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PSO Based Parameter Identification of Colman-Hodgdon Hysteresis Model of a Piezoelectric Actuator and PID Feedback Controller

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Abstract

In this paper, a dynamic model of a piezo-actuator based on Coleman-Hodgdon (C-H) hysteresis model is considered. The hysteresis model is established by identification considering the particle swarm optimization (PSO) technique. The identified model is tested considering a classical PID controller in order to achieve a tracking control of nano-positioning system driven by piezoelectric actuator. Experimental results through real-time implementation are presented and discussed. A good system performance was obtained with a tracking error less than 100 nm.

Keywords: Colman-Hodgdon model, systems identification, particle swarm optimization PSO technique, Piezo-positioning mechanism, PID controller

1 Introduction

The positioning stages are dedicated manipulators who have good repeatability and high accuracy positioning of sub nanometers to sub microns. In recent years, the positioning stage systems have been widely used in high precisions positioning applications due to their special proprieties of physical unlimited resolution, high stiffness and fast response. High performance nano-positioning stage are used in a variety of applications, such as fiber optical switches ([30], [24], [16]), micro force sensors ([21], [15], [3]), actuators for a scanning probe microscopy ([5], [25]), data storage [23], micro optical lens scanners ([27],[22]) and manipulative biological cells [11]. The positioning stage systems using the piezoelectric actuator PZT are the most popular employed in such applications. The major problem of the PZT is the presence of highly nonlinear hysteresis behavior between by the input voltage and the output position. For the last two decencies, many research projects were conducted for the modeling and control of hysteresis non-linearity. Different mathematical models, proposed in the literature, are built to describe the hysteresis behavior, such as Bouc-Wen model [12], Dahl model [32] and Macki et al., Adrians et al. use in [1] an electromechanical model combined with nonlinear first order differential equations to describe both hysteresis and the systems dynamics. In ([18], [11]), authors propose an extension to the classical Preisach operator to describe the stress-dependent characteristics of magneto-astrictive hysteresis. Lei w. et al.[17] propose a new modeling method for nonlinear rate-dependent hysteresis system based on LS-SVM. Janaideh et al. [2] propose a rate-dependent play hysteresis operator and applied it to the classical PI model in conjunction with density function to describe the rate-dependent hysteresis. In [35], authors use a novel fractional order model for the dynamic hysteresis to describe the rate-dependent hysteresis nonlinearities of PEAs.

In the current research, we propose the rate-depending model of Coleman-Hodgdon (C-H) with six parameters and we use particle swarm optimization PSO technique to identify the model parameters and, finally, we apply a PID feedback controller for motion tracking control of nano-positioning system.

2 Modeling and identification of piezo-actuator

The Coleman-Hodgdon (C-H) model was formulated in 1986 to introduce a continuous time model. This model describes the hysteresis in ferromagnetic soft materiel. A formulation of the C-H model is expressed by differential equations between the magnetic flux B and the magnetic field H ([28], [7]). By replacing the magnetic flux B by the output position x and the magnetic field H by the input voltage v, the model can be used to describe the hysteresis behavior in piezoelectric actuators ([19]) is given by;

$$x(U) = \begin{cases} (A_1 - A_2 e^{-A_3 V_R})U - A_4\left(1 - \frac{2e^{-A_5 U}}{e^{-A_5 V_m} + e^{-A_5 V_M}}\right) + A_6, \ if \quad \dot{U} \geq 0 \\ (A_1 - A_2 e^{-A_3 V_R})U + A_4\left(1 - \frac{2e^{A_5 U}}{e^{A_5 V_m} + e^{A_5 V_M}}\right) + A_6, \ if \ \dot{U} < 0 \end{cases} \qquad (1)$$

The model parameters ([31]) and the form of the hysteresis are given in Figure1.

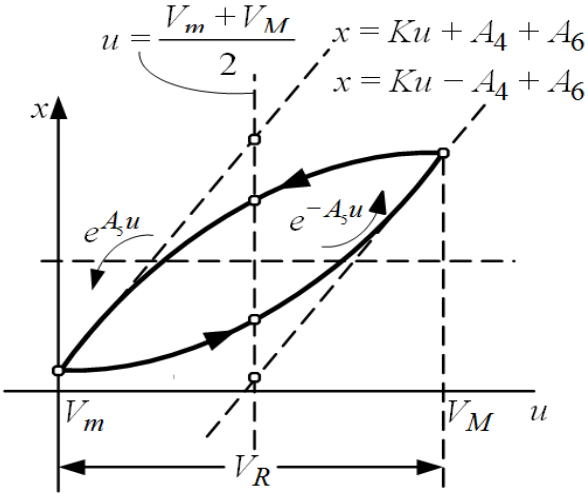

Fig. 1. Coleman-Hodgdon parameters in hysteresis curve

The parameters A_1, A_6 are calculated by tacking some hysteresis characteristics. The linear asymptote$x = Ku \pm A_4 + A_6$ represents the linear response if the hysteresis of the piezoelectric element is not present; with a slope of $A_1 - A_2 e^{-A_3 V_R}$. The exponential decay $e^{\pm A_5 V}$ to the right creates hysteresis behavior. The vertical line $u = (V_M + V_m)/2$ intersects the initial loading curve (x_0) at one point and the hysteresis loop at two points. The voltage range is$V_R = V_M - V_m$; where V_M and V_m are the maximum and the minimum input voltages respectively.The main difficulty of the C-H model comes from the nonlinearity of the model with respect to parameters. The identification of the C-H model parameters is a difficult process to realize. Several attempts based identification methods have been published nowadays ([29],[6],[4],[14]). The procedure presented here for identifying the C-H model parameters is based on Particle Swarm Optimization (PSO) technique. The PSO is also faster than other optimization algorithms (such as genetic algorithms) at finding the optimum because a smaller number of iterations are required. A comparison between the two optimization algorithms is given in [10], where in it is shown that, for a variety of problems, the PSO is faster and more efficient in terms of computational power. In this work, the overall speed of the alignment system was an important determinant; therefore, classic simple particle swarm optimization was chosen.

3 Particle swarm optimization

Particle swarm optimization (PSO) is an iterative optimization algorithm similar to the genetic algorithm which was introduced by Kennedy and Eberhart [13]. The PSO is a technique based originally on the social interactions of groups of animals, such as the flocking of birds or schooling of fish. A group of candidate solutions, referred to as particles, are moved around in the solution space according to two mathematical equations, until the optimized result, which is a maximum or minimum of one or several variables that satisfy the objective function is found. To converge towards a solution, each particle navigates in the solution space using its own experience and that of its peers, according to the following equations:

$$\overleftarrow{v}_i(t+1) = \overleftarrow{v}_i(t) + \varphi_1 r_1 \lfloor p_i - \overleftarrow{x}_i(t) \rfloor + \varphi_2 r_2 \lfloor p_g - \overleftarrow{x}_i(t) \rfloor \qquad (2)$$

$$\overleftarrow{x}_i(t+1) = \overleftarrow{x}_i(t) + \overleftarrow{v}_i(t+1) \qquad (3)$$

where φ_1 and φ_2 are constants that determine the balance between the influence of individual learning and group learning, r_1 and r_2 are random numbers between 0 and 1, p_i and p_g are the particle's previous best position and the group's best position, and x_i is the actual position in the search space. This version suffered from the problem of instability caused by particles accelerating out of the search space, and the premature convergence to a locally optimal solution. It was then proposed in [8] that the velocity should be made proportional to the maximum particle movement, which solved the first problem. Two of the most popular methods that are employed to solve the second problem are inertia and constriction. The inertial method was first proposed in [33], which introduced a new term called inertia W that varied in a decreasing linear fashion so as to allow initial exploration, followed by acceleration toward an improved global optimum:

$$\overleftarrow{v}_i(t+1) = \overleftarrow{v}_i(t)W + \varphi_1 r_1 \lfloor p_i - \overleftarrow{x}_i(t) \rfloor + \varphi_2 r_2 \lfloor p_g - \overleftarrow{x}_i(t) \rfloor \qquad (4)$$

$$W = (w_1 - w_2) \times \frac{t_{max} - t}{t_{max}} + w_2 \qquad (5)$$

where w_1 and w_2 are the upper and lower limits of the inertial weight, t is the current iteration, and t_{max} is the maximum number of allowed iterations. The constriction method was first proposed in [34], in which a new term called constriction factor χ was introduced to remove the need to limit the velocity:

$$\overleftarrow{v}_i(t+1) = \chi\{\overleftarrow{v}_i(t)W + \varphi_1 r_1 \lfloor p_i - \overleftarrow{x}_i(t) \rfloor + \varphi_2 r_2 \lfloor p_g - \overleftarrow{x}_i(t) \rfloor\} \qquad (6)$$

$$\chi = \frac{2}{2-\varphi-\sqrt{\varphi^2-4\varphi}} \ldots where \ldots \varphi = \varphi_1 + \varphi_2, \varphi > 4 \tag{7}$$

In [9] it was shown that combining both inertial and constriction strategies by setting the inertial weight W to be equal to the constriction factor χ improved the performance of the algorithm for a variety of problems. Considerable research has been conducted to further refine the PSO. Parameter tuning and dynamic environments are only some of the research areas. In this work, we used the version of particle swarm optimization that contained the inertial weight parameters as proposed in [33]. The governing equations are given as equations 3 and 4. The structure of this algorithm is given by the flowchart of figure 2 [20]

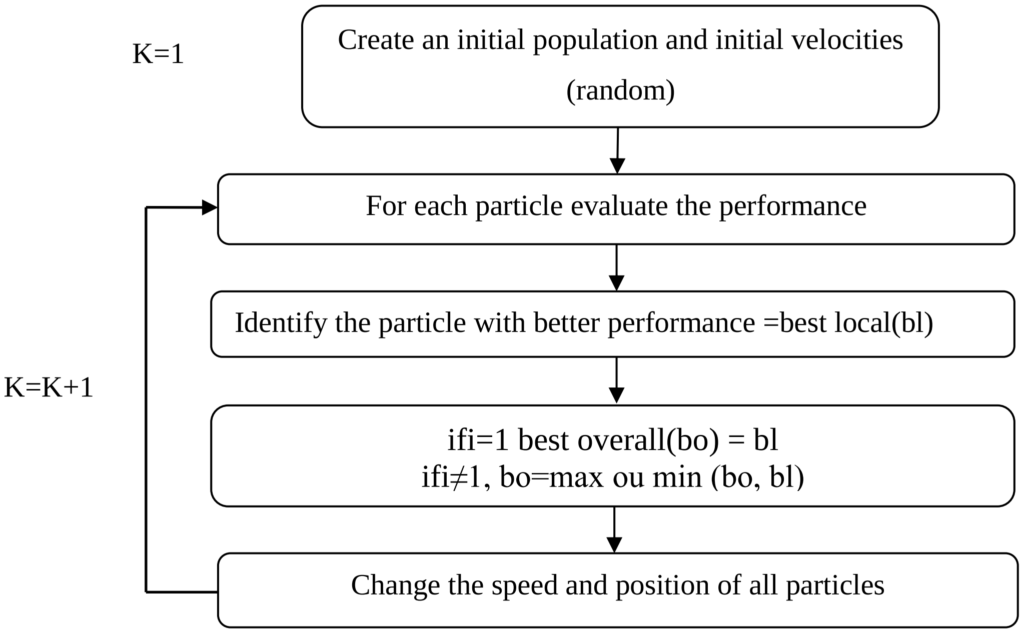

Fig. 2. The flowchart of the PSO algorithm

The parameters from the PSO algorithm is given in table 1.The input voltage of the piezoelectric actuator varies from 0~3.3V and the output displacement from 0-1880 μm. Fig.3 shows the nonlinear hysteresis of PEA when a sinusoidal voltage signal is applied to a piezoelectric actuator. Numerical simulations of the behavior of the experimental system were carried out by exploiting the Coleman-Hodgdon model with a frequency of 0.5 Hz, 1 Hz and 10Hz, from identification of system parameters are given in Figure3.For validation from the parameters obtained, the experimental results of the hysteresis response and the simulated results for a frequency of 1Hz is illustrated in figure 4.

Parameters	Value	Unité
A1	1e-008	$(\mu\mathrm{m\ V})^{-1}$
A2	0.46827	$(\mu\mathrm{m\ V})^{-1}$
A3	80.6817	V^{-1}
A4	0.0031324	$(\mu\mathrm{m\ V})^{-1}$
A5	-0.2	V^{-1}
A6	0.0010047	$(\mu\mathrm{m\ V})^{-1}$

Table 1. Identified parameters for the model using the PSO algorithm

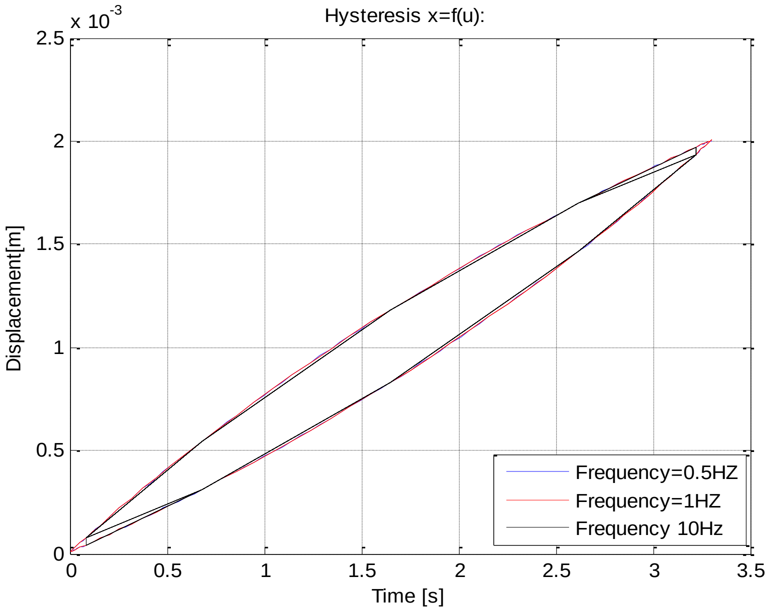

Fig. 3. Hysteresis of the driven stage to the sinusoidal input voltage

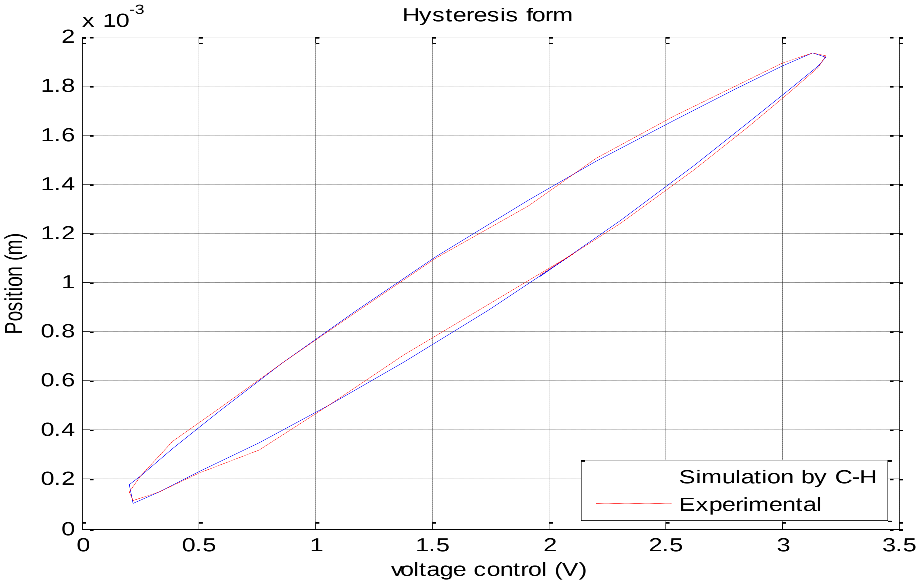

Fig. 4. Hysteresis cycle obtained by PSO compared to the experimental one

Figure 5 shows the result reflecting the evolution of the error as a function of the number of generations. Note the convergence to a minimum error value after 90generations, which proves the validity of the model studied. The figure 6 presents a comparison between simulated and observed experimental the evolution position. We observe a good agreement between the two results.

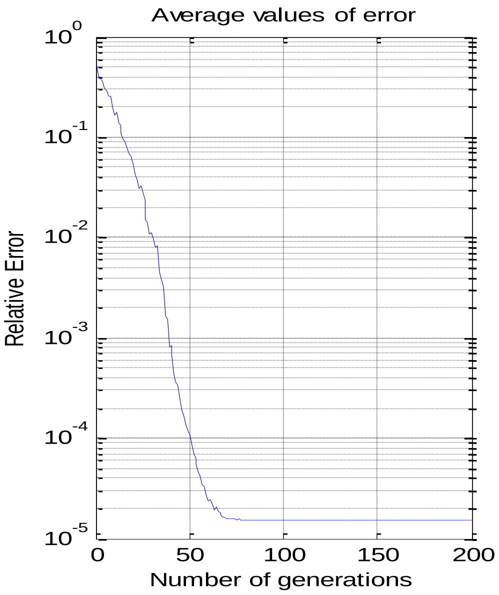

Fig. 5.Evolution of error

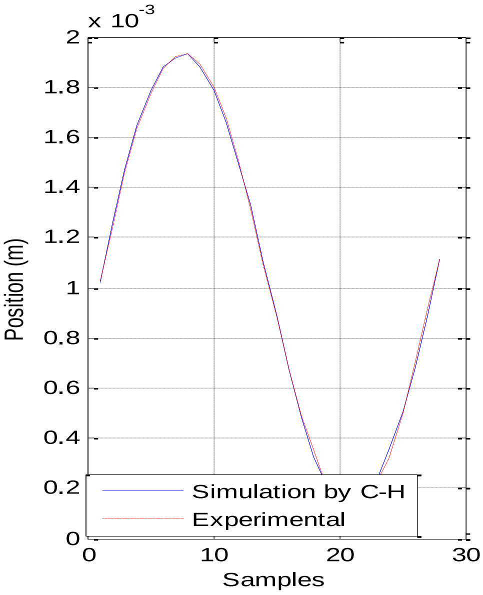

Fig. 6. Tracking response of the position

4 Experimental setup

In order to verify the feasibility of the C-H model used for PEA modeling and the effectiveness of identification method, a MC-3300-RV a SQL-RV-1.8 and NSD-2101 drive system from Squiggle Company is used and shown in figure 7. It is possible to control the motor position or speed. The mode selection in a closed loop is chosen to have a very precise position control.

Fig. 7. Squiggle piezomotor-driver

To achieve the control goal and visualize the systems variables, the experimental setup of the figure 8 is set. Is includes a piezoelectric motor with its driver, the reference signal, a computer, an oscilloscope and an acquisition card.

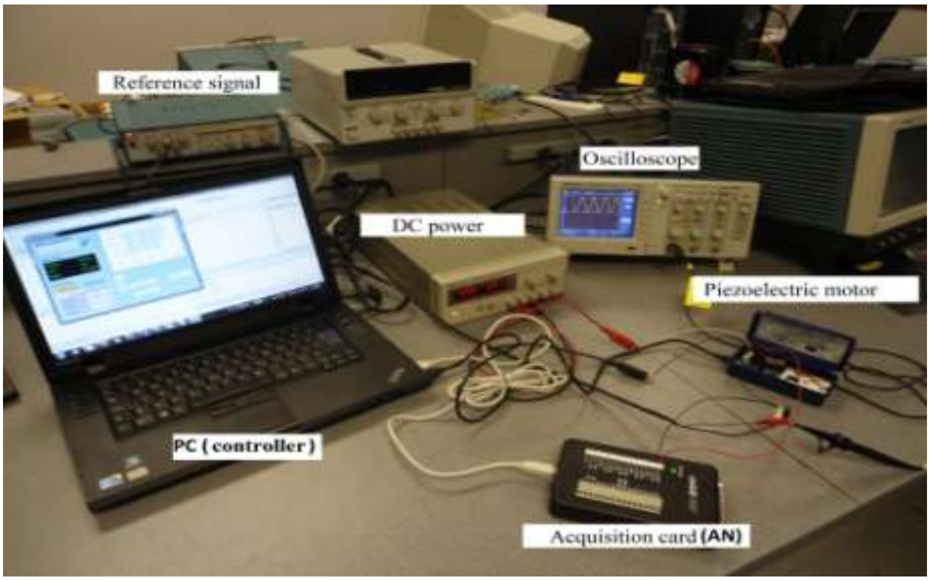

Fig 8. View of the overall experimental setup

5 Real-time implementation of a PID controller

The MPE model linking the position and voltage is analyzed and identified from experimental measurements. The hysteresis phenomenon present in the MPE is introduced in writing the full model for the implementation of the PID control. The implementation of the proposed control is carried out using Matlab software. This is done in real time with the following PID gains: K_p =1000,K_i= 100 and K_d=1. The frequency of the reference signal is set to 0.5Hz. Figure 9 illustrates the reference (blue) and the actual (red) positions. The control voltage, the reference and actual positions and the tracking error obtained by simulation are given in Figure 10.It is noted that the actual position obtained by MPE is about 1884.5 µm with an error of ± 100 µm.We use the maximum control voltages which corresponds to 3.3 V**.** We can also visualize the experimental position and its reference in figure 11.The simulation and experimental results are highly satisfactory, which leads to the validity of the model identified by the PSO technique.

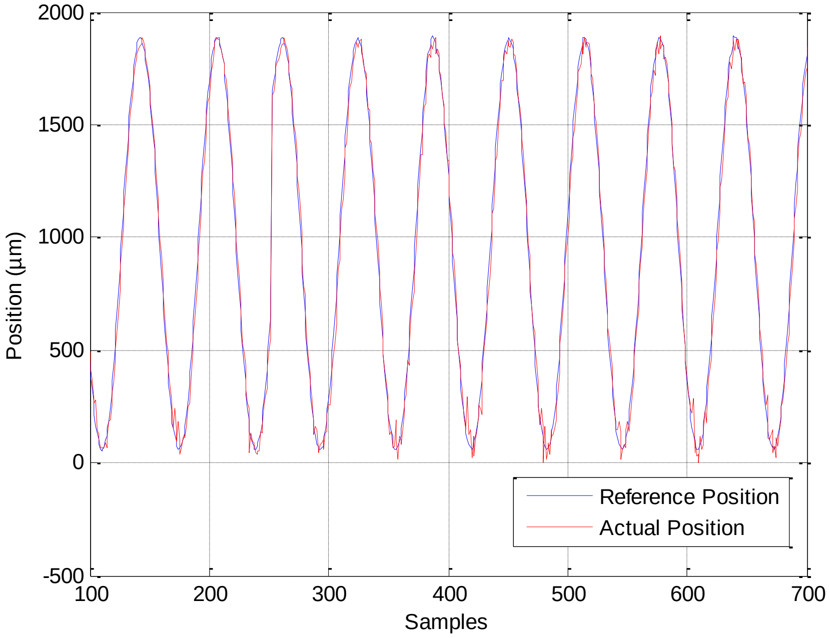

Fig. 9. Comparison between the actual position and the reference position

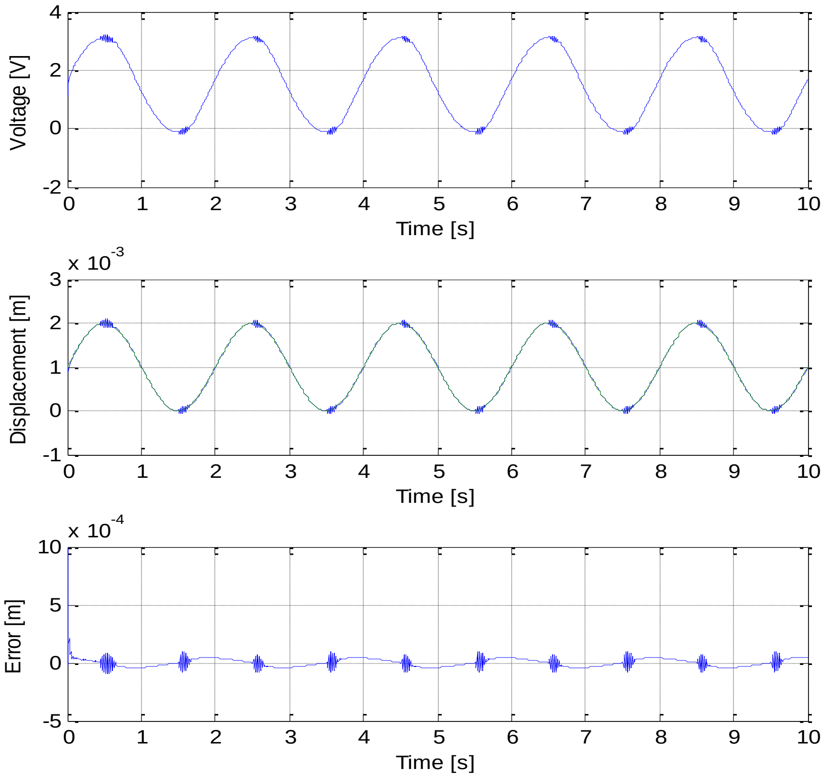

Fig. 10. Simulation results of the response PID control for a sinusoidal reference frequency (0.5Hz) a) Voltage control. b) Position. c) Tracking error.

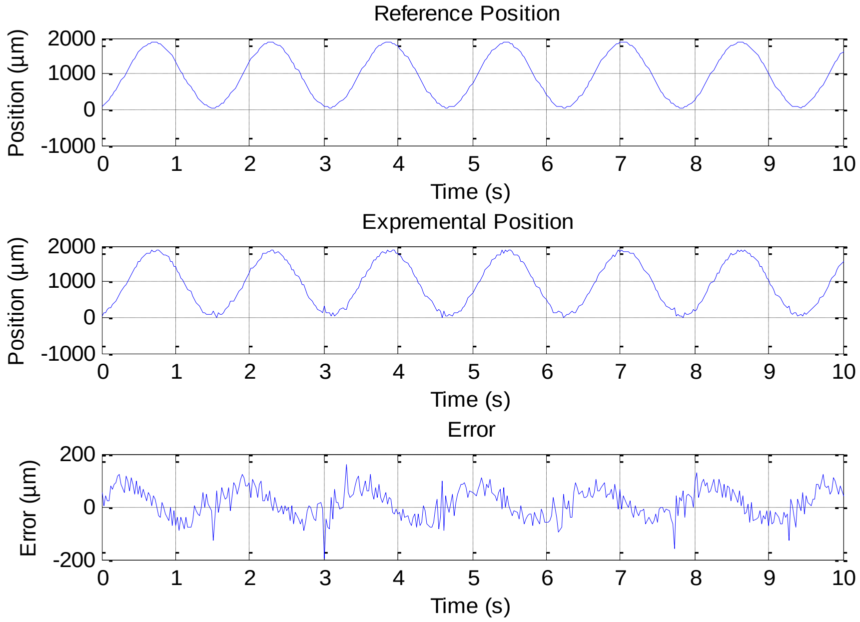

Fig.11. Experimental results a) Reference position. b) Actual position. c) Tracking error.

6 Conclusion

The PSO technique is applied to the system identification of a Piezo-actuator mathematical model. The Coleman-Hodgdon model is chosen and experimentally validated for several frequencies. The nano-positioning system driven by the piezoelectric actuator and using the proportional integral derivative PID controller is considered to validate the identified model. A good tracking is achieved by the nano-positioning stage. The experimental results show that the proposed model is valid and they correspond to simulation results.

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