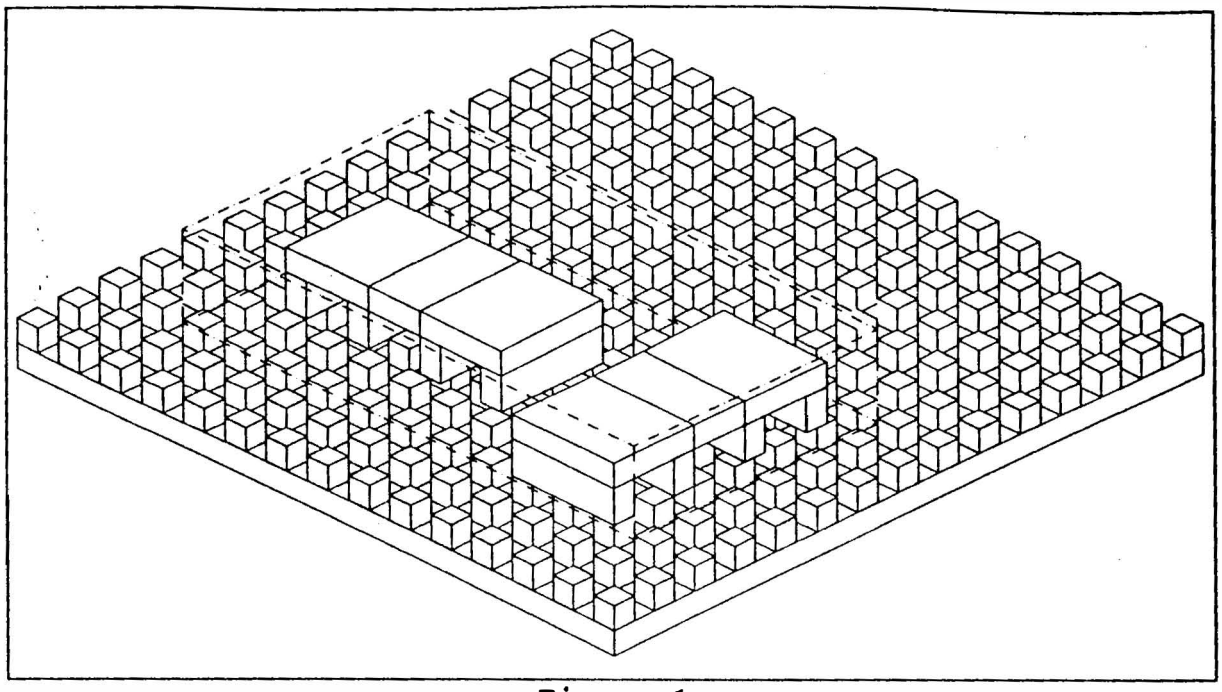

Figure 1

horizontal plane due to a thin air film of about 10μm, allowing three degrees of freedom. The moving assembly (the forcer) consists of two movers, like those of a hybrid linear motor. One mover is used to produce tangential tracking force in the *x* direction, and the other one in the y direction. Each mover consists of two electromagnets having command coils and a permanent magnet between them, which serves as a bias source. Each electromagnet has two poles, and all poles have the same number of teeth.

The toothed structure in both parts (mover and platen) have the same very fine teeth pitch. The accuracy of the platen features is a major contributor to the overall accuracy of the x-y surface motor. The stationary base must be fabricated with tight control of the flatness across the surface. It must also be capable of dissipating heat generated from eddy current losses associated with high tracking forces. The carefully designed geometry of the motor provides high dynamic accuracy and stability.

By turning on and off in an adequate sequence the current of the command coils on the electromagnetic poles, the forcer body advances to keep its teeth of the poles in alignment with the platen teeth. The current pulses may be generated for the *x* and y directions simultaneously, resulting in a motion at any angle with respect to the platen. All control currents are supplied to the forcer through an umbilical cord.

3. THE CONSTANT VELOCITY CONTOURING SYSTEM CONTROL

The block diagram of the constant velocity contouring system's control scheme is presented in figure 2 [4].

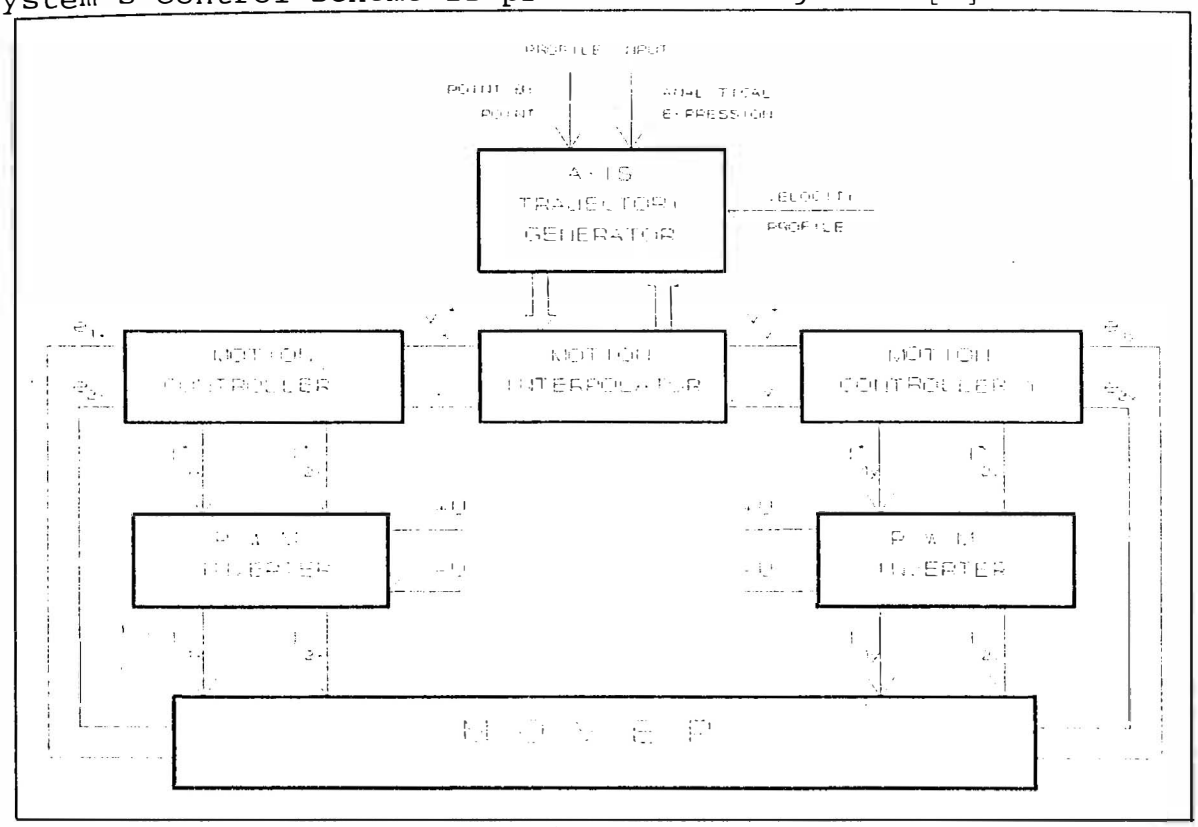

Figure 2

The prescribed motion profile can be given by the user point by point, or by the analytical expression of the desired trajectory. The two axis contouring software of the axis trajectory generator initiates a smooth continuous path for the movement of each axis by using three-order smooth spline interpolation functions or the given analytical expression. The motion interpolator receives positional data and converts this to the correct imposed velocity profile for both axis, decomposing the imposed tangential velocity after the two axes (v_x^* and v_y^*). In this manner the prescribed trajectory is accurately followed with the imposed velocity, assuring high accuracy during contouring operations.

Each axis movement of the contouring system is controlled by a separate motion controller. The control of the mover has to assure the imposed velocity profile and the positioning precision. Mover's speed is depending on the resulting tangential force and therefore the control has to act on the mover position and, eventually, on the coil currents. The two motion controllers are based on the quadrature field-oriented control method of the variable reluctance permanent magnet type motors described in detail in [5].

The back EMF generated in the un-energized coil of each mover is monitored in order to determine the current commutation moment, when the command current is commuted to an other coil of the corresponding mover with the necessary polarization [6]. For high efficiency the commutation will be made at an optimum control angle. So the developed tangential force will have small ripples and is controlled via the coil currents [7]. This way step integrity is guaranteed under all load conditions, because the start of each step is delayed until the previous step has been satisfactorily completed. From the back EMF generated in the un-energized coil of each mover the actual displacement on the given axis (x and y) can be determined too.

The motion controller compares the prescribed speed (v_x^* or v_y^*) with the actual motor speed (v_x or v_y). The information thus collected provides the reference currents for the constant voltage PWM inverters (i_{1x}^*, i_{2x}^*, respectively i_{1y}^*, i_{2y}^*). The controllers have to assure a certain magnitude for the control currents in order to obtain the imposed velocity. The two motion controllers are precisely synchronized to ensure perfect coordination of the two axis movement.

The total tangential force of one mover can be obtained by adding the tangential forces under the four corresponding poles:

$$F_t = K_{F_t} \sum_{i=1}^{4} \frac{\Phi_i^2 \sin\alpha_i}{(1+m\cos\alpha_i)^2} \tag{1}$$

where Φ_i is the magnetic flux through pole i and α_i is the angular displacement. The tangential force constant is:

$$K_{F_t} = -\frac{2\pi}{\tau} \frac{Z\delta' m}{\mu_0 A_p (2Z+\lambda-1)} \tag{2}$$

where τ is the teeth pitch, A_p the mover pole area, Z the mover's pole teeth number and δ' the equivalent air-gap. The motor constant m can be determined using:

$$m = \frac{\lambda[1+\lambda(2Z-1)]}{2(2Z+\lambda-1)} \tag{3}$$

where λ is the coefficient of the equivalent air-gap permeance.

The optimum value of the displacement α_0 is obtained from the relation [8]:

$$\frac{dF_{t_m}}{d\alpha} = 0 \tag{4}$$

where F_{t_m} is the medium tangential force, and α_0 will be given by the next equation:

$$\cos\alpha_0 + \sin\alpha_0 - 2k_i m \sin\alpha_0 \cos\alpha_0 = 0 \tag{5}$$

where k_i is the m.m.f.'s factor. With motor constant m small enough, the optimum angular displacement is:

$$\alpha_0 = -\frac{\pi}{4} \tag{6}$$

For a teeth pitch $\tau = 2mm$ the optimum displacement for the commutation is:

$$x_0 \approx 0.25mm \tag{7}$$

As above it was presented, in order to establish the right sequence of the command current pulses at each moment the position of the mover must be known. Four position states were determined in the following way:

- state 1 for $x \in [-0.25 \pm N\tau, 0.25 \pm N\tau)$,
- state 2 for $x \in [0.25 \pm N\tau, 0.75 \pm N\tau)$,
- state 3 for $x \in [0.75 \pm N\tau, 1.25 \pm N\tau)$,
- state 4 for $x \in [1.25 \pm N\tau, 1.75 \pm N\tau)$,

The correct command currents in function of the direction of displacement and of the position state can be taken from table 1.

DIRECTION	POSITION STATES			
	1	2	3	4
+	$i_1=0$ $i_2>0$	$i_1<0$ $i_2=0$	$i_1=0$ $i_2<0$	$i_1>0$ $i_2=0$
-	$i_1=0$ $i_2<0$	$i_1>0$ $i_2=0$	$i_1=0$ $i_2>0$	$i_1<0$ $i_2=0$

Table 1

For example, if the relative displacement of the mover in the x direction is 6mm, the corresponding position state variable is 1. If a movement in positive direction on the x axis has to be performed, then command coil number two from the corresponding mover to the x direction has to be energized with a positive current pulse.

4. DYNAMIC SIMULATION OF THE CONSTANT VELOCITY CONTOURING SYSTEM

In order to sustain the theoretical results obtained, the dynamic simulation of the constant velocity contouring system must be made. The main characteristics of the x-y surface motor can be acquired by computer simulation via a coupled circuit-field model.

This coupled mathematic model, presented in detail in several earlier papers [1], [3], [9], is composed of three main submodels:

- circuit submodel, where the command coil currents are computed by solving the usual voltage differential equations, taking fully into account the changes of coils inductances due to the variations of the magnetic fluxes through them.
- field submodel, where the magnetic fluxes through the motor are computed from the non-linear equivalent magnetic circuit, taking fully into account the modifications of the

operating points on the magnetization, respectively on the demagnetization curves of the iron core magnetic materials, respectively of the permanent magnet. The modifications of the four air-gap permeances, being functions of the mover-platen mutual position are taken into account, too.

- mechanical submodel, where the total tangential and normal forces of the motor are computed. The relative position of the mover is determined by integrating twice the displacement differential equation.

The computer simulation program based on this coupled circuit-field model allows a wide range of design variables to be evaluated without prototyping the contouring system. It can be used by the designers to help define system components behavior, the complex interactions between different system elements and check performance. The above presented mathematical model can be, and was extended for simulate other types of complex positioning systems [5].

5. RESULTS AND CONCLUSIONS

The geometrical dimensions and parameters of the x-y surface motor considered as example are given below:

- tooth width	1 mm
- slot width	1 mm
- tooth pitch (τ)	2 mm
- nr. of teeth per pole (Z)	5
- platen length	200 mm
- platen width	200 mm
- airgap (δ)	10 μm
- permanent magnet type	VACOMAX-145
- residual flux density	0.9 T
- coercive force	650 KA/m.
- nr. of command coil turns	200
- coil resistance	3.5 Ω
- pole area	760 mm^2
- width of the mover	40 mm
- motor's constant m	0.244

The simulated task is to perform an elliptic trajectory given by the following analytical expression:

$$\begin{cases} 70+70\sin\alpha \\ 85+85\cos\alpha \end{cases} \quad \alpha\in[0,2\pi] \tag{8}$$

The imposed maximum tangential velocity is:

$$v_{t_{max}} = 0.8 m/s \tag{9}$$

The maximal acceleration of the mover can be computed from the maximal tangential force, the mass of the mover and of the maximal load:

$$a_{max} = \frac{F_{t_{max}}}{m_m + m_{l_{max}}} = 50 m/s^2 \qquad (10)$$

For a linear ramping of the imposed velocity profile (see figure 3), the acceleration, respectively the deceleration time is given by:

$$t_{acc} = t_{dec} = \frac{v_{t_{max}}}{a_{max}} = 16 ms \qquad (11)$$

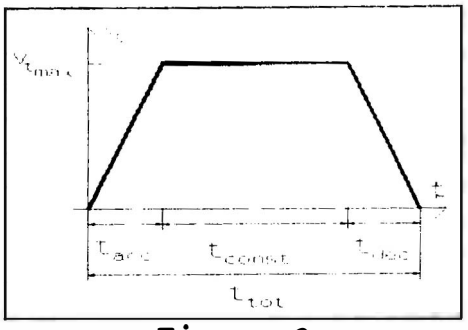

Figure 3

The length of the prescribed trajectory is:

$$l_{tot} = 484.42 mm \qquad (12)$$

The length of that part of the trajectory that has to be performed at constant tangential speed is given by:

$$l_{const} = l_{tot} - a_{max} t_{acc}^2 = 471.62 mm \qquad (13)$$

and can be executed in:

$$t_{const} = \frac{l_{const}}{v_{t_{max}}} = 589.52 ms \qquad (14)$$

The total motion task is to be performed in:

$$t_{tot} = t_{acc} + t_{const} + t_{dec} = 621.52 ms \qquad (15)$$

In the next figures results of the dynamic simulation of the constant velocity contouring system using x-y surface motor are presented.

In figure 4 the plot of the displacement of the x-y surface motor is presented. As it can be seen the forcer of the motor keeps on with the imposed elliptical positioning task given by expression (8).

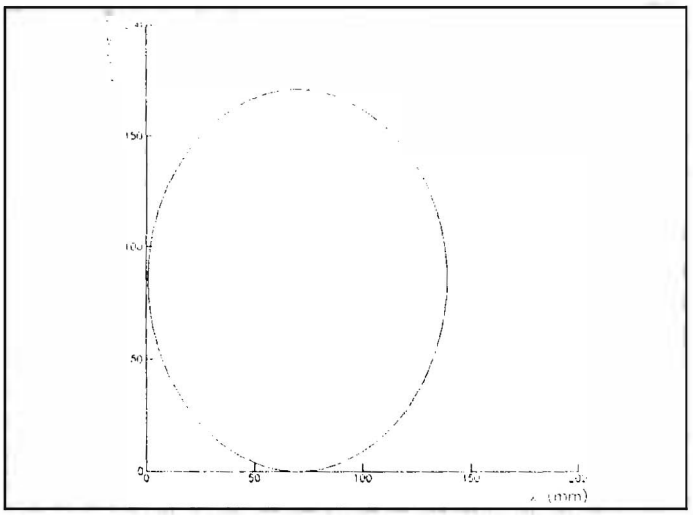

Figure 4

In the next figure (number 5) the plots versus time of the tangential velocity and of the speeds on the two axis (v_x and v_y) are shown.

The resulting tangential velocity (drawn with dashed line) follows strictly the prescribed

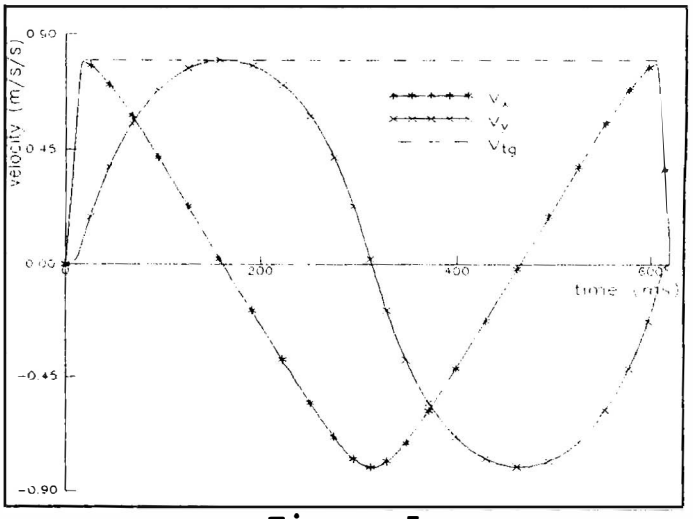

Figure 5

profile. The speeds on the two axis are virtually those necessary to perform the imposed trajectory.

In figure 6. the command current in coil 1 of the mover corresponding to the x axis, the produced tangential force of the same mover and the displacement on the x axis versus time are presented.

As it can be seen from the figures the tangential force has great values during the acceleration of the forcer. After this interval the imposed velocity is decreasing, so the mover is decelerated by the negative tangential tracking force. In the mean time the displacement on the x axis is increasing still the imposed velocity on this axis becomes nil. Beginning from this moment the mover has a displacement in the opposite direction, driven by negative tracking force.

After performing the half of the prescribed trajectory the imposed speed begins to increase. So the tangential force is now positive until the deceleration period starts. During this the tracking force is a breaking force and acts till the mover stops in the initial, starting position.

The current in one of the command coils has great values when significant tangential forces are required or when the tracking force changes its sign. It can be also observed that the frequency of the command coil current is decreasing together with the mover's speed.

The given characteristics of the x-y motor obtained via computer simulation stand by to sustain the theoretical results and to confirm that

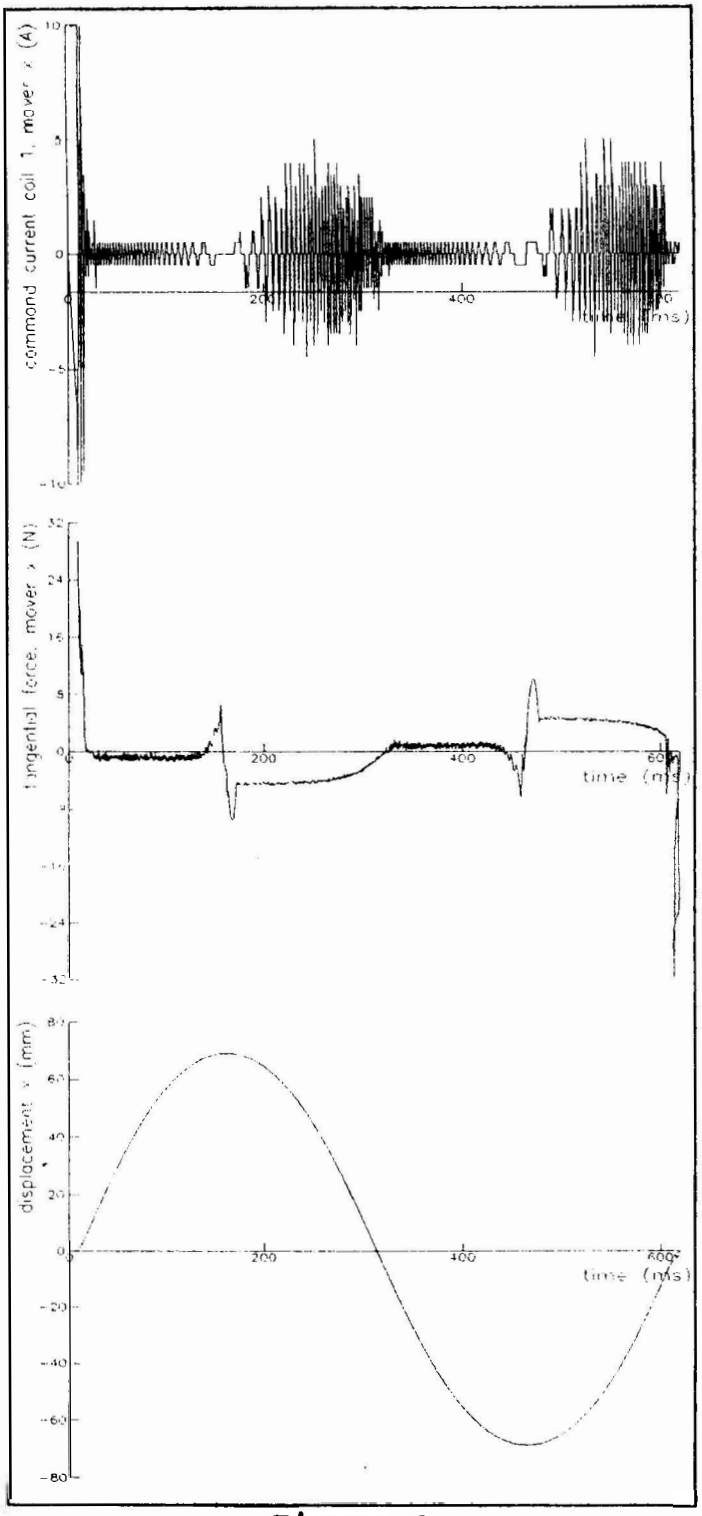

Figure 6

the control strategy for the constant velocity system presented in this paper is one of the best for these purposes.

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