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Behavioral Model and Simulation of Piezoelectric Nanopositioning Actuator

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***Abstract*—This paper presents modeling and simulations of Piezoelectric Nanopositioning Actuator, in past Classical actuators such as (electromagnetic, hydraulic and pneumatic) are the most used in the industry; new technologies based on different physical principles are being developed. In applications where the size of the actuator has to be minimized, or where fast response and high resolution are needed, the classical actuators fail to respond appropriately. For this reason, non-classical technologies are becoming more relevant. Among them, the piezoelectric actuators are proving to be a reliable solution for many engineering applications, ranging from micro and Nano positioning (machine tools, optic devices or modern microscopes biomedical, Nano-robots, and automotive). Modeling of Piezoelectric Nanopositioning Actuator it's not easy and the control of the actuator is not easy too, the main work had been done using real time measurements using LabVIEW software and Data Acquisition system using different applied voltage. Bouc-Wen discovers the model the dynamics and hysteresis behavior in PZT actuator. Electromechanical model, pizo actuator, current and force relationship, and hysteresis model are present**.

***Key Word*: Electromechanical actuator, nanopositioning applications, nonlinearity hysteresis modeling, piezoelectric actuator,**

I. INTRODUCTION

Curie and his brother Jacques observed that certain crystals respond to pressure by separating electric charge on opposing faces. The Curie named the phenomenon piezoelectricity [1]. In 1883, when Curie discovered the piezoelectric effect, he noted that certain materials, such as quartz crystals produce voltage when they are mechanically stressed. The term "piezoelectricity" was coined to express this effect; the word "piezo" is a Greek word which means "to press". The most popular piezoelectric material is Lead-Zirconate-Titanate (PZT) which is a ceramic, piezoelectric material is used to convert electrical energy to mechanical energy and vice-versa [2-3].

Piezoelectric sensors are used in a variety of applications to convert mechanical energy to electrical energy such as: pressure-sensing applications, detecting imbalances of rotating machine parts, ultrasonic level measurement, flow rate measurement, sound transmitters (buzzers), sound receivers (microphones), etc. [4]. However, piezoelectric actuators convert electrical energy to mechanical energy, and are used in many application, such as Scanning microscopy, Patch clamp, Gene manipulation, Vibration cancellation, R/W head testing, hydraulic valves, drilling equipment …etc. [5].

Recently, PZT actuators are used in nanopositioning applications where a highly precision position control is required; such as scanning tunneling microscopy, biomedical, Nano-robots, automotive, …etc. using PZT actuators have many advantages [5-6] regarding to electromechanical actuators: Piezoelectric actuators have excellent resolution in displacement, high stiffness, high electrical mechanical coupling efficiency, small size, small heat expansion, low power consumption and fast response, the piezoelectric actuators make motion in micro-meter range with sub micrometer precision, there are no moving parts in contact with each other limit to limit resolution, the piezoelectric actuators capable of moving loads of several tons, they can cover travel ranges of several (100 µm) [6] with resolutions in the nanometer range ,the piezoelectric actuators behave pure capacitive load, so they consumes virtually no power, the piezoelectric actuators do not produce magnetic field nor are they affected by them.

But the piezoelectric actuators have the disadvantage of hysteresis, resonant frequency and creep behaviors, which severely limit system performance such as giving rise to undesirable inaccuracy or oscillations, even leading to instability. Its different control strategies are developed to eliminate the hysteresis, creep and resonant frequency effect, to achieve stability and accuracy for PZT actuators [7-8].

II. DYNAMIC MODEL FOR PZT ACTUATOR

From dynamic point, the piezoelectric actuator can be equivalent as a damped mass-spring mechanic system by a linear time-invariant second order differential equation; as the applied voltage generates force, as shown in figure 1, and the equation can be written as in equation (1) [5], [9-10]: Piezoelectric actuators have excellent resolution in displacement, high stiffness, high electrical mechanical coupling efficiency, small size, small heat expansion, low power consumption and fast response. The piezoelectric actuators make motion in micro-meter range with sub micrometer precision, There are no moving parts in contact with each other limit to limit resolution, The piezoelectric actuators capable of moving loads of several tons, they can cover travel ranges of several (100 µm) [5] with resolutions in the nanometer range ,The piezoelectric actuators behave pure capacitive load, so they consumes virtually no power, The piezoelectric actuators do not produce magnetic field nor are they affected by them.

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The paper is organized as follows: Section I presents introduction and the literature work and research motivations in nanopositioning using PZT actuators. Section II presents the mathematical model of the system. In section III, we present the Simulink model and the simulation results of the proposed system. In section IV presents Hysteresis modeling of pizoactuator .Experimental results some concluding remarks are discussed in last section.

III. MATHEMATICAL MODEL OF THE SYSTEM

From dynamic point, the piezoelectric actuator can be equivalent as a damped mass-spring mechanic system by a linear time-invariant second order differential equation[11]; as the applied voltage generates force, as shown in figure 1, and the equation can be written as in equation (1) second-order linear differential equation [5], [9-10]:

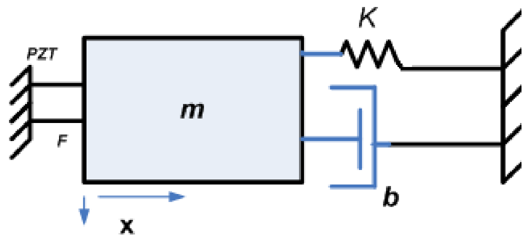

Fig. 1. The dynamic model of piezoelectric actuator.

$$m\ddot{x} + b\dot{x} + kx = f = dkv \qquad (1)$$

Where

- m : The effective mass of actuator,
- b : The damper coefficient,
- k : The stiffness,
- f : The generated force from applied voltage,
- d : The ratio of the displacement to the applied voltage,
- v : The applied voltage on PZT actuator.

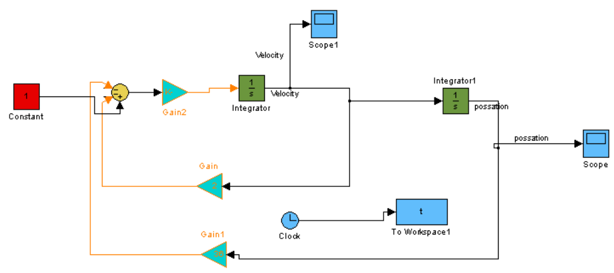

Fig. 2. The dynamic model of piezoelectric actuator simulink Matlab.

IV. SIMULINK MODEL OF THE PROPOSED SYSTEM

Figure 2 illustrates a dynamic model of piezoelectric actuator using MATLAB-Simulink model. While Figure .3 illustrates dynamic model of electromechanical actuator in this part we simulate the dynamic model and draw both current and Force in electromechanical actuator as shown in Figure 6 and Figure 7.

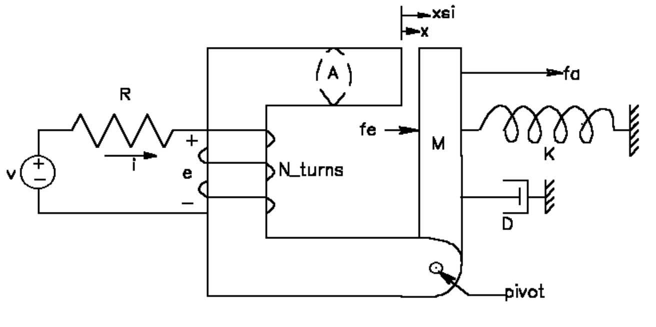

Fig. 3. Dynamic model of electromechanical actuator.

Dynamic model of electromechanical actuator is given by:

$$L = N^2 \frac{\mu_0 A}{x} = \frac{k}{x} \qquad (2)$$

Steady-state equilibrium equations:

$$V = RI$$

$$\frac{k}{2}\frac{I^2}{xx^2} = F_a + k(\varepsilon - x) \qquad (3)$$

DYNAMIC EQUATIONS:

$$v = Ri + e$$

$$f_a = M\frac{d^2x}{dt^2} + k(x - \zeta) + D\frac{dx}{dt} - f_e$$

$$e = \frac{d\lambda}{dt} = L\frac{di}{dt} + i\frac{dL}{dx}\frac{dx}{dt} = \frac{k}{x}\frac{di}{dt} - k\frac{i}{x^2}\frac{dx}{dt} \qquad (4)$$

$$f_e = \frac{1}{2}i^2\frac{dL}{dx} = \frac{k}{2}\frac{i^2}{x^2}$$

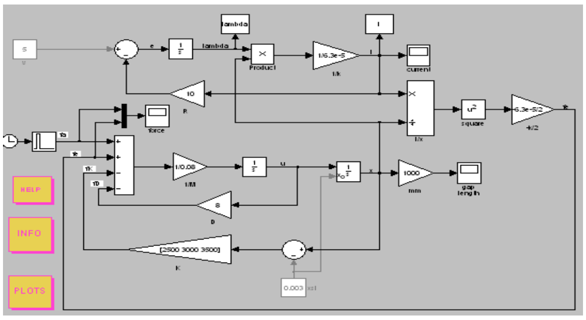

Fig. 4. The Dynamic model of electromechanical actuator in simulink Matlab.

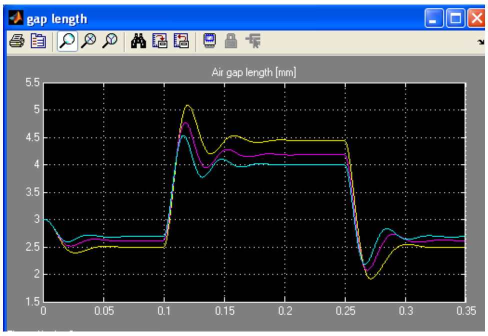

Fig. 5. The Air gap length in (mm).

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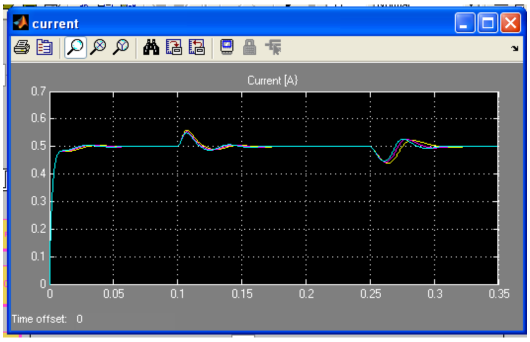

Fig. 6. The Current in electromechanical actuator in (Amps).

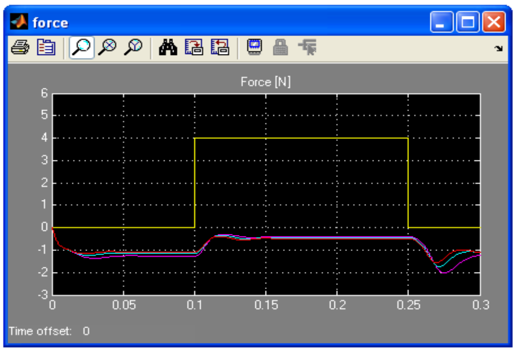

Fig. 7. Force in electromechanical actuator in (N)

V. HYSTERESIS MODELING OF PIZO ACTUATOR

In this part studying the hysteresis, hysteresis is a nonlinear phenomenon occurring in many engineering devices such as micro and nano piezoelectric actuators (PZA), the Shape

Memory Alloys (SMA), and the ferromagnetic elements system with hysteresis is usually difficult to describe accurately and may result in unstable behaviors if not controlled appropriately. Therefore, an accurate model of hysteresis is critical in order to develop suitable control algorithms for applications with these systems [16]. Several models have been developed to characterize systems with hysteresis and the Classical Preisach Model (CPM) has been known as the most familiar one to characterize hysteresis behaviors [17]. This model can further be represented by an infinite, higher order of polynomial or using analytical model [18]. Modeling, simulations and experimental work of piezoelectric nanopositioning actuator had been done to study the effect of the Hysteresis at different input voltage before and after the system saturation (maximum travelling range). Hysteresis is one of the most effects in nanopositioning system. In this case the PI 754 nanopositioning actuator system is used. This paper aims to develop a hysteresis model for a single axis piezoelectric nanopositionner stage at different operating points. The adopted methodology compares results based on the developed analytical simulated model using MATLAB with real time results using LabVIEW. Piezoelectric hysteresis is the different displacement behavior at the same voltage values either ascending or descending. As shown in fig. 8, ΔH is the maximum displacement different in traveling range of the two motion of the piezoelectric actuator. Δ H reflects piezoelectric materials' hysteresis [19].

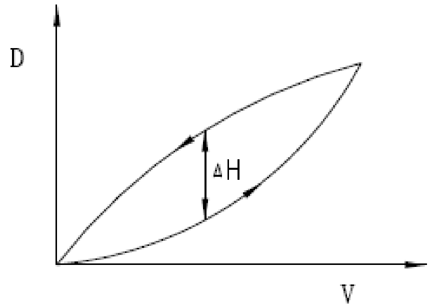

Fig. 8. Piezoelectric materials' hysteresis [8].

Many research activities have been reported for hysteresis behavior in piezoelectric materials. In general, research on hysteresis uses one of two methods. The first method is to find the hysteresis reason of piezoelectric materials, such as domain model in [20-21]. While the second method for modeling is to consider hysteresis as a black box and identifies the hysteresis characteristics using a numerical analysis approach, such as Preisach model in [22], slide model in [23], and neural networks model in [24]. Discrete Preisach model its one of the famous model for hysteresis in numerical analysis. Another model using analytical expression shown in equation (5) using Matlab to plot the hysteresis family of curves at different values of the related variables. The family of hysteresis loops can be described by a generalized transcendental equation in parametric form as follows:-

$$x(\alpha) = \pm a\cos^m \alpha \pm b_x \sin^n \alpha$$
$$y(\alpha) = b_y \sin\alpha \qquad (5)$$

Where a is the split point coordinate, b_x, b_y are the saturation point coordinates; *m*, *n* are integer numbers: *m*=1,3,5; *n* =1,2,3 ; and $\boldsymbol{\alpha}$ is a real parameter Such that $(-\infty \le \alpha \le +\infty)$. Using Matlab code to solve equation (5) and plot the result at different values of variables as shown in figure 9. In figure 10, the horizontal axis denotes the applied voltage, and the vertical axis denotes the displacement of piezoelectric actuator in micrometers. When the voltage increased, the displacement also increased until reaches saturation voltage. The saturation voltage depends on the travelling range of piezo actuator.

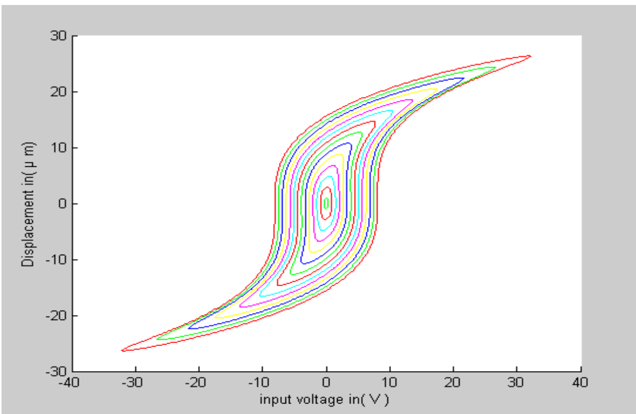

Fig. 9. Analytical model of hysteresis simulated by MATLAB.

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The maximum displacement is regarded maximum input voltage of nanopositioning; this voltage is referred to as the saturation voltage. When the applied voltage descends from the saturation voltage to zero, the displacement descends. The displacement of descending is different than the displacement of ascending. The two curves don't change, and are named limit G0(x) and F0(x) [13]. In order to describe the limit curves, using Least Quadric (LQ) to fit the data.

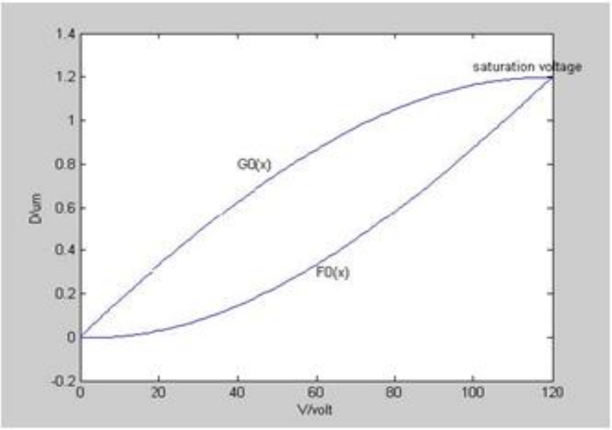

Fig. 10. Model using numerical analysis [8].

Another model using the analytical expression given by equation (5) using Matlab to plot the hysteresis curves family at different values of the related variables. The family of hysteresis loops can be described by a generalized transcendental equation in a parametric form as shown in equation (5). The simulation result using Matlab is shown in figure .9.

VI. EXPERIMENTAL RESULTS

In this section, the proposed system used for real-time experiments is shown in figure. 11. The main core of the set up includes National instruments simulation and real time measurements tool LabVIEW which is used to simulate and transfer real data to the nano system through the data acquisition card (DAQ NI 6361 24 Chanel Data Transfer System) .

In figure.11 LabVIEW Code for real time measurements consists of Signal Express: Simulates a triangle wave, DAQ Assistance Express, write the measurements to file, bundle by name all in for loop for multi measurements, X-Y plotter for hysteresis measurements at different input voltage, the output of the measurements file transferred to excel sheet to draw the output. Figure 6 shows the real time measurements of hysteresis in Piezoelectric Actuator. The real time displacement is recorded in both text file and real time output as shown in Fig.7 with the measured input voltage displayed in the *x* axis and the displacement of Nanopositioning Actuator in the *y* axis and showing the relation of traveling in both ascending and descending of Nanopositioning Actuator. Two sets of experiments were carried out.

The first set of experiments uses a 10 Hz triangular wave. Triangular wave is used because of its constant velocity. This is followed by varying the amplitude linear motion with varying velocity to demonstrate the capability to model rate-dependent. The last experiment is to fixing the frequency with varying the amplitude of the Triangular wave.

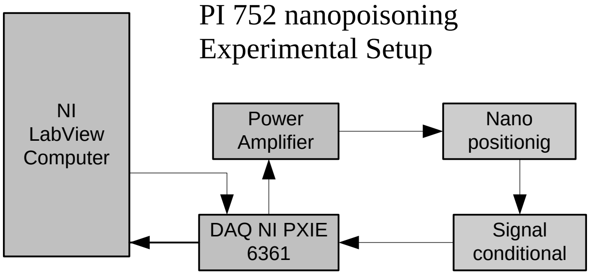

Fig. 11. Block Diagram for Experimental setup.

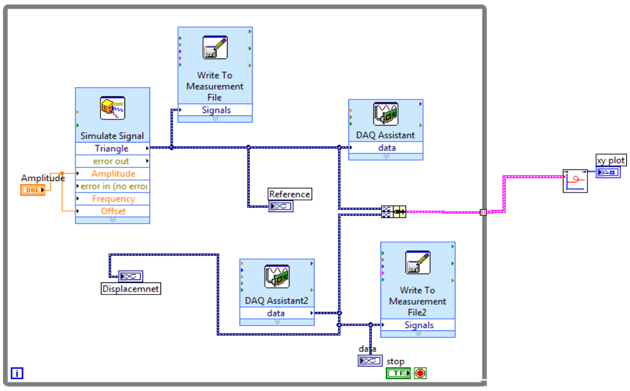

Fig. 12. LabVIEW Code for real time measurements

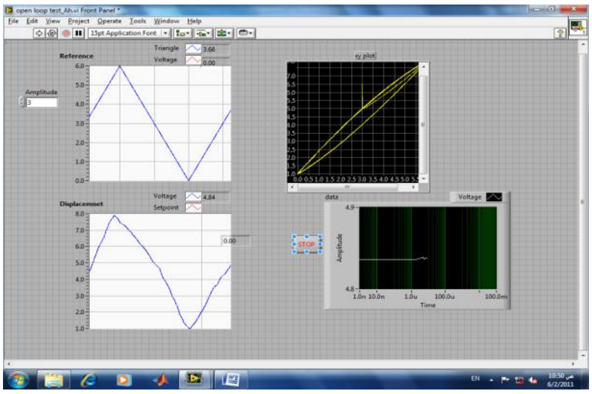

Fig. 13. Real time measurements of hysteresis in Piezoelectric Actuator using LabVIEW.

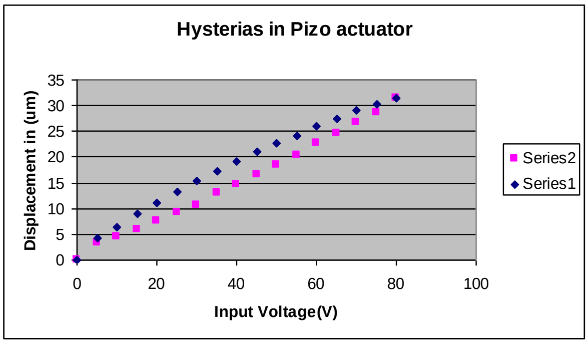

Fig. 14. Real time measurements of hysteresis in Piezoelectric Actuator using excel.

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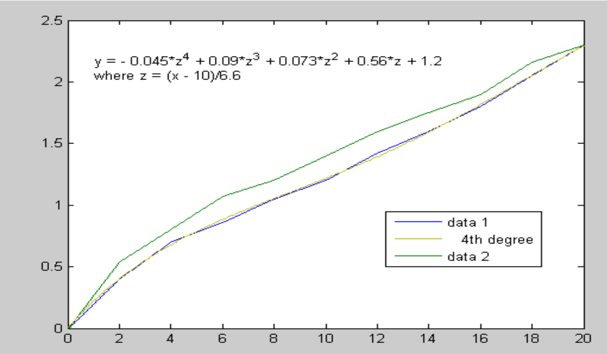

Fig. 15. Real time measurements of hysteresis in Piezoelectric Actuator using 4th degree of polynomial.

Using the real data form output text file was plotted and curve fitting using the 4th degree polynomial for fitting data as attached in fig.8 the fitting equation and Coefficients are:

y = p1*z4 + p2*z3 + p3*z2 + p4*z+ p5
p1 = -3.2816e-005, p2 = 0.0016491, p3 = -0.028874, p4 = 0.29472, p5 = 0.014196

Using different operation of measurements for Piezoelectric Actuator With triangular wave of different amplitude and same frequency and measure the real time hysteresis in x-axis is the input voltage and in y-axis is the displacement in (μm). Figure.15 shows the error from real measurements of the displacement related to the time.

VII. CONCLUSION

In this paper, we have verified and study the comparison between Piezoelectric and Classical Actuator. Develop hysteresis model for a single axis piezoelectric nanopositioning stage at different operating points using an experimental setup with LabVIEW program and setup. The adopted methodology is to compare results between the analytical model using MATLAB and the real time results using LabVIEW. The experimental results for real time measurements had been acquired for the piezoelectric nanopositioning stage using data acquisition system from National Instruments. The experimental setup is described and output results for simulation and real time measurements are compared to validate the adopted approach. Measured real time hysteresis using the setup and simulation results are presented and discussed. It is proved by experimental tests that the model can describe the hysteresis of piezoelectric actuator, and the error between simulated and measured results is presented.

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