Available online at www.sciencedirect.com

SCIENCE DIRECT®

Mechatronics 15 (2005) 1175–1189

MECHATRONICS

Investigation of the micro-step control positioning system performance affected by random input signals

Ali Selk Ghafari, Mehdi Behzad *

Sharif University of Technology, School of Mechanical Engineering, P.O. Box 11365-9567, Tehran, Iran

Accepted 31 May 2005

Abstract

This paper gives the results of simulation and experimental investigation on the effects of random signals on the accuracy of micro-stepping control positioning. For studying and simulation of the effect of random noise signals on performance of the accurate position control systems, such as Hybrid Stepper Motors (HSMs), a micro-step driver and controlling unit using PID controller has been designed and constructed. Several parametric studies have been carried out including different white noise power and micro-step per revolution. Tracking problem for a HSM model has been simulated, and the experimental study for similar cases has been carried out by implementing the designed controller in real-time operation by using Real Time Windows Target Toolbox of Matlab software and Simulink. Simulation and experimental results show that random noise source changes current profile and affects the accuracy of positioning. Performance of the proposed PID controller under the implementation of random noise on phases one and two of stepper motor has been proved to be accurate enough even under disturbance load currents, on the system. Experimental and simulation results show the good performance of designed controller in tracking problem, affected by various random noise powers and motor speeds in different micro-step positions. Moreover there is an excellent agreement between experimental and simulation results.

* Corresponding author. Fax: +98 21 6000021.
E-mail address: m_behzad@sharif.edu (M. Behzad).

0957-4158/$ - see front matter
doi:10.1016/j.mechatronics.2005.06.007

Keywords: Random signals; Micro-step; Stepper motor; Real time; Positioning accuracy

1. Introduction

Stepper motors are widely used in precision positioning applications such as robotic positioning systems. In many applications where motor drives are used, reliability is of high concern. Stepper motors have been employed extensively in open-loop controls. Chrifi-Alaoui and Lebrun [1], pointed that originally stepper motors were designed to provide precise positioning control within an integer number of steps without using position sensors. That is, they are open-loop stable to any step position, and consequently no feedback is needed to control them. But, using the stepper motor in an open-loop configuration results in very low performance. According to Rahman and Aun-Neow Poo [2] and Selk Ghafari et al. [7], stepper motors have the potential to convert a conventional motor with a fixed step-size into one with a programmable step angle, thereby motor positioning resolution is improved. As a result gearing and its associated backlash problems can be avoided when improved resolution is required. Some of the problems of motor dynamics are also minimized by such a controller. A micro-stepping controller in the open-loop would typically control motor current at discrete levels. In particular, micro-stepping controllers can be implemented by using feedback from shaft-mounted position sensors to regulate the currents in the motor windings and reject the disturbance in the control loop.

Most micro-stepping motor drivers require control lines for digital to analog converters to set the reference for the pulse width modulation (PWM) current regulator and phase inputs for current polarity control. In more sophisticated drivers there are also inputs required for the PWM current-control mode to operate in slow, fast, or mixed decay. Accuracy of phase winding currents profile is an important issue in accurate positioning. Some external sources—such as the AC power line, motors, computers, and internal sources, such as micro-processors, and switched mode power supplies produce noise. Real electronic circuits and components such as resistor, capacitor, linear integrated circuits (ICs), and amplifiers, produce a certain level of inherent noise, therefore noise is one of the most important elements in power and driver systems. Experimental and simulation study of the random noise effect added to the stepper motor currents profile on positioning accuracy is studied in this paper. Experimental and simulation study show that random white noise source distort the phase currents profile which may affect the tracking positioning accuracy in closed-loop system. In these circumstances the loading on the current profiles is described by statistical means, mean, mean square values or power spectral density (PSD) of the loading current. The most widely used controller in industrial applications, with a good disturbance attenuation properties, is PID controller (proportional–integral–derivative) which can easily be tuned. The ability of PID controllers to compensate most practical industrial processes has led to their wide acceptance in industrial applications. Koivo and Tanttu [3], for example, suggest that there are perhaps 5–10% of control loops that cannot be controlled by SISO PID controllers. Experimental and simulation results show the good performance of designed controller in tracking problem, affected by various random noise powers and motor speeds in different micro-step positions. Moreover there is an excellent agreement between experimental and simulation results.

2. Stepper motor micro-stepping drive

Normally a stepper motor is driven in full step or half step mode. This means that the motor currents are switched on and off according to a special pattern. At each switching event the motor shaft moves a small step. Using micro-step mode the currents in the motor coils are not switched on and off, but they are modified continuously with the shape of a sine and cosine wave respectively. The sine/cosine waves allow the motor to move continuously from one pole (whole step position) to the next. As the current increases in one coil it decreases in the other one, resulting in the rotor advances smoothly. Micro-stepping is a way of moving the stator flux of a step more smoothly than in full or half-step drive modes. The most important characteristics of micro-stepping is improved position resolution, reduction in ripple torque, specially at lower motor speeds. By micro-stepping, with its higher frequency pulse rates and smaller step angles, the overshoot is reduced and the resonance is not triggered. The torque stays the same for any angle because the current is always correctly proportioned between the two coils. This results in less vibration, and makes noiseless stepping possible down to 0 Hz [4].

3. Stepper motor dynamical model

The most important characteristics of stepper motors can be described by a nonlinear phase flux model as [5,13]:

$$\lambda_{\mathrm{f}} = \lambda_0(1 - \mathrm{e}^{-i_j f_j(\theta)}) \quad j = 1, 2 \tag{1}$$

λ_0 is the saturated flux linkage, while j represents the phase number and $f_j(\theta)$ represents the positional dependence and is expressed as a strictly positive Fourier series function:

$$f_j(\theta) = a_0 + \sum_{n=1}^{\infty} a_n \cos(n\theta) + b_n \sin(n\theta) \tag{2}$$

Basically, the model of Hybrid Stepper Motors consists of the electrical and mechanical parts. The mechanical model can be expressed in the state-space form as follows [4–7]:

$$\begin{cases} L(i_a,\theta)\dfrac{di_a}{dt} = v_a - Ri_a + K_\omega \sin 1(N\theta) \\ L(i_b,\theta)\dfrac{di_b}{dt} = v_b - Ri_b + K_m\omega\cos(N\theta) \\ J\dfrac{d\omega}{dt} = -K_m i_a \sin(N\theta) + K_m i_b \cos(N\theta) \\ \qquad\qquad -B\omega - C\mathrm{sign}(\omega) - K_d \sin(4N\theta) - \tau_l \\ \dfrac{d\theta}{dt} = \omega \\ T_m = \sum_{j=1}^{2} T_j(i_j,\theta) = \sum_{j=1}^{2} \dfrac{\partial}{\partial\theta}\displaystyle\int_0^i \lambda(i_j,\theta)\,di \\ \lambda_j(i_j,\theta) = \displaystyle\int_0^t (v_j - R\cdot i_j)\,d\tau \end{cases} \tag{3}$$

where v_a, v_b, i_a and i_b are respectively the voltages and currents in phases a and b; ω, θ, B and C are the rotor speed, angle position, viscous and coulomb friction coefficients respectively. Further$R$, L, N, J, K_m, K_d, τ_l, T_m and λ are the resistance, the inductance of the phase winding, the number of rotor teeth, the rotor inertia, the motor torque constant, the detent torque constant, the load torque, the output torque of the motor and flux linkage respectively. The complete model given by (3) will be used for all simulations with all nonlinearities and without any approximation.

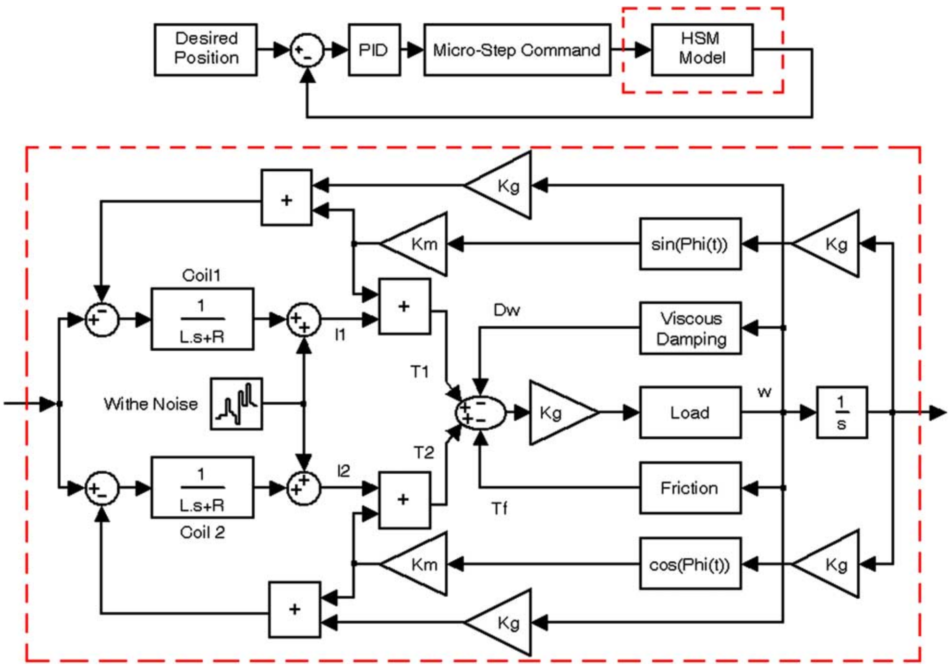

Fig. 1. Block diagram of simulated HSM in closed-loop system.

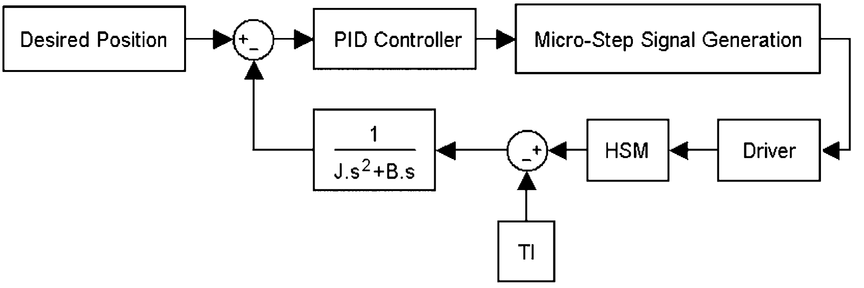

Fig. 2. Block diagram of closed-loop system with PID controller.

According to linear variation of phase flux in micro-step points, second-order system will ideally have input–output dynamics described by the transfer function [7–9,13]:

$$G(s) = \frac{\omega_n^2}{s^2 + 2\xi\omega_n s + \omega_n^2} \tag{4}$$

$$\begin{cases} \omega_n^2 = \dfrac{NK_\mathrm{m}I_M}{J} \\ 2\xi\omega = \dfrac{B}{J} \end{cases} \tag{5}$$

where I_M is the phase current pick value.

4. PID controller design

Due to their simple structure and robust performance, PID controllers are the most commonly used controllers in industrial process control. The transfer function of a PID controller has the following form:

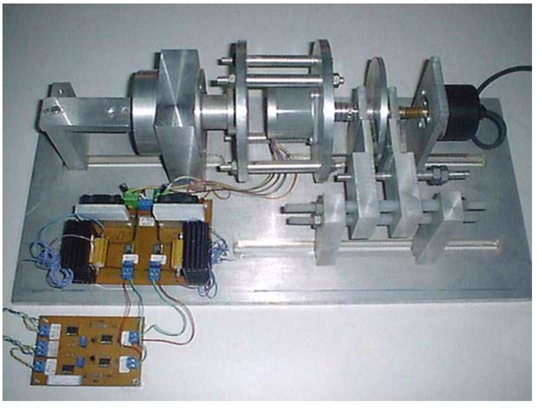

Fig. 3. Mechanical setup and micro-step driver used for experimental study.

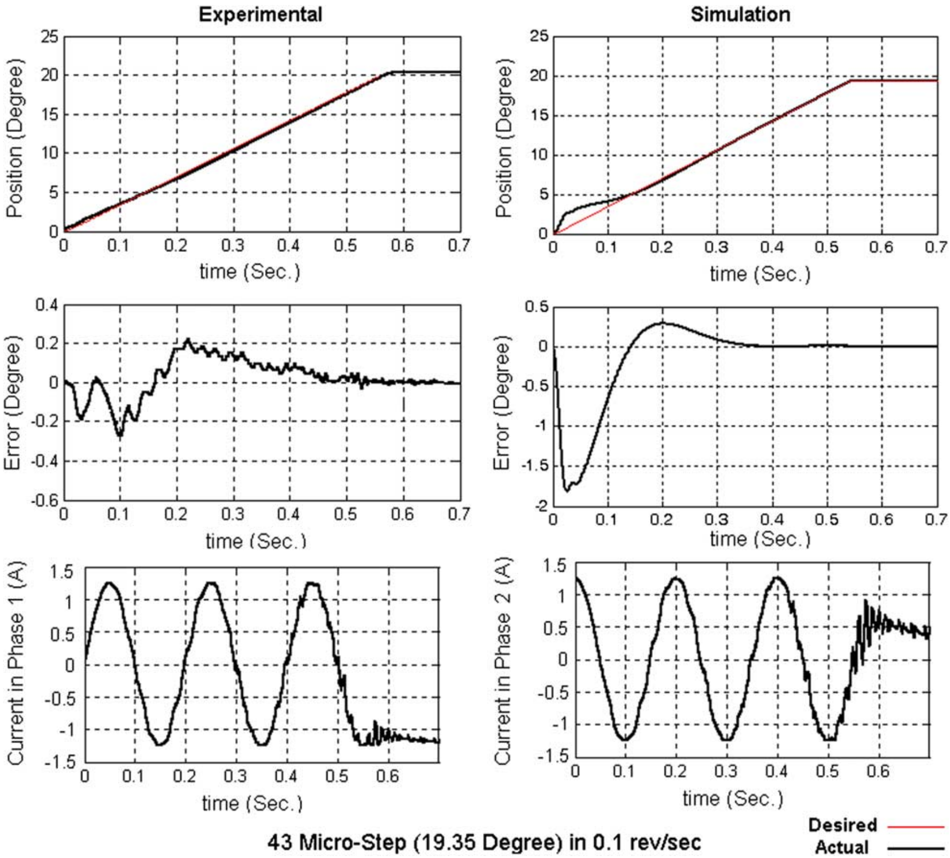

Fig. 4. Tracking problem for 43 micro-step in 0.1 rps with sine/cosine phase current profiles.

$$G_c(s) = K_p + K_i/s + K_d s \tag{6}$$

where K_p, K_i and K_d are the proportional, integral and derivative gains, respectively. Another useful equivalent form of the PID controller is:

$$G_c(s) = K_p(1 + 1/(T_i s) + T_d s) \tag{7}$$

where $T_i = K_p/K_i$, $T_d = K_d/K_p$. T_i and T_d are known as the integral and derivative time constants, respectively. The parameter of the PID controller can be manipulated to produce various response curves from a given process. Finding optimum adjustments of a controller for a given process is not trivial. In practice, the PID gains are usually tuned by experienced human experts base on some rule of thumb. There are several tuning rules for PID controller such as: Ziegler and Nichols (1942), Chien and Kitamori (1979), Aström and Hägglund (1984, 1988) [10].

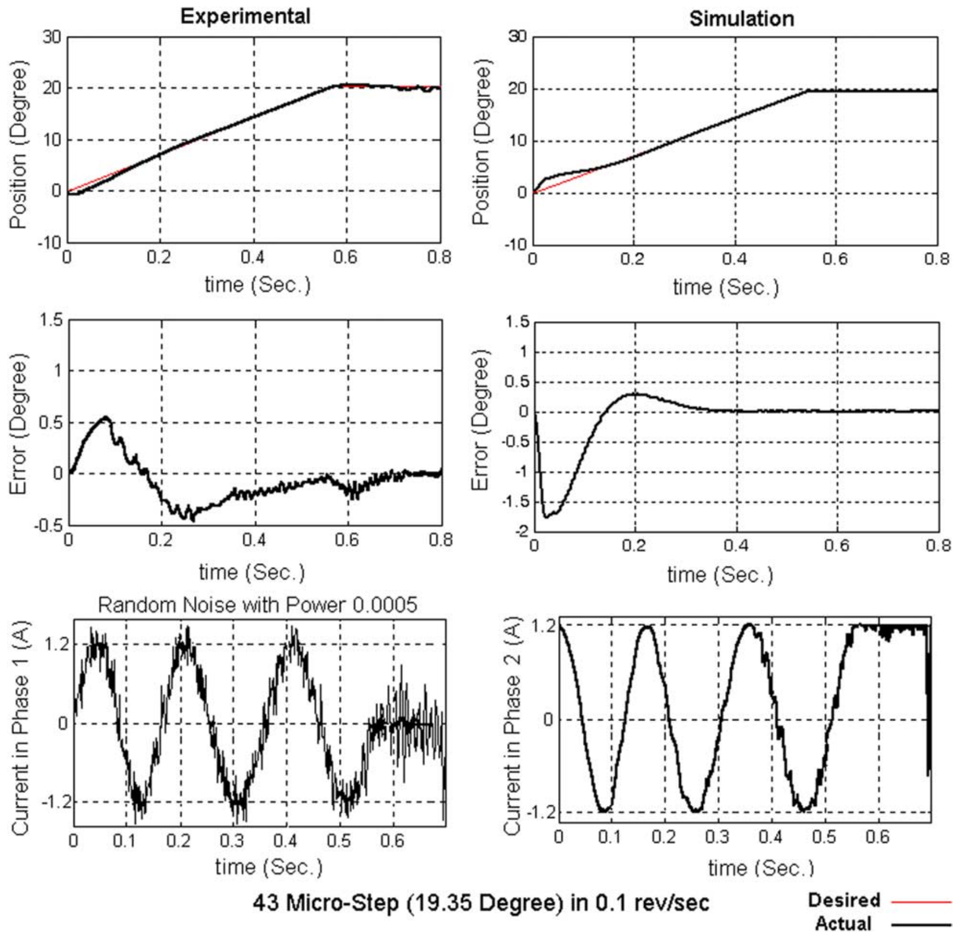

Fig. 5. Tracking problem for 43 micro-step in 0.1 rps with a random noise on phase 1 current (power = 0.0005).

5. White noise source

External sources—such as the AC power line, motors, fluorescent lights and computers, and internal sources, such as digital clocks, micro-processors, and switched mode power supplies are the main sources of noise in laboratories affecting the performance of micro-stepping control systems. Noise may either be transient in nature, have fixed frequencies such as harmonic or mixer products, or broad band random noise. An ideal electronic circuit produces no noise of its own, so the output signal from the ideal circuit contains only the noise which comes from the original signal. But real electronic circuits and components such as resistor, capacitor, linear integrated circuits (ICs), and amplifiers, do produce a certain level of inherent noise of their own. At any temperature, electrons in any material are in constant random

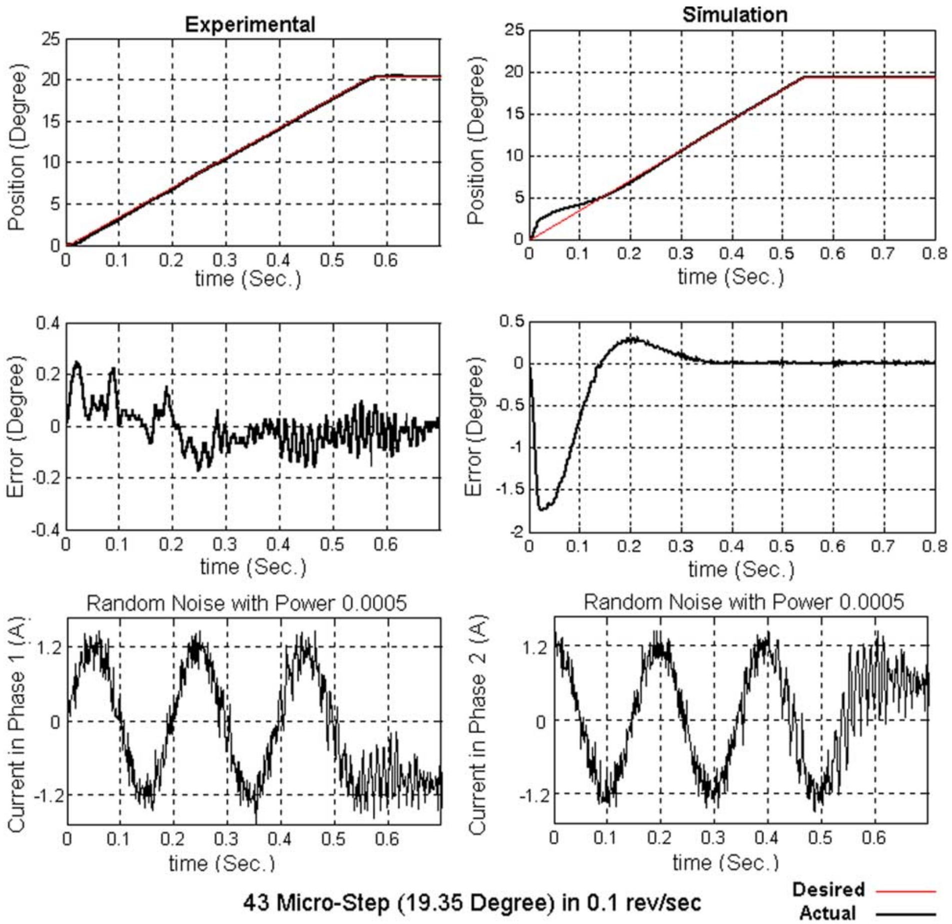

Fig. 6. Tracking problem for 43 micro-step in 0.1 rps with a random noise on two phase currents (power = 0.0005 and 0.0005).

motion. Because of the inherent randomness of that motion, however, there is no detectable current in any one direction. In other words, electron drift in any single direction is cancelled over short time periods by equal drift in the opposite direction. Electron motions are therefore statistically uncorrelated. There is, however, a continuous series of random current pulses generated in the material, and those pulses are seen by the outside world as a noise signal [12].

6. Simulation and experimental study and results

According to [7] parameters of transfer functions in micro-steps of whole step position are identified. The parameters of the real motor used in this study are:

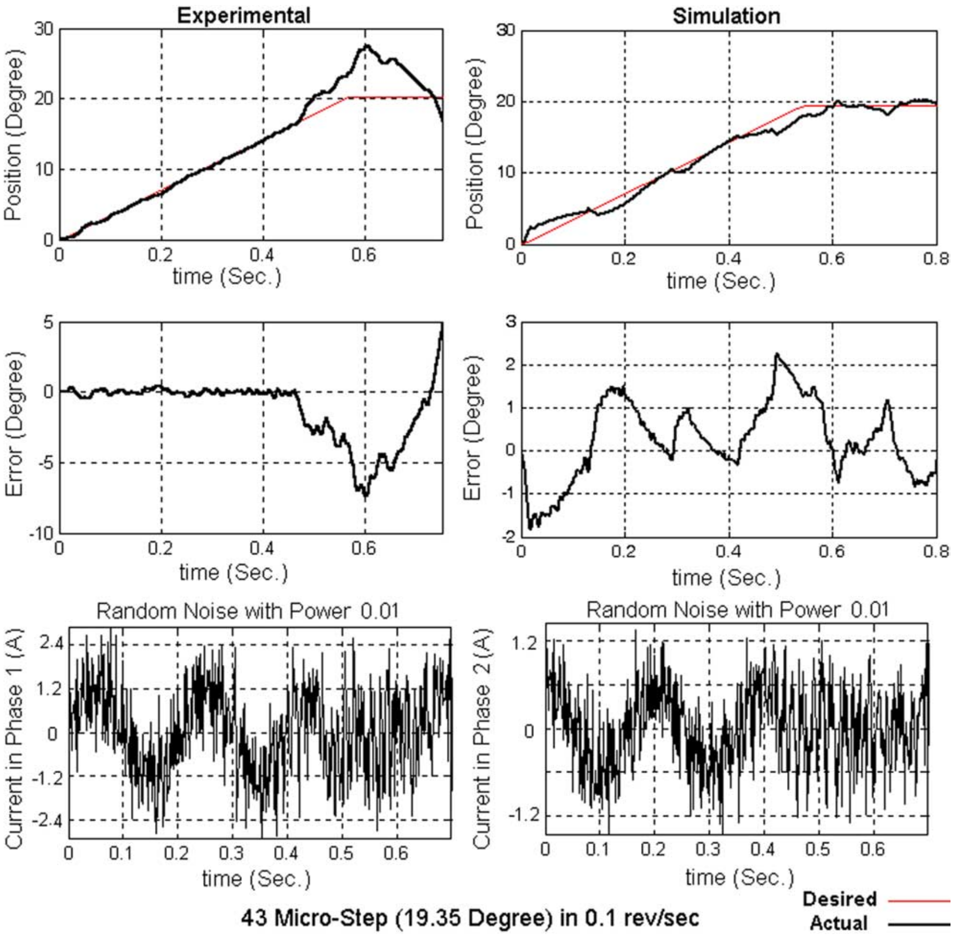

Fig. 7. Tracking problem for 43 micro-step in 0.1 rps with a random noise on two phase currents (power = 0.01 and 0.01).

the number of rotor teeth, $N = 50$;
the nominal stator resistance, $R = 2.2\ \Omega$;
the nominal winding inductance, $L = 2.2$ mH;
the rotor and load moment of inertia, $J = 1.9849 \times 10^{-4}$ kg m^2;
the viscous–friction coefficient, $B = 0.0123$ kg m^2/s;
the motor torque constant, $K_m = 0.252$ N m/A;
nominal phase current, $I_M = 1.2$ A;
gear ratio, $K_g = 1$.

PID controller gains were tuned according to Gain Scheduling PID Fuzzy controller design procedure. According to experimental error and derivative of error,

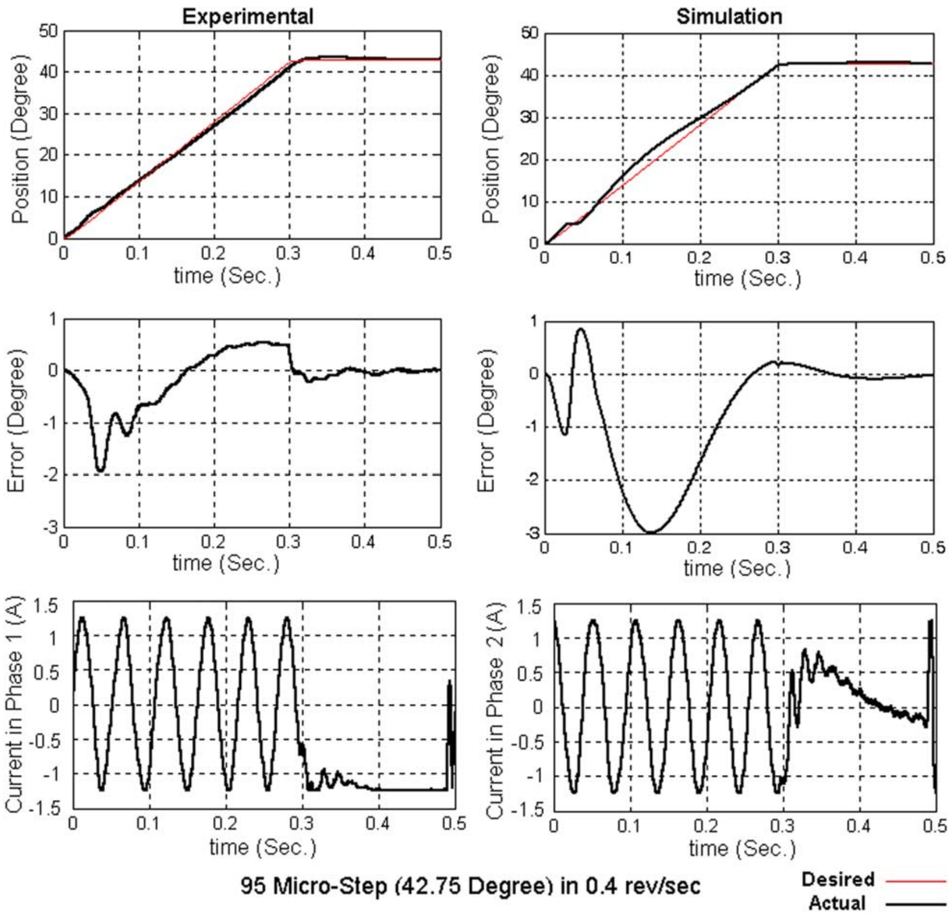

Fig. 8. Tracking problem for 95 micro-step in 0.4 rps with sine/cosine phase current profiles.

triangular membership functions for error and derivative of error were designed, logarithmic membership functions are considered for normalized K_p and K_d, by considering T_i with reference to T_d and using product inference engine, singleton fuzzifier and center average defuzzifier, PID controller gains are obtained and use in this study as [11]:

$$K_p = 0.4652 \quad K_i = 0.0288 \quad K_d = 0.123 \tag{8}$$

To study the effect of white noise power added to the phase current profiles, on tracking problem in closed-loop micro-step control, simulation and experimental study has been carried out. The block diagram of simulated HSM in closed-loop control system used in this study is shown in Fig. 1.

The block diagram of closed-loop system with PID controller used in the experimental investigation is shown in Fig. 2.

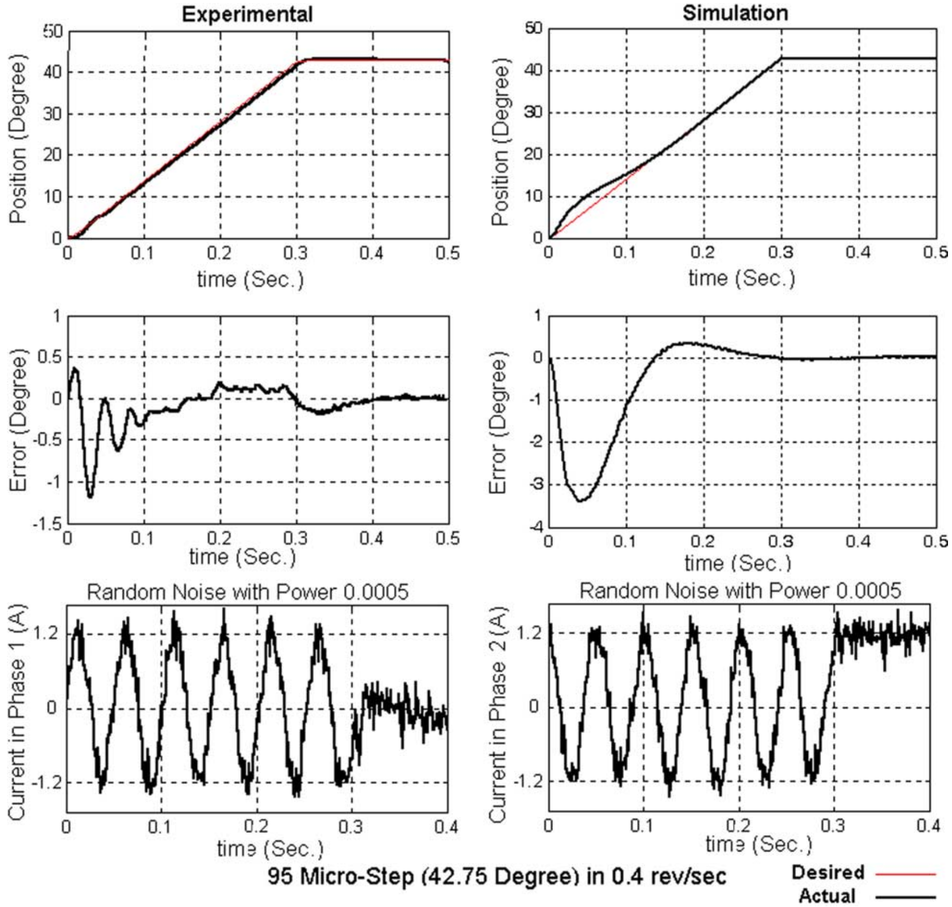

Fig. 9. Tracking problem for 95 micro-step in 0.4 rps with a random noise on two phase currents (power = 0.0005 and 0.0005).

The hardware used to study the effect of phase current profile on micro-step positioning accuracy are Mechanical Setup, Hybrid Stepper Motor, 20000 PPR Heidenhain Encoder, Push-Pull Drivers, Computer, Axiom5412H and PCL833 boards. The mechanical setup used in this study has an optimal design which enables one to change and replace different stepper motors with different size and torque easily. A mechanical brake has been developed to apply load torque as inertial load. The software for simulation study of phase current profiles and experimental implementation of PID controller on the Hybrid Stepper Motor is Real-Time Windows Target and Simulink Toolboxes of Matlab software. Using Real-Time Windows Target Toolbox of Matlab software, C code of Simulink is generated and compiled, which enable us to start real-time execution on Microsoft Windows with interfacing to real hardware using PC I/O boards. Experimental setup and micro-step driver is shown in Fig. 3.

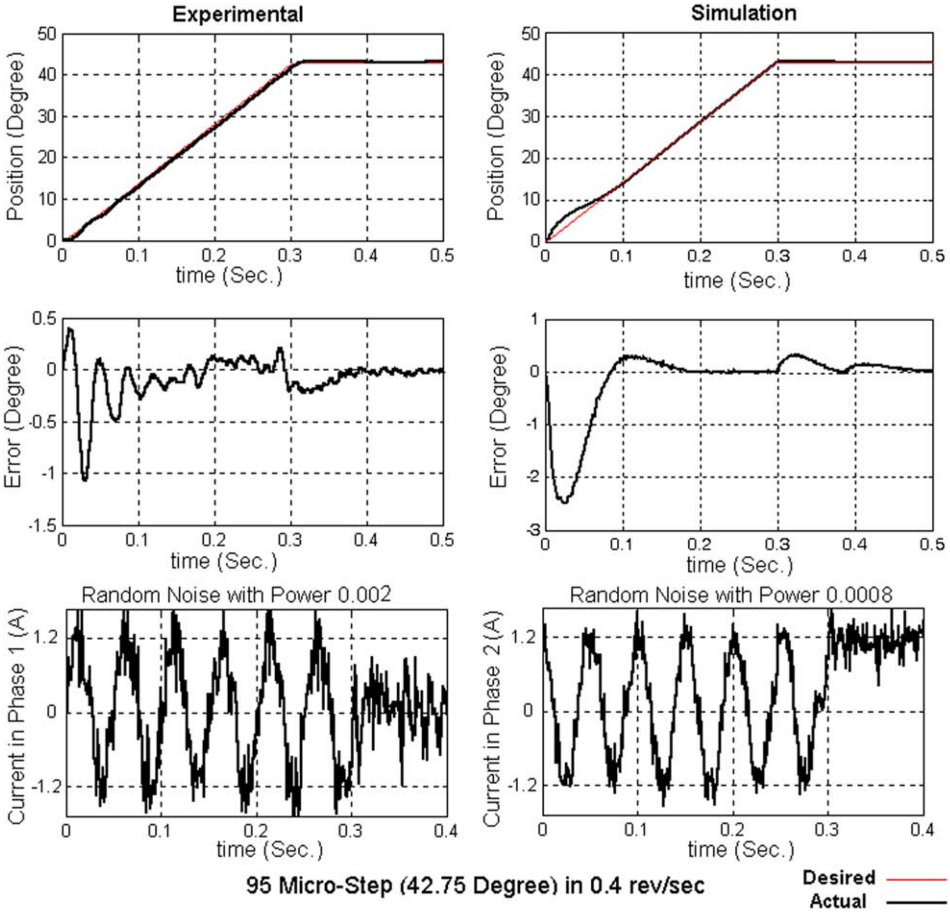

Fig. 10. Tracking problem for 95 micro-step in 0.4 rps with a random noise on two phase currents (power = 0.002 and 0.0008).

Various powers of white noise signal is added to the phase current in the simulation and experimental investigation on the effect of phase current profiles distortion on position tracking of Hybrid Stepper Motor in micro-step operation. As white noise is a wide band and random signal, then its mean value will be zero. The mean square value of the signal, which is the magnitude of dissipated noise power is used as a variable in this study. Tracking problem with various random noise power on phase current profiles for 43 and 95 micro-step in 0.1 and 0.4 rev/s respectively are shown in Figs. 4–11. In all these figures, there are six graphs showing the position and tracking error of the system in degree and the currents in phase one and two in Ampere. Fig. 4 shows the tracking error for sine/cosine phase currents in the system. It can be seen that the error in simulation and experimental cases, decreases rapidly and approaches zero in less than 0.2 s. In Fig. 5 the results for a random white

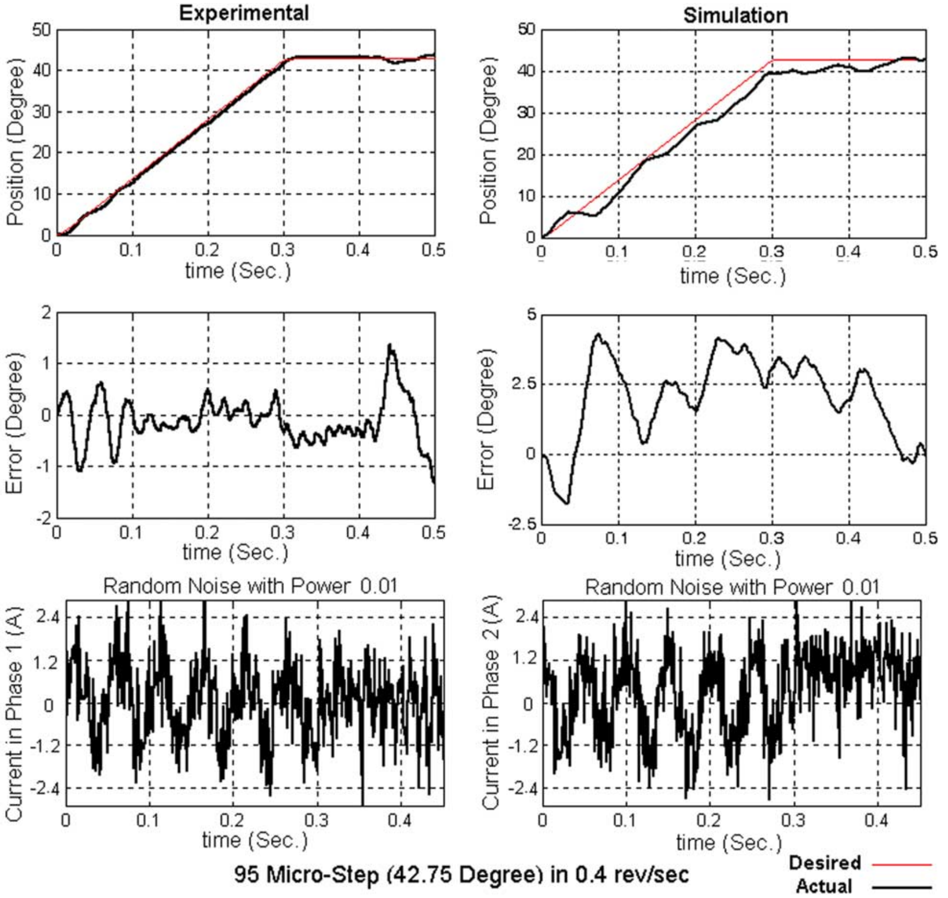

Fig. 11. Tracking problem for 95 micro-step in 0.4 rps with a random noise on two phase currents (power = 0.01 and 0.01).

noise of power 0.0005 on phase one is given. In experimental cases produced position error that was shown in Fig. 4 has minimum pick value with respect to other cases shown in Figs. 5–11. However all position errors decrease rapidly and become zero. One can see the effect of white noise power on the tracking error in the system with 43 micro-step in 0.1 rev/s in Figs. 5–7. The main result of this part is that increasing the white noise power in phases one and two which results in a very poor positioning accuracy and large errors in simulation and experimental cases. The same approach is continued in Figs. 8–11 in which 95 micro-step in 0.4 rev/s and different values of white noise power are implemented to investigate the tracking error. It can also be concluded that increase in the random signal power increases the tracking error in both simulation and experimental cases. In all experimental cases fluctuation and variation of tracking error is larger than simulation study, which can be due to the rotor permanent magnet nonhomogen structure, and hystersis property.

In Figs. 7 and 11 it can be seen that the system cannot follow the desired position although a PID controller is used. This is mainly because the amount of noise power is very higher than what one expects in the real industrial applications. With a reasonable amount of random noise level the PID controller performance in different conditions can be seen in other figures such as Figs. 4–6 and 8–10.

7. Conclusions

White noise is one of the most important elements in power electronics drivers. Studying the effect of the white noise source on precise position control system performance, such as HSM is an interesting problem. Effects of applying white noise in the currents of HSM on the position accuracy of a PID closed-loop micro-step system has been investigated in this paper. Comparison of the simulation and experimental results obtained with and without white noise with different power for white noise show that the random signal on each or both of phases can severely affect the positioning accuracy and tracking error. Although PID controller is a robust controller, it can not overcome the error introduced by implementing high power of white noise on the phase currents of stepper motor. In practical cases white noise power in driver circuits, is very smaller than used in this study, therefore the excellent performance of the proposed PID controller under the application of limited values of white noise powers in the phase currents is proven. Simulation and experimental results of tracking a desired position for HSM in micro-stepping operation agreement are shown completely.

References

[1] Chrifi-Alaoui L, Lebrun A. H-infinity feedback control of a permanent magnet stepper motor. In: 23rd international conference on industrial electronics, control and instrumentation, 1997, vol. 1, p. 108–13.
[2] Rahman MF, Poo Aun-Neow. An application oriented test procedure for designing micro-stepping step motor controllers. IEEE Trans Indust Electron 1998;35(4):253–7.
[3] Koivo HN, Tanttu JT. Tuning of PID controllers: survey of SISO and MIMO techniques. In: Proceedings of the IFAC intelligent tuning and adaptive control symposium. Singapore: 1991. p. 75–80.
[4] Selk Ghafari A, Vossoughi GR. Simulation and experimental study of real-time robust control of hybrid stepper motor with QFT method in micro-step operation. In: Proceeding of IEEE international conference on mechatronics, ICM04. Istanbul, Turkey: 3–5 June 2004.
[5] Islam MS, Husain I. Self-tuning of sensorless switched reluctance motor drives with online parameter identification. In: IEEE-IAS annual conference proc., Rome, 2000. p. 1738–44.
[6] Bodson M et al. High performance nonlinear feedback control of a permanent magnet stepper motor. IEEE Trans Contr Syst Technol 1993;1(1):5–14.
[7] Selk Ghafari A, Vossoughi GR. Real-time parameter identification of two phase hybrid stepper motor in micro-stepping operation. In: 6th Iranian manufacturing engineering conference, SMEIR. 22–25 December 2003.
[8] Acarnley PP. Stepping motors: a guide to modern theory and practice. 3rd ed. Peter Peregrinus Ltd. Publication; 1992.

[9] Kenjo T, Sugawara A. Stepping motors and their microprocessor controls. 2nd ed. Oxford Press; 1994.
[10] Lin Nicolae Calistru CT. Mixed H2/H-infinity PID robust control via genetic algorithms and MATHEMATICA facilities. In: European symposium on intelligent techniques. 3–4 June 1999.
[11] Selk Ghafari A, Alasty A, Design and real-time experimental implementation of gain scheduling PID fuzzy controller for hybrid stepper motor in micro-step operation. In: Proceeding of IEEE international conference on mechatronics, ICM04. Istanbul, Turkey: 3–5 June 2004.
[12] Carr JJ, Brown JM. Introduction to biomedical equipment technology. 4th ed. Pearson Education; 2000.
[13] Selk Ghafari A, Behzad M, Meghdari A. Experimental investigation on the effects of random signals on micro-step control positioning accuracy. In: Proceedings of the 9th mechatronics forum international conference, mechatronics 2004. Ankara, Turkey, p. 253–7.