EXPERIMENTAL INVESTIGATION OF PIEZOELECTRIC TUBE ACTUATORS DYNAMICS

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Abstract- This paper aims to investigate the dynamics of piezoelectric tube actuators. It demonstrates the effect of the frequency and the amplitude of the excitation voltage on the displacement of the actuator. In this research, an experimental setup comparable with a nanopositioner of atomic force microscopies was designed and assembled. The piezoelectric tube was excited by a number of triangular voltage functions. Experimental results show a voltage-displacement loop influenced the hysteresis phenomena as well as vibration and creep. It was clearly observed that the loop becomes widened at higher frequencies due to more significant influence of vibration.

Index Terms- Piezoelectric Tube, Hysteresis, Nanopositioning, Atomic Force Microscopy.

I. INTRODUCTION

Scanning Probe Microscopes (SPMs) are instruments that enable researchers and engineers to study and manipulate matter at nanometer scale [1, 2]. Atomic Force Microscopes (AFMs) are the most broadly used type of SPMs [3]. Piezoelectric tubes are the foremost actuators in atomic force microscopy [4, 5]. Use of these actuators in SPMs was suggested by Smith and Binning in 1986 [6]. By that time, tripod positioners were used in probe scanning. Piezoelectric tubes presented higher accuracy, wider range of operation frequency range and easier manufacturing process compared to tripod positioners [7]. In addition, their smaller size facilitated vibration isolation [8]. This class of piezoelectric actuators are likely to remain the most widely used positioning actuators not only in SPMs, but also in other micro and nanoscale positioning tasks for years [2].

Piezoelectric actuators in general are compact in size, capable of developing nanometer resolution in displacement [9]. They have high stiffness and can produce considerable force output [7]. Consequently, they have been used in a variety of applications such as fiber optics [10], ultrasonic technology [11] , inkjet printers [12-14], surgery [15-17] and precise machining [18-21].

It is known that the nonlinear phenomena of hysteresis and creep as well as vibration exist in piezoelectric materials [22, 23]. However, the dynamics of piezoelectric tubes has not been fully explored yet, partially due to the difficulty of experimentation and complexity of their nature. Some researchers have shown the nonlinearity of piezoelectric tubes is insignificant, at least for specific operating areas; that is, hysteresis and creep are negligible [24, 25].This paper experimentally investigates this matter and finds out at amplitudes/frequencies higher the ones studied by the aforementioned research, the effect of hysteresis is clear. The arrangement of this paper is as following: Piezoelectricity is briefly explained in section II. Section III reports the Experimental Setup and Data Collection, followed by Results, Discussion, and Conclusion, presented in sections IV and V.

II. PIEZOELECTRICITY

Piezoelectric materials are considered smart because they are able to respond to external variations (e.g. loads) and internal changes (e.g. damage) [26]. These materials can exceptionally couple electrical voltage and mechanical force [27]. Piezoelectric materials are made of crystals (e.g. quartz), ferroelectric polycrystalline ceramic substances, piezoceramics (e.g. barium titanate (BaTio3)) and lead zirconatetitanate (PZT) [28]: the PZT is a widely used piezoelectric material [29]. A typical PZT unit cell is illustrated in Fig. 1.

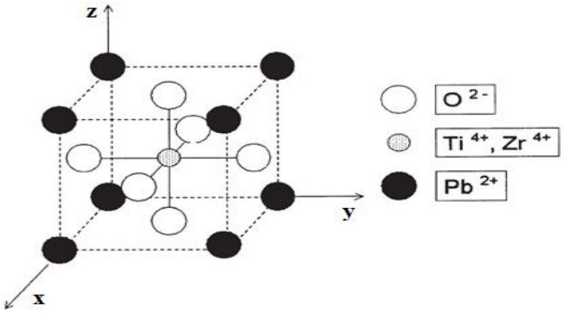

Fig. 1 A typical PZT unit cell [30].

Piezoelectricity, the interaction of mechanical and electrical quantities in piezoelectric materials, was discovered in the 1880s; the first experiment on a piezoelectric material was performed by the Curie brothers on quartz, SiO2 [29]. Subsequently, it was discovered that piezoelectric materials are deformed by applying an electrical voltage [26]. The modality of the material charge distribution explains this characteristic of piezoelectric materials. Charge distribution in materials is either symmetrical or non-symmetrical. As Fig. 2 (a) demonstrates, in the symmetrical charge distribution, the applied mechanical force does not move the resultant gravity center of ions; whereas, in the non-symmetrical charge distribution, the gravity center of ions is altered under the applied mechanical force, as shown in Fig.2 (b). The piezoelectric material has a non-symmetrical charge distribution. Therefore, applying mechanical force on piezoelectric materials results in generating an electric voltage across the material. Conversely, the material is displaced, when an electric voltage is applied.

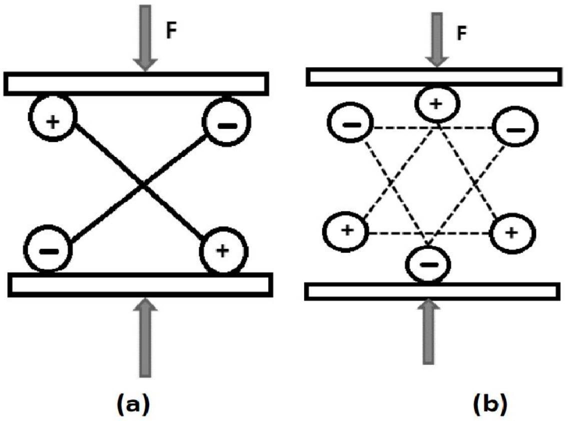

Fig. 2 (a) Symmetrical and (b) non-symmetrical charge distribution of a material.

III. EXPERIMENTAL SETUP AND DATA COLLECTION

In this research, a piezoelectric tube with the diameter, thickness and length of 9.53, 0.66 and 56.5 mm was employed. The tube has one inner and four equally distributed outer electrodes (segments). A schematic of such a typical piezoelectric tube is shown in Fig. 3. The inner and three outer electrodes were earthed, and one outer electrode was excited using a signal generator and a PDm200 miniature high voltage amplifier as illustrated in Fig. 4. A resistor of 50 MΩ was also used within the arrangement to stabilize the system as recommended in [31].

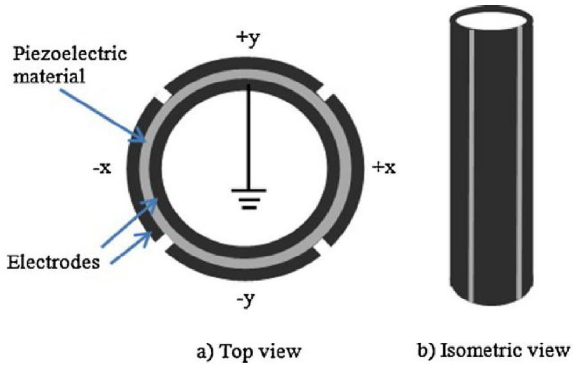

Fig. 3 A schematic of a piezoelectric tube actuator

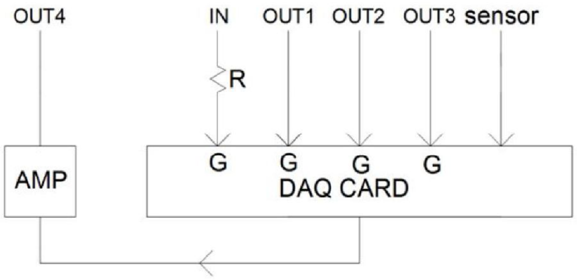

Fig. 4 The arrangement of imported and exported signals to/from the data acquisition card as well as grounded electrodes. IN and OUT stand for inner and outer electrodes of the tube.

An aluminum cube of 40x40x25 mm^3 is mounted on the tube. The displacement of one side of this cube aligned with the excited electrode of the tube. It was measured using a Philtec D20 optic-fibre displacement sensor with a built-in voltage amplifier. Micro-meters [11] were employed for sensor calibration. The actuator and sensor probes were located on a 3D printed plastic stand, particularly designed for this experiment and firmly clamped to the table. An NI9201 data acquisition card system was employed to connect different aforementioned components; LabVIEW 2012 software was used to record and display the data during the experiment. Components of the experimental are shown in Fig. 5.

For the purpose of data collection from piezoelectric actuators, the operation sampling frequency is normally chosen around 10 times higher than the first resonance of the actuator. The first resonant frequency of a similar tube has been identified 941 Hz [25]. Therefore, a sampling frequency of 10 kHz or a sampling time of 10-4s was chosen. Three different triangular voltage functions were used in experiments, with an identical amplitude of 100 V and frequencies of 60 Hz, 80 Hz, and 100 Hz.

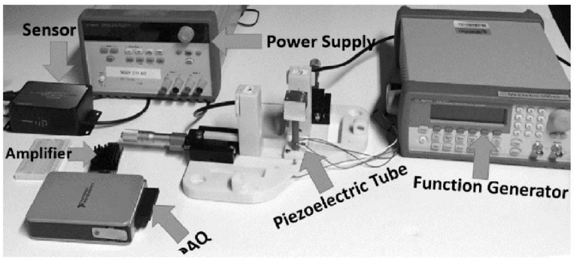

Fig. 1 Components of the experimental setup

IV. RESULTS AND DISCUSSION

A sample of the triangular voltage function is shown in Fig. 6. The resultant displacement of the piezoelectric actuator in microns was plotted against the applied voltage for one and one-hundred cycles in Fig. 4. The data shown by red dashed line have been post-processed, using a finite-impulse-response filter, inspired by Hanning window with three coefficients was employed to reduce measurement noise:

$$xfiltered(k) = \frac{1}{4}x(k) + \frac{1}{2}x(k-1) + \frac{1}{4}x(k-2). \qquad (1)$$

It was observed with the increase of voltage, the displacement increases too. However, when the voltage went back down, the displacement did not take the same path as it did when it increased. This phenomenon is commonly referred as the hysteresis and is caused by polarization of microscopic particles [32]. Although, the loop is in fact influenced by hysteresis, vibration and creep [33].

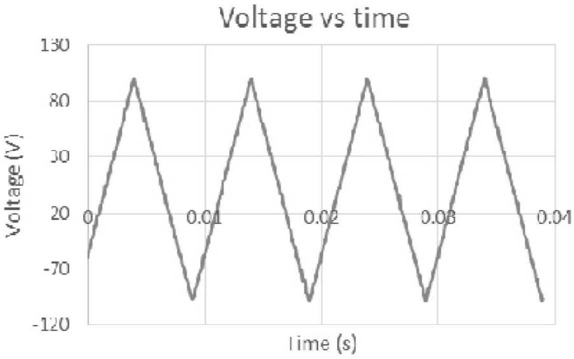

Fig. 6 **A sample voltage function**

Triangular voltage functions are equivalent to a series of sinusoidal functions, according to Fourier series, as shown in (2):

$$\begin{aligned} x(t) &= \frac{8}{\pi^2}\sum_{k=0}^{\infty}\frac{(-1)^k}{(2k+1)^2}\sin\left((2k+1)(2\pi ft)\right) \\ &= \frac{8}{\pi^2}\left(\sin(2\pi ft) - \frac{1}{9}\sin(2\pi ft) + \ldots\right). \end{aligned} \qquad (2)$$

Consequently, each triangular function can excite an infinitive number of vibrational modes and result in a change in the tube vibrational response. This change is dependent on the number of excited frequencies in the vicinity of tube natural frequencies, their corresponding amplitude, and their closeness to the natural frequencies. Such changes in tube vibrational behavior can be observed in Fig. 8, where the loop becomes wider and more pronounced as the frequency of the applied voltage increases. This change might be interpreted as frequency-dependent dynamics of hysteresis [34] which, in fact, seems to be mainly inherited by vibrations rather than hysteresis. Fig.7 depicts the change of loop width for three different frequencies to illustrate the effect of excitation frequency on the actuator's response.

In right hand side diagrams of Fig.8, the loop seems to be thicker. This thickness is a result of the gradual loss of the amplitude in sequential loops during operation, namely creep. Creep is the result of the remnant polarization of microscopic particles within the piezoelectric material [35]. Amplitude loss of different loops shown in right-hand side diagrams of Fig.8 have been depicted in Fig.9. These results show that the creep is more dominant at lower frequencies.

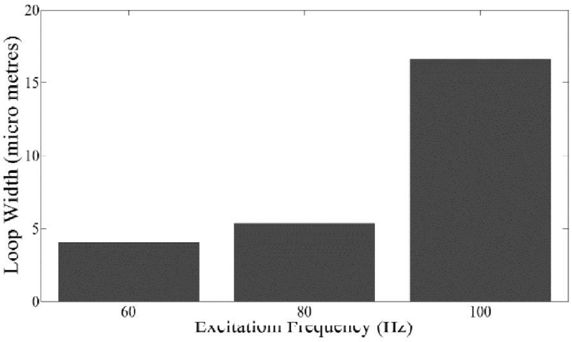

Fig. 7 **Maximum loop width at different excitation frequencies**

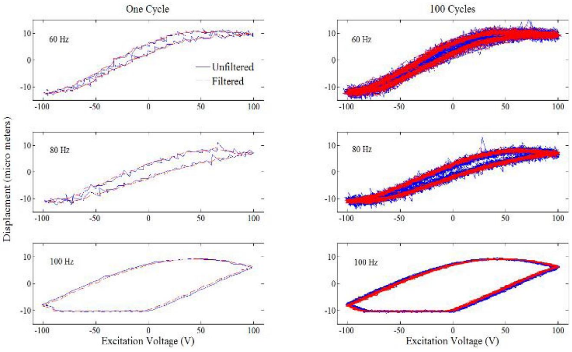

Fig. 2 **The displacement plotted against voltage for the three frequencies**

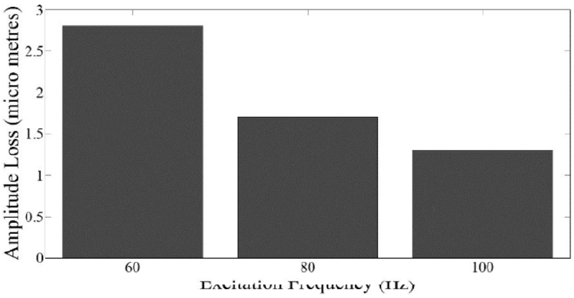

Fig. 3 **Amplitude loss in 100 cycles at different excitation frequencies**

CONCLUSION

In this research, the dynamics of a piezoelectric tube actuator was experimentally investigated using an innovatively designed experimental setup and three research outcomes were achieved:

(i) It was observed that radial displacement of a piezoelectric tube actuator increases/decreases with the increase/decreases of the applied voltage on the actuator. However, decreasing and increasing paths starting/ending at the same points are different and form a loop collectively. Similar observations have been reported in the literature for other types of piezoelectric actuators (e.g. stacks) under the general title of hysteresis, but not for tube actuators. Some research papers, based on experiments carried out at fairly low excitation voltage amplitude and frequencies, have shown the hysteretic behavior of piezoelectric tube actuators is negligible. This paper shows that hysteresis is considerable in piezoelectric tubes at least in the amplitude and frequencies investigated in this research.

(ii) It was observed that the voltage-displacement loop becomes wider with the increase of frequency. The same observation has been reported in some research papers for other types of piezoelectric actuators. This behavior has been called frequency-dependent hysteresis with no physics-based explanation or justification. However, this observation was appropriately explained in this paper as a consequence of vibration.

(iii) It was observed that displacement amplitude decreases as operation goes on, while the amplitude of excitation voltage is consistent. This observation matches with creep phenomenon. Experimental results illustrates that creep is more significant at lower frequencies.

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