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Microstepping Control of Hybrid Stepper Motor Using Fuzzy Logic for Robotics Application.

Amal Mohamed
Electronics Research Institute., Dokk.i,Cairo., Egypt., amal@eri.sci.eg

Aziza Zaki
Electronics Research Institute., Dokki,Cairo., Egypt.

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MICROSTEPPING CONTROL OF HYBRID STEPPER MOTOR USING FUZZY LOGIC FOR ROBOTICS APPLICATION

استخدام المنطق اللامحدد للتحكم فى المحرك الهجينى ذو الخطوة وتطبيقه فى الروبوت

Amal Z. Mohamed, Aziza M. Zaki*
Electronics Research Institute, Dokki,Cairo, Egypt.
Email: amal@eri.sci.eg.

خلاصه:

يركز هذا البحث على استخدام متحكم تتابع الموقع ذو كفاءة عاليه فى الاداء للمحرك الهجينى ذو الخطوة وتطبيقاته فى التحريك المباشر لذراع روبوت. والنموذج الرياضى لمثل هذا النظام يتصف باللاخطية وعدم التاكد والتحكم باستخدام التتابع يتطلب مطابقة موقع زاوية الجزء الدوار للمحرك للموقع المطلوب أثناء التشغيل . ونظرا لصعوبة هذه المشاكل تم استخدام المنطق اللامحدد للتحكم في التتابع للموقع والذي صمم على الخطوات الميكرونية لمثل هذا المحرك وتم الحصول على نتائج لا ختبار اداء هذا النظام.

ABSTRACT.

The work on this paper focuses on the design of high accuracy and high performance of positioning tracking controller of the Hybrid stepper system (HSM), realized for the application of direct drive robot (DDR). The control problems characterized by mathematical models exhibit significant nonlinearity and uncertainty. Also high tracking performance requires that the actual system trajectory matches the desired trajectory as close as possible. Fuzzy logic control (FLC) technique has been used widely in many practical and industrial applications with large degree of uncertainty and nonlinearity. The design of this position tracking system based on microstepping controlled HSM is achieved by implementation of FLC techniques. Simulation results are obtained to illustrate the performance of the controlled system. Practical work is done to test the HSM incremental motion operation.

Keywords: Hybrid stepping motor, microstepping operation, Fuzzy logic control, robotics application.

1. INTRODUCTION.

Stepper motors are incremental -motion actuators. They are generally used in microcomputer, office factory automation applications, and now they are widely used in robotics. Since the hybrid stepper motors have higher efficiencies, maintain very high resolution due to the small step angle and other advantages

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over the variable -reluctance, and permanent-magnet type stepping motors, they are the most commonly used stepping motors in industry [1-2]. The main appeals of HSM in robotics are their use as direct drive actuators.

Direct drive robot consists of a mechanical arm with electrical motors directly coupled to the joints. The absence of conventional transmission mechanism between the motor and their loads provides several advantages such as no backlash, low friction, and high stiffness. These advantages have a favorable impact on the performance of precision positioning robots for trajectory control. The electrical design of a direct drive robot motor seems to have been studied much less [3]. Brushless motors well suited to this application are of two types: the permanent-magnet synchronous motor and the switched reluctance motor. The prototype motor used in this work is a hybrid stepper motor, which combines the design principle of the variable-reluctance, and permanent-magnet motors.

Speed and position regulation, speed and position tracking, or torque and force control are major areas of interest in motion control in robotics [4].

In this work we presented and described the implementation of position tracking control system of a HSM for a direct drive robot application. The direction of this work is illustrated in the following sections:

First, initial step is performed toward the development of the dynamic models of the HSM with the controlled system and the single arm robot system.

Second, a Fuzzy logic technique is used to design the position trajectory controller for a class of electromechanical system, which involves the HSM with the link. The fuzzy trajectory controller (FTC) is responsible of reducing the effect of nonlinearity and uncertainty in the controlled system [5]. The input to this controller is the desired position trajectory and the feedback signal represents the actual position of the system. The output from this controller is the control signal which represent the switching pulses per sec (frequency) of the driving unit of the HSM to keep track of the number of motor steps or pulses per second. Finally, a prototype implementation for position tracking system of the HSM is described. Simulation results and experimental results are presented of the HSM with the position trajectory controller.

2. HYBRID STEPPING MOTOR DESCRIBTION.

Hybrid step motors (HSM) combine the principles operation of the variable reluctance motor and the permanent magnet type of step motors. The rotor consists of a permanent magnet (PM) that is magnetized parallel to the shaft axis to create a pair of poles. On this magnet, two end caps are fitted at both ends. These end caps consist of equal number of teeth N_r. The stator is one single unit (laminated) where the winding slots are parallel to the motor shaft. Torque in a

HSM is produced by interaction of the rotor-and the stator produced fields. The rotor field is produced by PM and hence stays constant. The stator field and therefore T_e is proportional to the phase current. There are two excitation modes of operation. The single-phase excitation, where each of the stator phases is exited one at a time and the rotor moves by a step for each change in excitation. The two-phase excitation, where two of the stator phases are simultaneously excited to provide a better damping of the rotor. The HSM with the driving power unit is shown in fig 1.

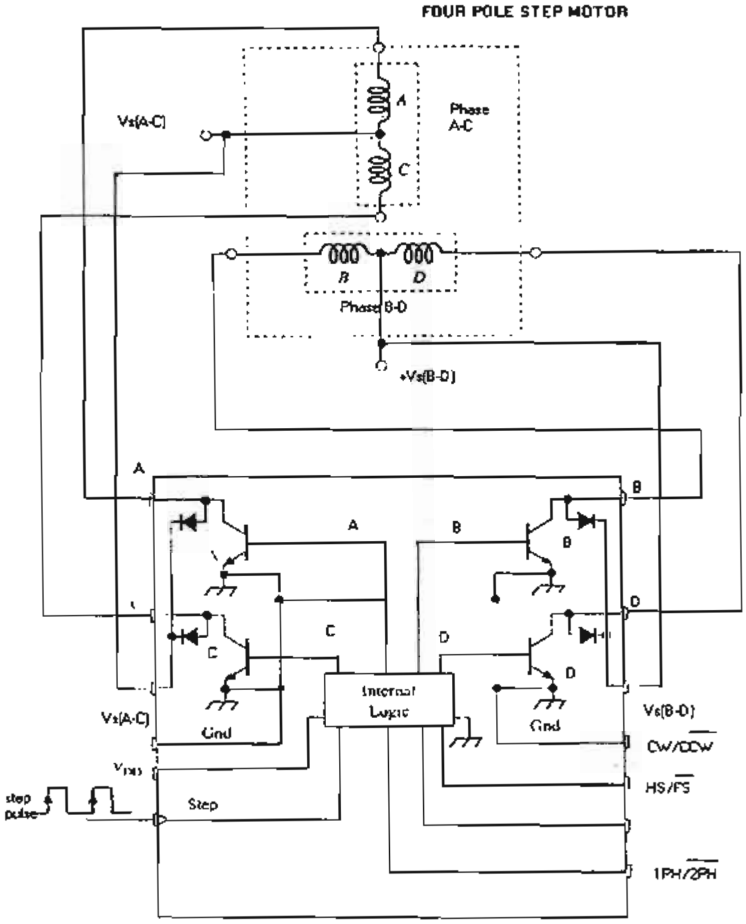


Fig. 1 Hybrid step motor with the driving power circuit.

3. MATHEMATICAL MODEL OF THE CONTROLLED SYSTEM.

The objective in this section is the development of a nonlinear mathematical model that includes the dynamics of the HSM as well as the dynamics of the robot manipulator. The basic expression relating terminal voltage and phase currents of electrical motors is given by [6]:

$$v_{ph} = R_{ph} i_{ph} + \frac{d\lambda_{ph}}{dt} \tag{1}$$

where: v_{ph}, R_{ph}, i_{ph} and λ_{ph} are the stator voltage, winding resistance, stator current and flux linkage of stator phase respectively. Of course the mechanical variables, rotor position θ, and rotor velocity ω, influence these electrical dynamic through the flux linkage derivative. The phase flux linkage is given by:

$$\lambda_{ph} = L_{ph} i_{ph} \tag{2}$$

From equations. (1) & (2) we obtain:

$$v_{ph} = R_{ph} i_{ph} + L_{ph} \frac{di_{ph}}{dt} + e_{ph} \tag{3}$$

In HSM, as the rotor rotates, an emf e_{ph} is induced in the phase winding. The polarity of this induced voltage is such as to absorb power from the electrical source v_{ph} and its magnitude is proportional to the rotational speed ω.

$$e_{ph} = k\ \omega \tag{4}$$

3.1. HSM Motor Dynamics.

The dynamic model of the HSM is a set of differential equations given by [7]:

$$\frac{di}{dt} = (L)^{-1}\left[v_{ph} - r_{ph} - k\omega i\right] \tag{5}$$

$$\frac{d\omega}{dt} = (J)^{-1}\left[B\omega + T_e - T_l\right] \tag{6}$$

$$\frac{d\theta}{dt} = \omega \tag{7}$$

3.2. Direct-Drive Robot Dynamics.

The dynamic model of the robot manipulator has been described in many publications [8-9]. The schematic structure of the single-link robot is shown in fig. 2. The payload is considered as a point mass *m*, which is located at the end of a massless link of length *l*. The input to the robot is the driving torque generated from the motor T_e, and the states of the system are given by the joint position q and velocity $\dot{q}$. The single-link robot arm dynamic equation is given by:

$$T_e = ml^2\ddot{q} + mgl\sin q \qquad (8)$$

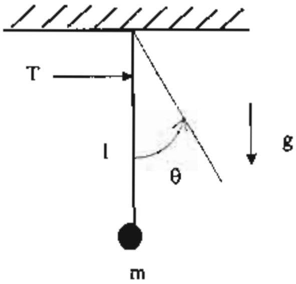


Fig. 2 Single-link robot arm.

4. MICROSTEPPING OPERATION.

We mentioned that the HSM has two mode of excitation schemes, the single-phase and the two-phase excitation that cause the rotor to move by one step-angle for each change in excitation. Combining the single-phase and two-phase excitations make it possible to achieve half-step rotations for each change of excitation. The procedure for half-stepping can be extended to subdivide the motor step-angle into very small steps called micro-steps. This requires that the magnitudes of the phase currents be precisely controlled. Assuming the torque characteristics for a HSM to be sinusoidal, and the equilibrium position for i_A, excitation as $\theta = 0$, T_A and T_B with i_A, i_B respectively can be expressed as:

$$T_A = -K\, i_A \sin\theta \qquad (9)$$

$$T_B = K\, i_B \cos\theta \qquad (10)$$

Where K is the motor torque constant and the rotor position θ is measured in electrical degrees. When both phases are excited simultaneously with i_A ,and i_B, the total torque developed is:

$$T_{AB} = K(-i_A \sin\theta + i_B \cos\theta) \qquad (11)$$

To change the rotor angle θ by a micro- step angle μ, the two phase current are precisely controlled to two discrete levels such that [1]:

$$i_A = I_R \cos\mu \tag{12}$$

$$i_B = I_R \sin\mu \tag{13}$$

Where I_R is the rated phase current. Therefore, from these equations,

$$T_{AB} = K I_R \ (-\cos\mu \sin\theta + \sin\mu \cos\theta) = -K I_R \sin(\theta - \mu) \tag{14}$$

To obtain very small stepping angles, the phase supply voltage, can be modulated either by amplitude type or pulse-width modulation type (PWM).

5. THE HSM CONTROL SYSTEM.

In this section we present and describe the prototype control system of the HSM. The HSM Specifications are given in appendix A with its driving board in appendix B. The operation of a stepper motor requires the presence of the following elements:

1. A control unit: Usually a microprocessor based unit, which gives step and direction, signals to the drive unit card, the microprocessor kit used is 8088.
2. Drive unit card: This converts the signals from the control unit in to the required stepper motor sequence, it is type compatible with the used HSM.
3. Power supply : Giving the required voltage and current for the drive card.

Typical Stepper motor control system is shown in fig. 3.

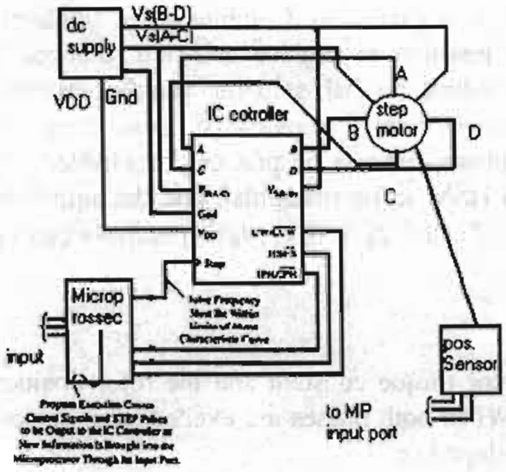


Fig. 3 The HSM control system.

5.1 Position Trajectory Control of drive system.

The control scheme of the trajectory tracking control HSM with the DDR is shown in fig. 4. The DDR system is commanded to move from initial position to a target position, following a desired trajectory profile. Generally, the objective is to design a fuzzy trajectory controller (FTC) for position tracking system with minimum tracking error in specific time.

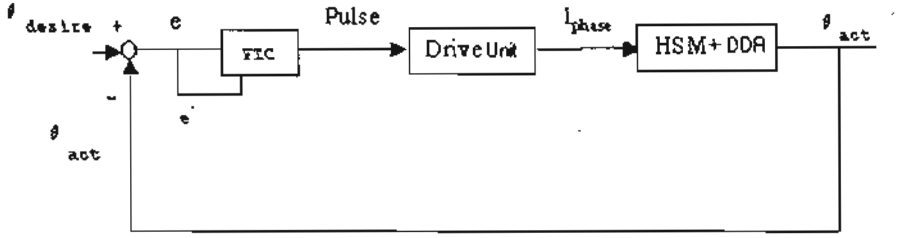


Fig. 4 The control scheme of the joint drive system.

5.2 FTC Controller Description:

The input to the FTC trajectory controller is position error, which represents the difference between the desired input trajectory profile and the actual output from the DDR system. Also the second input to the FTC is derivative of this error signal. The output from this controller is the control signal which represent the number of pulses per second or (frequency). This train of pulses is feeding the drive unit of the HSM to keep track of the desired profile. There are three regions in trajectory profile. The first one is the acceleration region, the second is the constant speed operation, and the third is the deceleration region. These three regions are represented by three fuzzy sets. More description of determining the fuzzy conditional statements and the membership functions of these sets are given in [10-11]. The tracking performance results are given in the following section.

6. SIMULATION RESULTS.

The first test, is done for the HSM with the DDR system implementing the FTC trajectory control scheme, the simulation results are shown in figures. 5&6. The simulation results are obtained using simulink toolbox and FLC toolbox of Matlab. The joint arm is commended to change smoothly from the initial position $\theta = 0$ to the target position $\theta = 90$ in 10 second following the desired sigmoid (S function) as shown in fig. 5 trajectory. It is seen from the figures that the desired trajectory and actual output profile of the joint arm are very close, and the peak value of the error is 1.5 degree. The simulation results shown in figures. 5, and 6 are obtained according to inconsiderable disturbances in the DDR system. It is shown that the tracking response of the DDR is matched with the desired trajectory, and the maximum. Tracking error is drooped to less than 0.1 degree. The second test is done with applying the conventional PID controller. The simulation results are shown in figs 7&8. It is clear that the error signal is oscillating and takes more time to reach the steady state value of 0.1. It is evident that the tracking performance of the FTC trajectory controller is noticeably better than the PID.

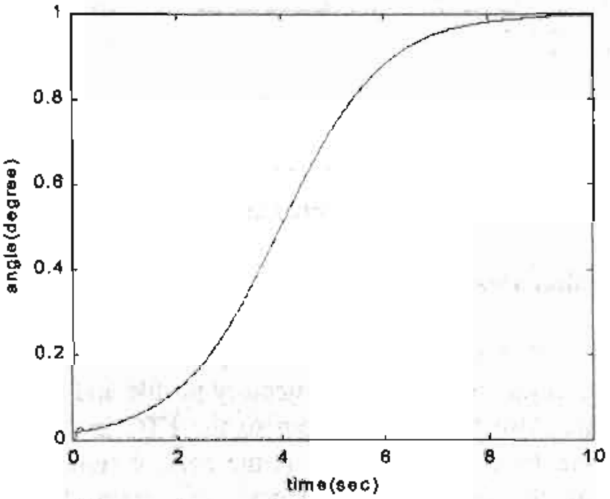


Fig. 5 Tracking performance of the DDR system with FTC.

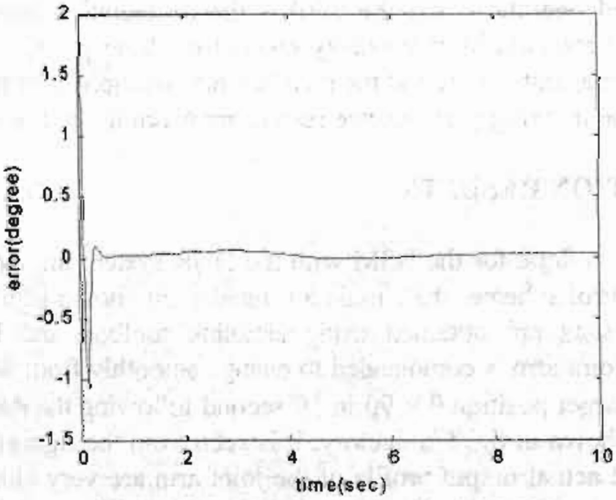


Fig. 6 Tracking error signal with FTC.

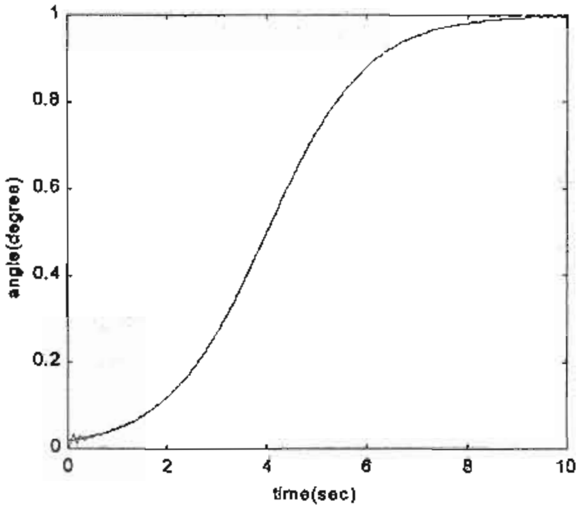


Fig. 7 The tracking performance of the DDR System with PID controller.

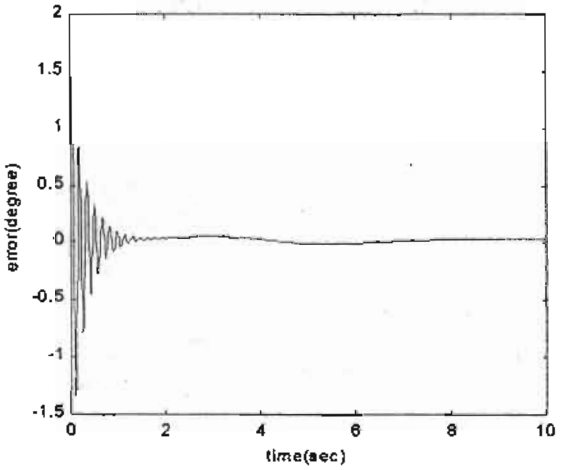


Fig. 8 The tracking error signal with PID controller.

7. EXPERIMENTAL VERVICATION.

The prototype of HSM system is tested in the laboratory using the following components, a 4-phase HSM, IC driver, 8088 microprocessor kit, a power supply of 15V and 3A and other preferable interfacing circuitry.

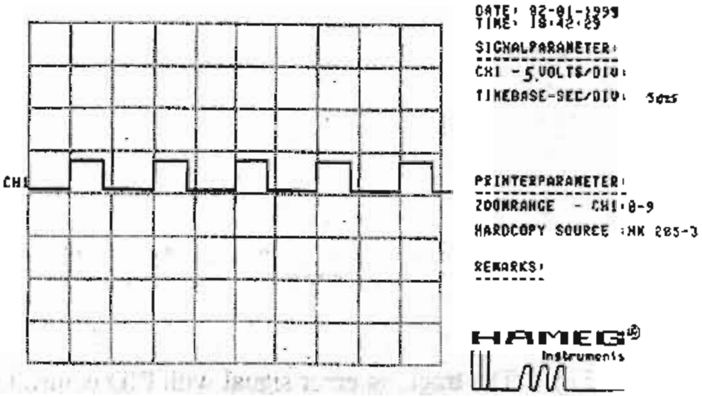
The dynamic characteristics of the HSM system, which involve the incremental motion operation, acceleration and deceleration performance, is tested with different input control frequencies. We also tested the full-step operation as well as the half-step operation.

7.1 The Full-Step Operation:

In the full step, there are two cases: single-phase drive and two-phase drive:
The two phases are always excited. In this case the oscillation damps more quickly than in the case of single phase excitation. Figure 9 illustrates the control frequency of 100 Hz and the motor current of this mode.

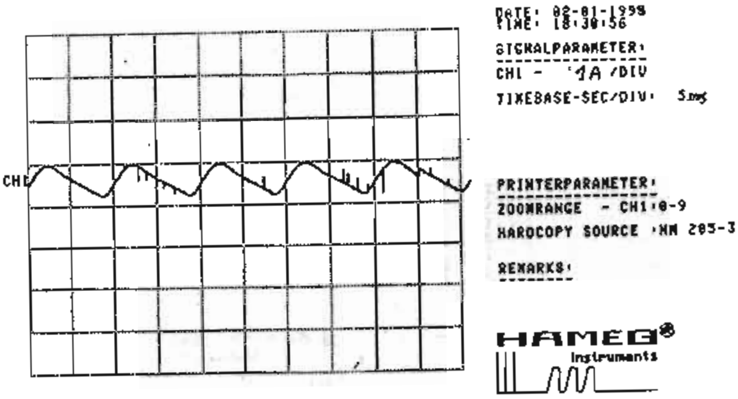
7.2 The Half-Step Operation:

Half-stepping necessitates driving both coils, and the most universal technique exploits a 2-1-2 on activation series that combines two-phase and single-phase excitation. Through this test the drive system affords some advantages such as smoother rotation at low speed operation, less resonance, and ratioed output current. Figure 10 illustrates the system performance under this operation.



a- The input control frequency.

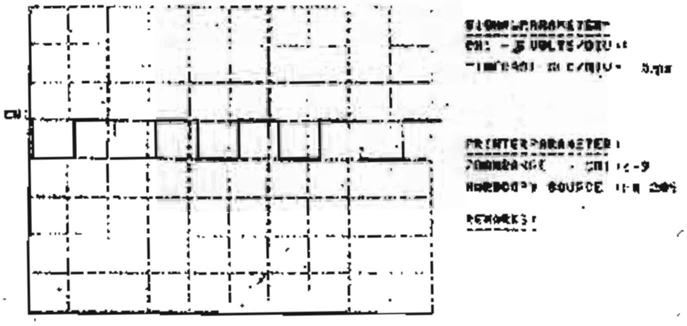
Oscilloscope output waveform. 5Volts/Div.



b- The phase current waveform.

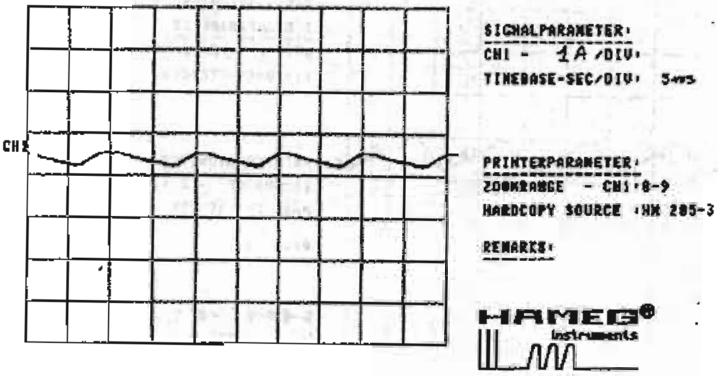
Oscilloscope output waveform. 1Amp/Div.

Fig. 9 The full-step performance.



a- The input control frequency.

Oscilloscope output waveform. 5Volts/Div.



SIGNALPARAMETER:
CH1 - 1A /DIV:
TIMEBASE-SEC/DIV: 5ms

PRINTERPARAMETER:
ZOOMRANGE - CH1:8-9
HARDCOPY SOURCE :HM 205-3

REMARKS:

b - The phase current waveform.
Oscilloscope output waveform. 1 Amp/Div.

Fig. 10 The half-step performance.

7.3 Acceleration and Deceleration operation.

In tracking control of the HSM system the motor is operated following certain trajectory. This trajectory consists of three regions. The first one is the acceleration region, the second is the constant speed operation, and the third is the deceleration region. This means that the motor is started with stepping rate at or below the starting frequency, and then the rate is increased with time until the desired speed (max speed) is reached. Likewise the motor must be decelerated to some speed below its max stop rate without positioning error.

In the tracking control the motor is commanded to move from initial position of $\theta_0 = 0$ to the final position $\theta_\delta = 90^0$. The step angle of the operated motor is 1.8^0 therefore the number of required steps to reach the final position is 90/1.8= 50 steps. The motor is started with starting frequency of 100 Hz and accelerated up to 300 Hz. with 25 steps. The first pulse interval equals:

T1 =1/F1 i.e 1/100=0.01 sec.

Such slow motion for demonstration. The rate of deceleration is started at 300 Hz, and decreased to the stepping rate and this is done in the last 25 steps. The final pulse interval at which deceleration started is:

Tf=1/Ff i.e 1/300= 0.033 sec.

The practical position trajectory profile for this operation is shown in figure 11.

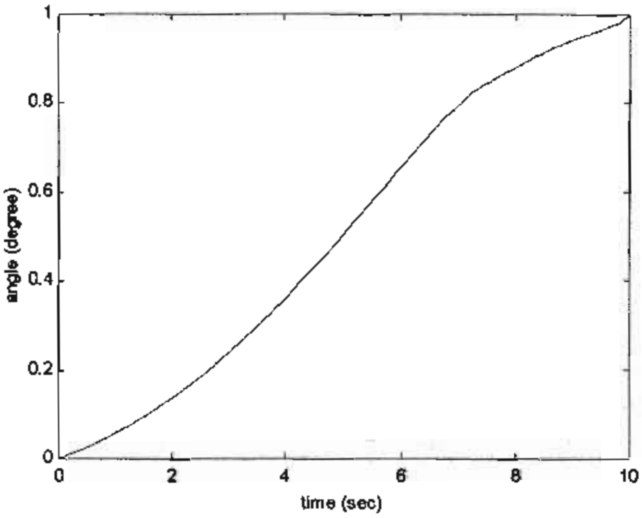


Fig. 11 The practical position trajectory profile

By comparing this practical position trajectory shown in fig. 11 by the other trajectories obtained from simulation results as shown in figs. 5&7, there are some differences due to the linearization made in simulation of the system model.

8. CONCLUSION.

This paper introduces intelligent position tracking schemes for HSM coupled directly to single-link robot arm (DDR), These intelligent control schemes utilize the fuzzy logic control technique. The performance of the position tracking system has good response with the implementation of the FTC scheme. Experimental work is presented to demonstrate the dynamic characteristics of the HSM system, which involve the incremental motion operation, acceleration and deceleration performance. We also tested the full-step operation and the half-step operation of such motor.

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Appendix (A)

HSM Specification:

The hybrid stepping motor used in this prototype system has the following specifications:

The RS stock number : Type 23 (440-442)
The rated voltage : 5.1 V
Rated current : 1 Amp
Winding resistance : 5 Ohm
Winding Inductance : 9 mH
Detent Torque : 30 mNm
Holding torque : 500 mNm
Step angle :1.8 degree
Step angle accuracy : 5%

Appendix (B)

Driving Board Specification:

The 4-phase unipolar stepper motor IC drive board 332-098 has the following technical specifications:

Current consumption	600 mA.
On board auxiliary output	12 V d.c., 50 mA max. Regulated.
Switching logic control inputs	Level "0" 0 V, Level "1" 12 V
a) Full step	Level "1"
b) Half step	Level "0"
c) Clock	1 Hz – 25 Hz