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CHARACTERISTICS OF SMART PIEZOELECTRIC ACTUATORS FOR PRECISE MOTION APPLICATIONS

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In this paper, the static and dynamic characteristics of piezoelectric actuators (micromanipulator) are investigated theoretically and experimentally. A physical measurement setup is established for bimorph bending actuators. The actuator deflection is calculated for different driving voltages and compared with the measured values. Transient response due to a step input was very fast, the bandwidth obtained was 101Hz.The Transient, and frequency responses are obtained under different operating conditions.

KEYWORDS: *Piezoelectric actuator, Bimorph*

NOMENCLATURE

α *(x)*	The bending angle at any position x (rad)	*P*	vector of electrical polarization (C/m^2)
d_{31}	Piezoelectric Coefficient (mm/V)	*V*	Applied voltage (V)
E	vector of electric field (V/m)	*W*	Width of piezoelectric actuator (mm)
H	Thickness of piezoelectric actuator (mm)	δ *(x)*	The deflection at any position x (mm)
L	Length of bimorph actuator (m)		

1. INTRODUCTION

Piezoelectric materials are a good choice for systems such as micromanipulators due to their fast reaction times and miniaturization possibilities [1]. Piezoelectric actuators are becoming increasingly important in today's positioning technology [2]. Piezoelectric bending actuators, such as bimorph has been widely used in areas related to precision position control, loud-speakers, vibration damping, noise control, relays, phonograph pick-up, acoustics, and pressure sensing [3]. Piezoelectric actuators have several advantages such as quick response, large generative force, and high electromechanical coupling [4].This research presents a single-degree-of-freedom micromanipulator suitable for space robots applications requiring lightweight, simplicity, and immunity from magnetic fields [5]. End effectors of space-based robots must also be simple and lightweight. Therefore, a piezoelectric bending actuator is an ideal solution for an end effector. An Important characteristic of a piezoelectric bending actuator is the deflection of the bender's tip dependent on an alternating driving voltage. Many studies have been done on studying the behavior of piezoelectric actuators; the investigation of the nonlinear behavior of piezoelectric bimorph structures under exposure to high electric fields takes place both, in analytic and experimental form [6]. The modeling of asymmetrical piezoelectric bimorph structures is discussed and the static behavior regarding the expected bending moment is determined [7]. An analytical description of the free tip deflection of a piezoelectric bimorph by means of matrix calculus is presented [8]. The universal deformation state equations to trimorph bending structures are extended [9, 10]. The Free tip deflection of piezoelectric multilayer beam bending actuators under the influence of an electrical load is presented [11]. The dynamic behavior of a bimorph bending structure excited to bending vibrations by external harmonic forces, bending moments, pressure loads and electrical driving voltages is described [12]. A dynamic driven bimorph with a flexible plate attached at the free bender's tip is extended [13]. The system of differential equations describing the dynamics of a bimorph is formulated [14].

The present work aims to evaluate the behavior of the piezoelectric micromanipulator under different input voltages. This micromanipulator is suitable for handling small objects. Section 2 presents the basics of bimorph actuators and the equations of deflection and bending. Section 3 presents the experimental setup with all system components. Section 4 contains theoretical and experimental results and discussion. Section 5 contains the mechanism of micromanipulator. Finally a conclusion of this work is given in section 6.

2. PIEZOELECTRIC BIMORPH BENDING ACTUATOR

Bimorph actuator is one of the most widely used bender actuators in both academic studies and industrial applications. The application of bimorph actuators includes piezoelectric switches, relays, valves, pumps, motors, printer heads, piezoelectric fans and quick focusing lens. The bimorph actuator is usually fabricated by sticking two piezoelectric plates. It has two configurations different in poling direction and wire connections: series and parallel. The series bimorph is antiparallelly poled and wire connected at the top and bottom electrode. The parallel bimorph is unanimously parallelly poled and wire connected at the top, inner and bottom electrodes. The top and bottom electrodes are applied with the same electric potential [15]. Bimorph actuator is a special case of multilayer bending actuator. The basic geometry of bimorph actuator is shown in Fig. (1). In this figure two piezoelectric layers are bonded together in the same polarization. The basic dimensions and extensive parameters are appeared. After applying an electric field, the bimorph actuator will be deflected as shown in Fig. (2).

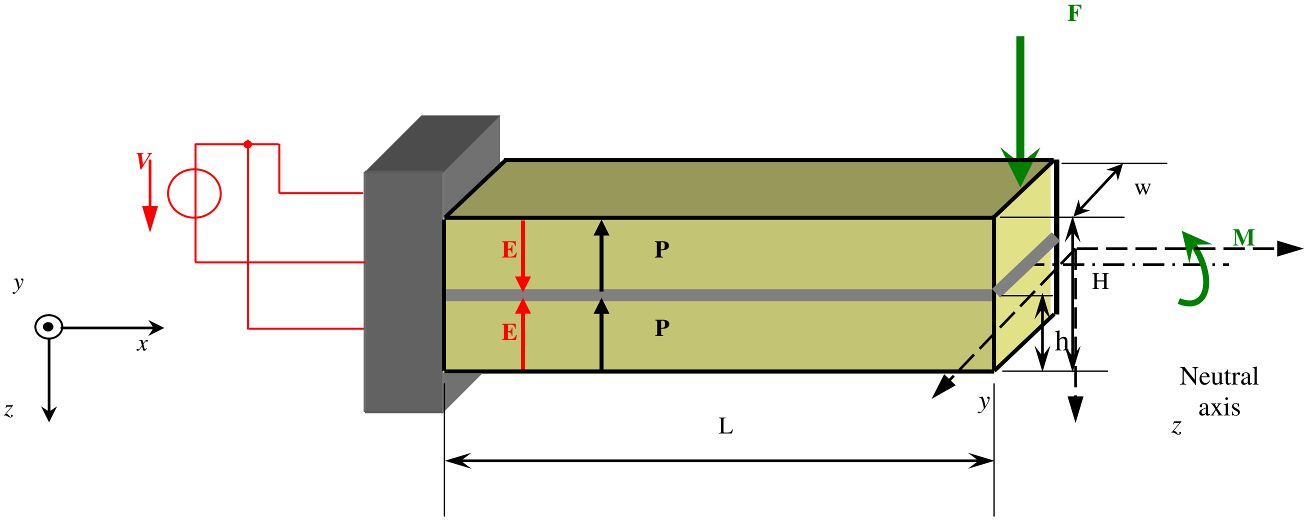


Figure (1) Basic dimensions, extensive parameters, polarization, and applied electric field acting on the Bimorph actuator

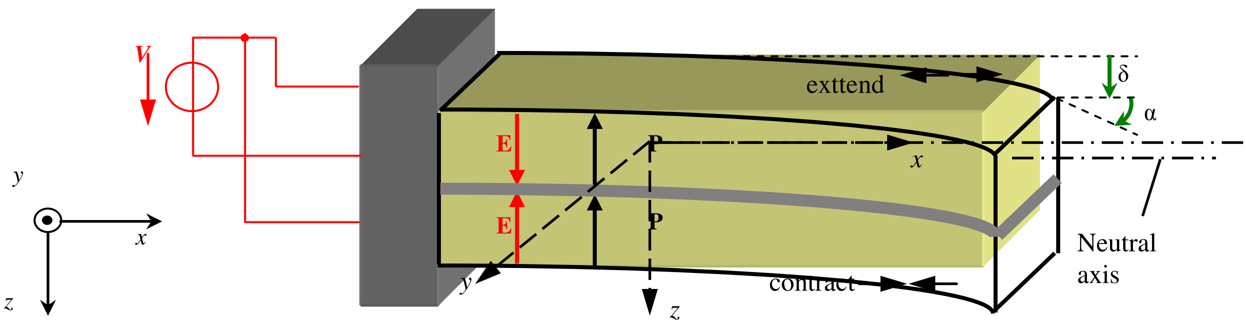


Figure (2) Basic intensive parameters of Bimorph actuators after applying electric field

$$\delta(x) = \frac{3 * d_{31} * x^2}{H^2} * V \;, \qquad (1)$$

$$\alpha(x) = \frac{6 * d_{31} * x}{H^2} * V \;, \qquad (2)$$

The analytical bending curvature and analytical bending angle of the bimorph system are given by [16].

3. EXPERIMENTAL SETUP

The complete experimental setup of the piezoelectric bimorph actuator including all components and sensors is clearly shown in Fig. (3). The apparatus consists of a piezoelectric bending actuator [16], mounted to a mechanical breadboard and driven by a piezo-linear amplifier (Model EPA 007). The EPA-007 is a very compact high voltage linear non-inverting amplifier [17], which is used as a high voltage drive source for the piezoelectric actuating device. The manipulator position is measured using a commercial high-resolution capacitive position sensor mounted on a carriage moving with lead screw [18]. A DC power supply and function generator are used to generate drive voltages to the piezo driver. A piezoelectric bending actuator consists of two layers of piezoelectric material bonded together with opposite polarity in the form of a cantilever beam. The application of an electric field to the actuator causes one layer to extend slightly and the other layer to contract slightly in *x* direction as shown in Fig. (2). The differential length causes the beam to bend towards the contracting layer. By regulating the applied electric field precisely; it is possible to control the movement of the beam tip. The tip of this particular bimorph actuator has a range of motion of ± 1.26 millimeters [17].

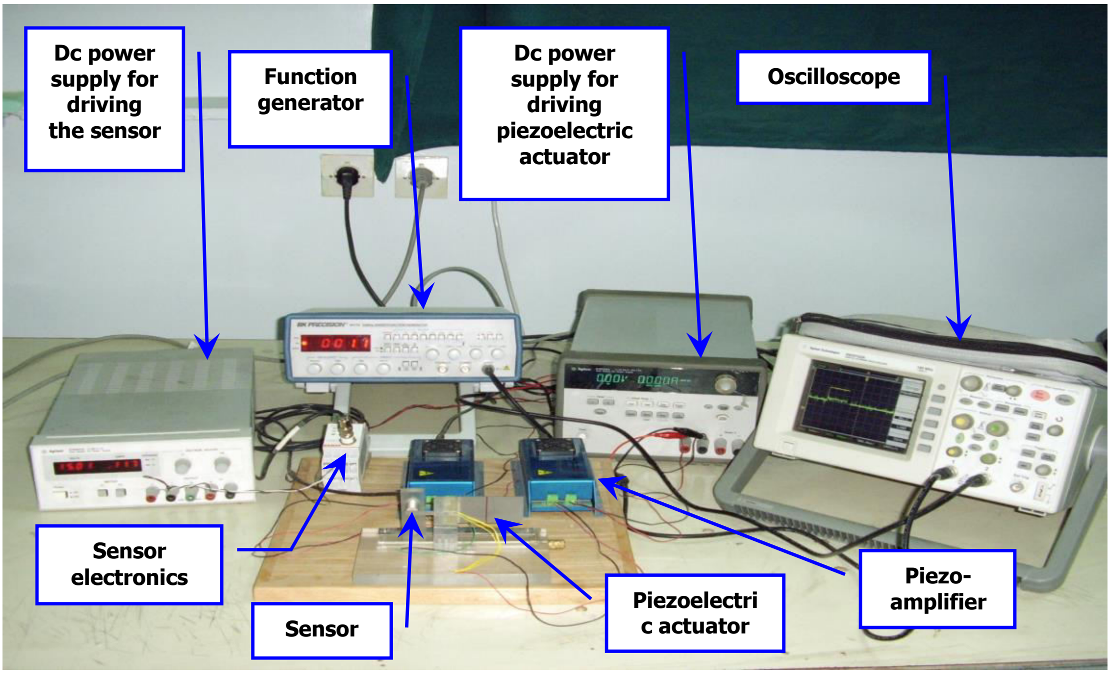


Figure (3) Photographic view of the experimental setup

A general layout of the experimental setup is shown in Fig. (4). A Piezoelectric actuator is driven by applying a voltage V to have a certain deflection δ, at the tip of the actuator measured by a position sensor, carried on a moving carriage. A lead screw of 1 mm pitch is used in moving the carriage along the length of the actuator. Calibration curve of the sensor is shown in Fig. (5).

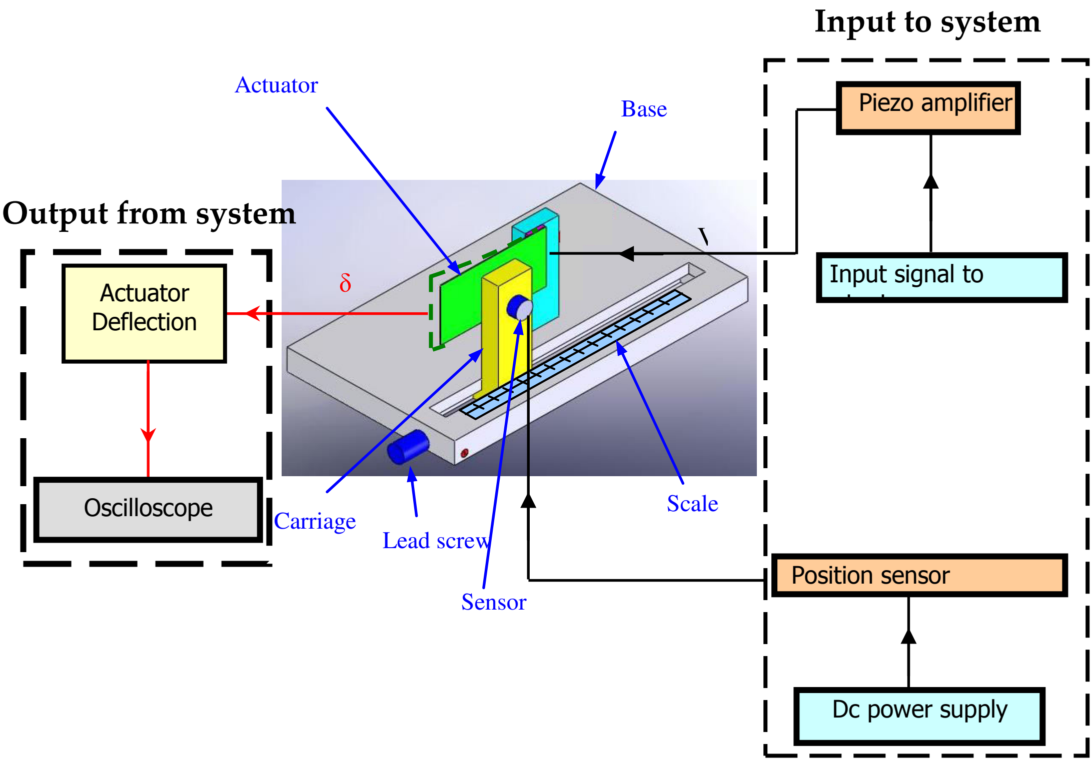


Figure (4) General layout of the experimental setup

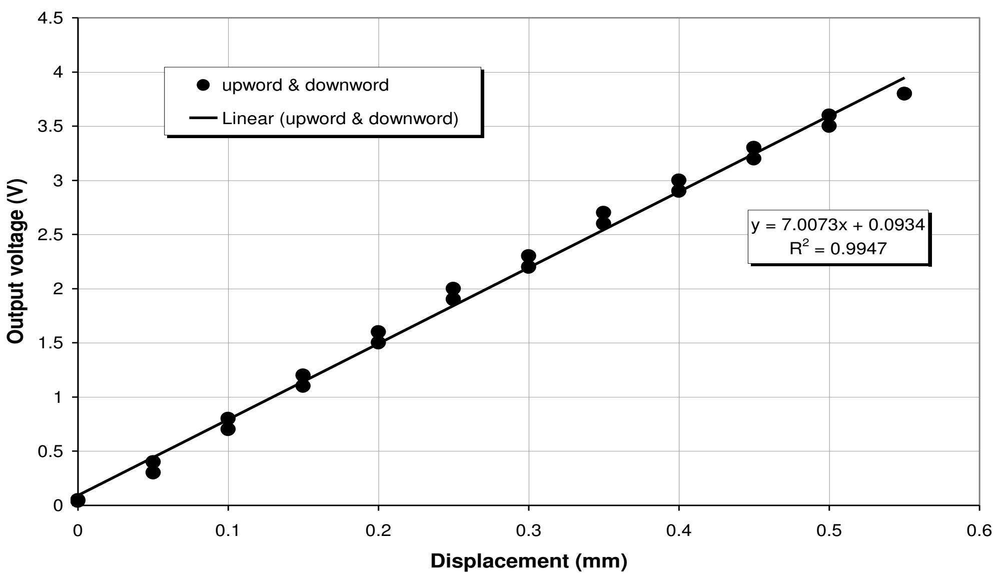


Figure (5) Calibration curve of the position sensor

4. RESULTS AND DISCUSSION

The approximate linear input-output relationship between the applied voltages V to bimorph actuator and the output deflection $\delta(x)$ was measured, as diagrammed in Fig.(6). This relation shows the static displacement of a cantilevered bimorph actuator at the tip position *(x=L)*. Figure (6) indicates that the displacement is linearly proportional to the applied voltage.

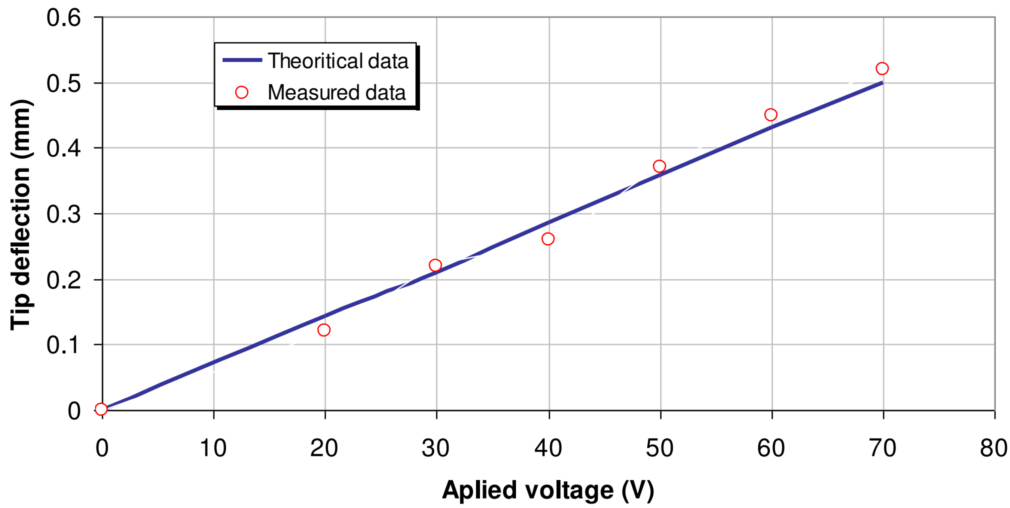
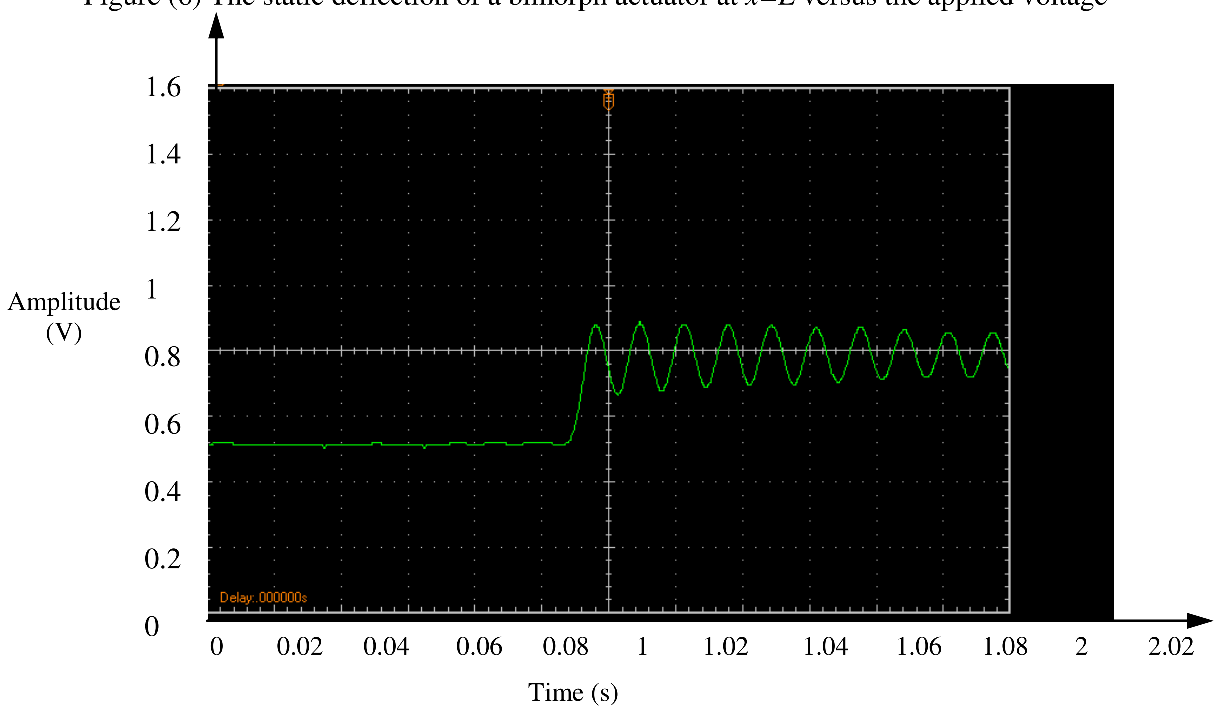
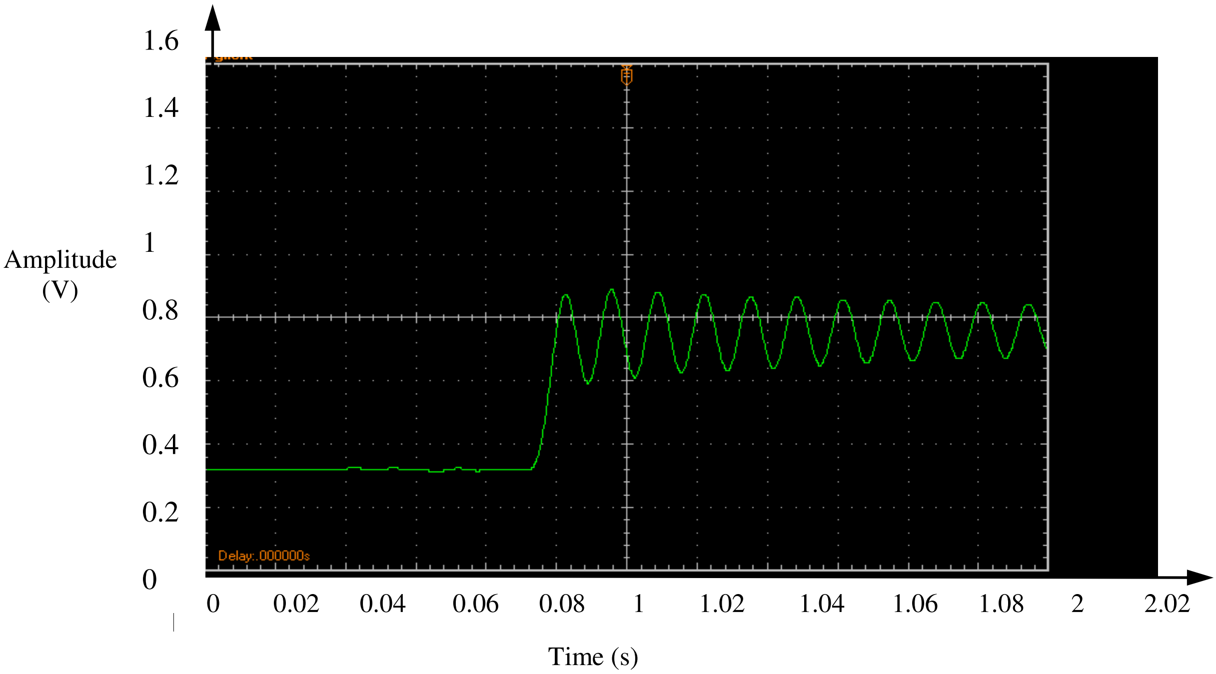


Figure (6) The static deflection of a bimorph actuator at *x=L* versus the applied voltage



(a)



(b)

Figure (7) Transient response due to step different voltages (a), (b)

The displacement response of the actuator due to different voltages are shown in Fig. (7) (a), (7) (b) respectively. From the measurement result in Fig. (7) (a) the rise time is approximately 5.8 ms and 6.1 ms in Figure (7) (b).

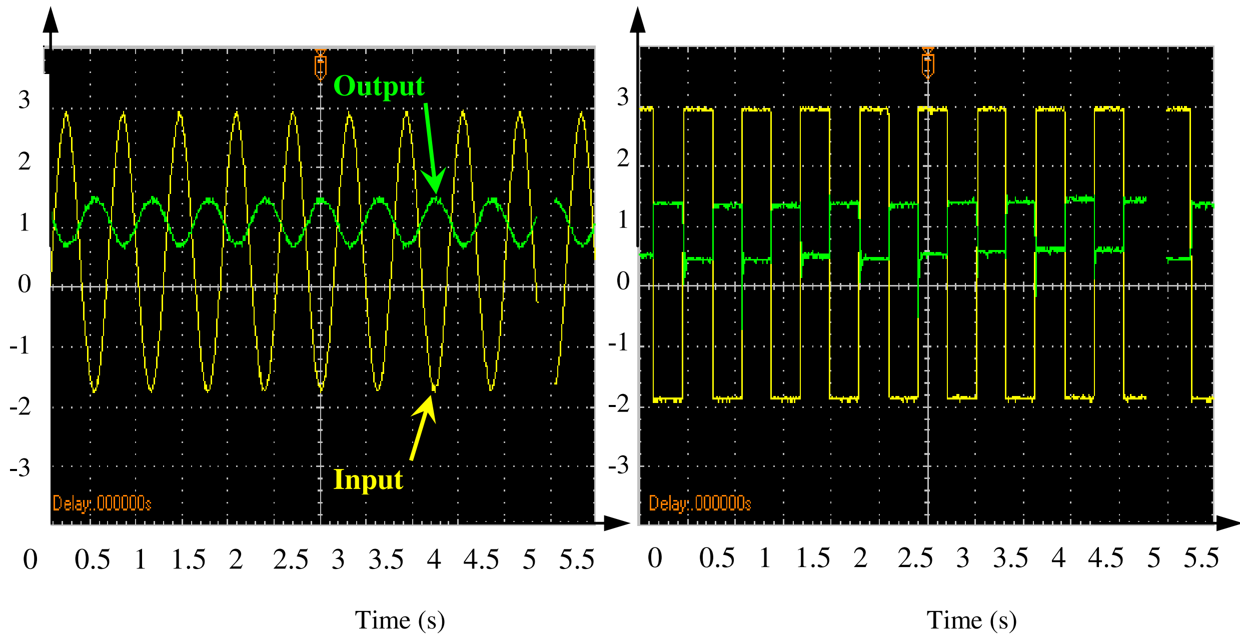


Figure (8) (a) Sine wave signal v =3 V,f =1Hz (b) Square wave signal v =3 V,f =1H

Figure (8) shows the representive dynamic displacement response under different Ac driving signals of the actuator where the frequency and the amplitude of the driving signals are 1 Hz and 20 V, respectively.These results are measured using osilliscope (DSO3152A Agilent Technologies). One can clearly see that in the output response of the square-wave a fast transient vibration accompanying displacement overshoot at the front edge of the square –wave driving voltage. Sine-wave output signals shows a good response rather than square-wave signals. Therefore,it is better to select a sine –wave as a control signal for dynamic precsion positioning.

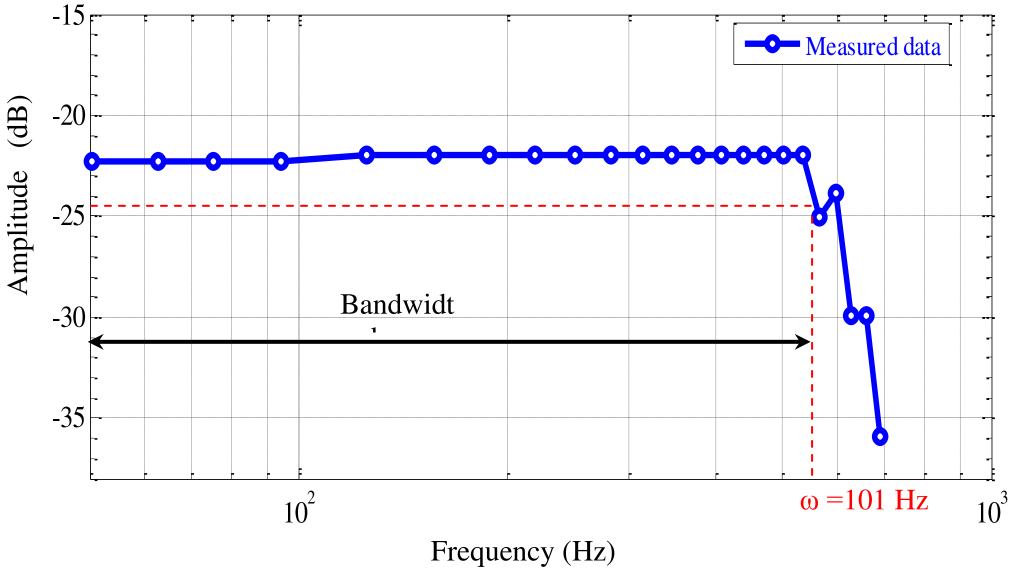


Figure (9) Variation of the deflection with the frequency for bimorph actuator

The Frequency response of the tip is measured in the laboratory with an input signal of 5 V in the frequency range : 0.2-110 Hz, and the results are shown in Fig. (9). The bandwidth estimated from the obtained results is 101 Hz for the bimorph actuator. In Fig. (9) the peaks and valleys show the poles and zeros of piezoelectric transfer function, where the mechanical behavior of the piezoelectric actuator is modeled by a single mass-spring-damper system.

5. MECHANISM OF THE PROPOSED MICROMANIPULATOR

Figure (10) illustrates a two-fingered parallel micromanipulator with a position sensor at the tip of each fingers. Each finger is basically expressed with a piezoelectric bimorph actuator. The maximum displacement of the actuator is approximately ±1.26 mm. Accordingly , the resulting actuator tip is sufficient for grasping small objects. To compensate for small displacement of the finger, one of the fingers is fixed and the other is supported on a carriage moving on a lead screw of 1 mm resolution. Experiment with a small object (strain gage) is performed. The size of the strain gage is: 17.5 mm × 7.5 mm × 0.1 mm (length, width, and thickness).By applying the same voltage to each fingers with a gap of 0.1 mm ,a small object such as the strain gage can be carried with those two parallel piezoelectric bimorph fingers.

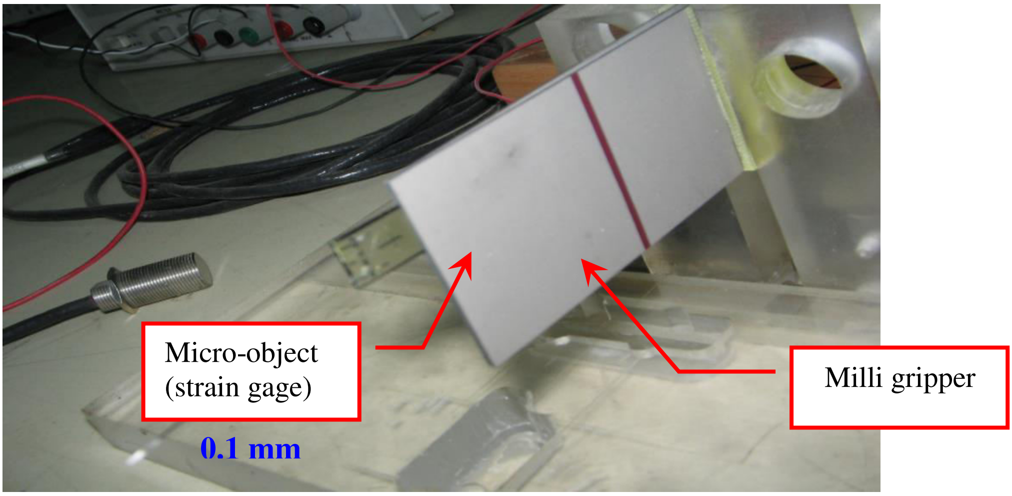


Figure (10) The micromanipulator carries a small object (strain gage)

6. CONCLUSION

The deflection of piezoelectric actuators is obtained theoretically and experimentally with good agreement. The transient response due to a step input is measured, and the results give a fast rise time, where a Bandwidth of 101 Hz.

7. REFERENCES

[1] Ricardo Pérez, Joël Agnus, Cédric Clévy, Arnaud Hubert, and Nicolas Chaillet "Modeling, Fabrication, and Validation of a High-Performance 2-DoF Piezoactuator for Micromanipulation", IEEE/ASME transactions on mechatronics, Vol. 10, no. 2, April 2005

[2] Jing-Chung Shen , Wen-Yuh Jywe , Huan-Keng Chiang , Yu-Ling Shu "Precision tracking control of a piezoelectric-actuated system", Precision Engineering, Vol. 32, pp , 71–78 , (2008).

[3] Qing-Ming Wang, Xiao-Hong Du,Baomin Xu, and L. Eric Cross "Electromechanical Coupling and Output Efficiency Bending Actuators", IEEE transactions on ultrasonics, ferroelectrics, and frequency control, Vol. 46, no. 3, may 1999.

[4] Kui Yao,weiguang Zhu,Kenji Uchino,zhe Zhang,andLeong Chew Lim. " Design and Fabrication of a High Performance Multilayer Piezoelectric Actuator with Bending Deformation", IEEE transactions on ultrasonics, ferroelectrics, and frequency control, Vol. 46, no. 4, july 1999.

[5] James B. Dabney and Thomas L. Harman, "Prototype Micromanipulator of Space Robotics Applications", ISSO Annual Report, (2006).

[6] Q. M. Wang; Q. Zhang; B. Xu; R. Liu; L. E. Cross. Nonlinear piezoelectric behavior of ceramic bending mode actuators under strong electric fields.Journal of Applied Physics, Vol. 86, No. 6, pp. 3352-3360, September 1999.
[7] M. Brissaud; S. Ledren; P. Gonnard. Modelling of a cantilever non-symmetric piezoelectric bimorph. Journal of Micromechanics and Microengineering, Vol.13, pp. 832-844, July 2003.
[8] C.Huang;Y.Y.Lin;T.A.Tang. Study on the tip-deflection of a piezoelectric bimorph cantilever in the static state. Journal of Micromechanics and Microengineering, Vol. 14, pp. 530-534, January 2004.
[9] T.S.Low;W.Guo. Modeling of a Three-Layer Piezoelectric Bimorph Beam with Hysteresis. IEEE Journal of Microelectromechanical Systems, Vol. 4, No. 4, pp. 230-237, December 1995.
[10] Q. M. Wang; L. E. Cross. Constitutive Equations of Symmetrical Triple Layer Piezoelectric Benders. IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, Vol. 46, No. 6, pp. 1343-1351, November 1999.
[11] D.L.DeVoe;A.P.Pisano. Modeling and Optimal Design of Piezoelectric Cantilever Microactuators. IEEE Journal of Microelectromechanical Systems, Vol. 6, No. 3, pp. 266-270, September 1997.
[12] J.G.Smits;A.Ballato. Dynamic Admittance Matrix of Piezoelectric Cantilever Bimorphs. Journal of Microelectromechanical Systems, Vol. 3, No. 3, September 1994.
[13] K. Yao; K. Uchino. Analysis on a composite cantilever beam coupling a piezoelectric bimorph to an elastic blade. Sensors & Actuators A, Vol. 89, pp. 215-221, 2001.
[14] A.Fernandes;J.Pouget. Analytical and numerical approaches to piezoelectric bimorph. International Journal of Solids and Structures, Vol. 40, pp. 4331-4352, 2003.
[15] Tao Li , Y.H. Chen, J. Ma "Static and dynamic high voltage limitation of series and parallel bimorph actuators" Mechatronics ,Vol 19,pp 520–528 ,(2009)
[16] Yang Jing, Jianbin Luo, Xiaoxing Yi,Xin Gu "Design and evaluation of PZT thin-film micro-actuator for hard disk drives" Sensors & Actuators,Vol 116,pp 329-335,(2004)
[17] Piezo systems,Inc.catalog available at www.piezo.com
[18] www.kaman.com

(دراسة خواص المشغلات البيزوكهربية الذ كية لتطبيقات ذات حركات دقيقة)

يتناول هذا البحث دراسة الخواص الاستاتيكية والديناميكية للمشغلات البيزوكهربية وقد تم دراستها نظريا وعمليا وقد تم بناء الجهاز الخاص بالبحث موضع الدراسة للمشغل البيزوكهربي ذو الطبقتين,وتم حساب قيمة انحناء المشغل عند ظروف تشغيل مختلفة للجهد الكهربى المدخل وتم مقارنة هذة النتائج المحسوبة بالمعادلات النظرية مع النتائج المقاسة عمليا ونتيجة لذلك لوحظ ان استجابة النظام اللحظية لوحدة ادخال قياسية (الخطوة القياسية) كان سريعا للغاية ,وقد وجد ان حزمة الترددات تقدر ب 101 هرتز.