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EXPERIMENTAL AND NUMERICAL CHARACTERIZATION OF PIEZOELECTRIC MECHANISMS DESIGNED USING TOPOLOGY OPTIMIZATION

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Abstract. *Multi-actuators piezoelectric devices consist of a multi-flexible structure actuated by two or more piezoceramic portions, whose different output displacements and forces are tailored according to the excitation properties of the piezoceramic materials and the desired working locations and directions of movement. Such devices have a wide range of application in performing biological cell manipulation, for microsurgery, and in nanotechnology equipment, and the like. However, the design of multi-flexible structures is a highly complex task since the devices have many degrees of freedom and, employ a variety of piezoceramics, requiring a carefully tune of the movement coupling among the device parts to prevent motion in undesirable directions. In prior research, topology optimization techniques have been applied to design these devices with minimum movement coupling among the piezoceramic parts. In this work a number of these devices were manufactured and experimentally analyzed to validate the results of the topology optimization. X-Y nanopositioners consisting of two piezoceramic portions were addressed and designs considering low and high degrees of coupling between desired and undesirable displacements were investigated to evaluate the performance of the design method. Prototypes were manufactured in aluminum using a wire EDM process, and bonded to piezoceramics (PZT5A) polarized in the thickness direction and working in d31 mode. Finite element simulations were carried out using the commercial ANSYS software application. Experimental analyses were conducted using laser interferometry to measure displacement, while considering a quasi-static excitation. The coupling between the X-Y movements was measured and compared with FEM results, which showed that the coupling requirements were adequately achieved.*

Keywords: *Piezoelectric Actuators, MEMS, Nanopositioners, Topology Optimization, Laser Interferometry*

1. Introduction

Microdevices have a wide range of applications in precision mechanics (Smith and Chetwynd, 1992) such as cell manipulation, microsurgery tools, nanotechnology equipment, electronic microscopy instruments, lens positioner for laser interferometer, and mainly microelectromechanical systems (MEMS) (Ishihara et al., 1996; Reynaerts et al., 1998). Therefore, it consists in a technology in development whose applications are growing in the world. However, the development of these micro-tools requires the design of micromechanisms with many degrees of freedom that perform complex movements without presence of joints and pins, due to manufacturing constraints of micro-tools scale. This can be achieved by applying the compliant mechanism technology. In a compliant mechanism the movement is given by the structure flexibility rather than the presence of pins and joints (Howell, 2001), which makes possible to transmit nanometers and micrometers displacements.

The microdevices considered in this work (Ishihara et al., 1996; Reynaerts et al., 1998) consists in a compliant mechanism (multi-flexible structure) actuated by two or more piezoceramics that generates different output displacements and forces in different specified points of the domain and directions, for different excited piezoceramics. We will call this microdevice a multi-actuated piezoelectric flextensional device or piezoelectric mechanism (Claeyssen et al., 2001). The multi-flexible structure acts as a mechanical transform by amplifying and changing the direction of the piezoceramics output displacements. Figure 1 illustrates two examples of this kind of device: a XY nanopositioner and a microgripper with 3 degrees of freedom (X and Y displacements, rotations, and open/close movement of gripper jaw).

In the piezoelectric micro-tool design, since many piezoceramics are involved, the movement coupling among them

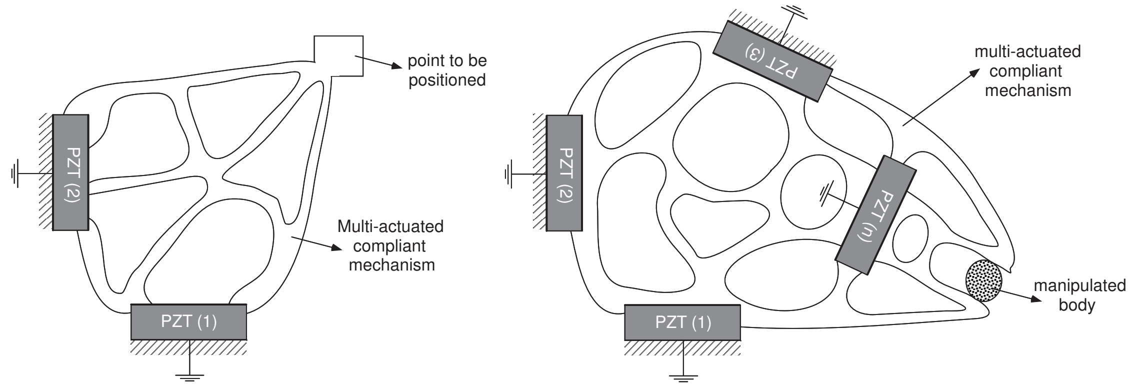


Figure 1. Concept of a multi-actuated flextensional piezoelectric devices. a)XY nanopositioner; b) Piezoceramics are responsible for XY displacements, rotation, and open/close movement of jaw.

becomes critical, that is, movements in undesired directions may appear. Thus, these are very complex devices to be designed by using only physical intuition of the problem. However, some of these multi-actuators, such as XY piezoelectric nanopositioner, have been developed in the past by using simple analytical models, experimental techniques (Chang et al., 1999), or finite element analysis (Claeyssen et al., 2001; Ku et al., 2000). The difficulty in reducing coupling among the movements motivated that a powerful and systematic design method, such as topology optimization, has been recently applied to help to design these devices. Topology optimization is a computational design method that combines optimization algorithms and finite element method (FEM) to find the optimum topology of mechanical parts considering a desired objective function and some constraints. It is a method more general than the parametric and shape optimization methods, where only some dimensions, or the shape of the structure are optimized, respectively. The main advantage of topology optimization is that allows us to find new holes in the structure and, therefore, the weight reduction obtained is much larger than the reduction obtained using other structural optimization methods (Bendsøe and Sigmund, 2003).

In this work, some prototypes of these novel multi-actuated piezoelectric flextensional devices were manufactured and analyzed to characterize their behavior. These prototypes designed by topology optimization (Carbonari et al., 2004) are illustrated in Figure 2, and they consist essentially of PZT5A piezoceramics bonded with epoxy to an Aluminum flexible structure manufactured by using a wire EDM (Electrical Discharge Machining) machine. These flexible structures have complex forms that can provide movements with minimum coupling among actuated piezoceramics.

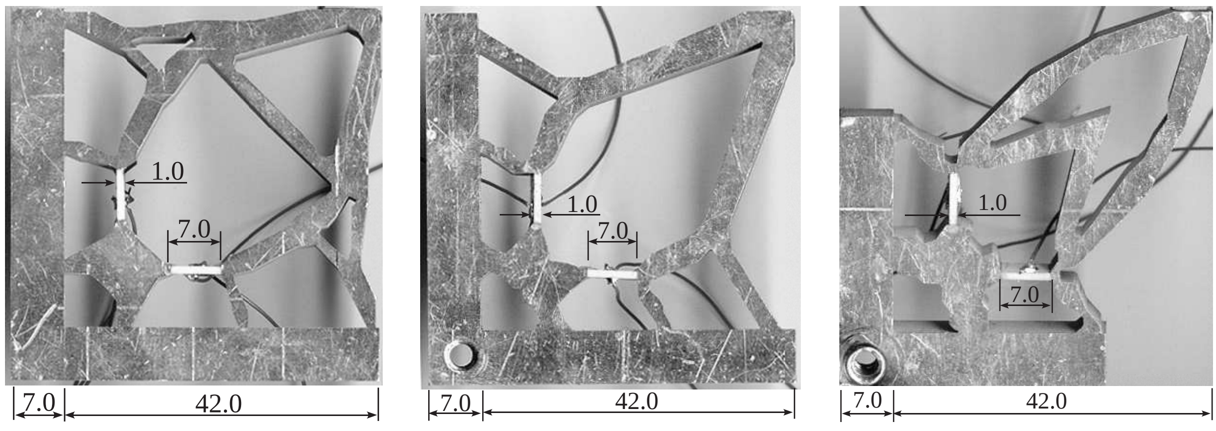


Figure 2. XY nanopositioner prototypes (unit mm); a) XY05b, b) XY05, and c) XY08.

Experimental displacement measurements were performed to evaluate the prototype performances in terms of movement coupling and output displacement. Since these devices are used in static or quasi-static mode (that is, lower than first resonance frequency), displacements and amplifications are determined by considering very low excitation frequencies. To measure piezoelectric mechanisms displacements, a low cost laser interferometer is applied. The principle of laser interferometry for length metrology is to measure displacements from a phase shift of an optical wave due to the movement of a sample. The displacement of the sample is obtained in terms of the known laser wavelength (λ). A phase difference of π corresponds to a displacement of $\lambda/4$. This is a sensitive and efficient method to measure small displacements and deformations. The coupling was measured by measuring displacements in perpendicular directions in the desired point.

These results were compared with the finite element simulation results obtained by using ANSYS^{TM} (Kohnke, 2003) software, a commercial FEM package.

The paper is organized as follows. In section 2a brief description of topology optimization procedure applied to design multi-actuated piezoelectric devices and their assembly is given. In section 3 finite element models of these devices are discussed. In section 4 laser interferometry technique applied to measure displacements and the experimental set up are detailed. In section 5 measured displacements are presented and compared with the simulated results obtained by FEM. Finally in section 6 some conclusions are given.

2. DESIGN OF MULTI-ACTUATED PIEZOELECTRIC DEVICES USING TOPOLOGY OPTIMIZATION

The design of multi-actuated piezoelectric flextensional devices by using topology optimization has been developed in previous works (Carbonari et al., 2004). The performance of these piezoelectric mechanisms depends on the distribution of stiffness and flexibility in the coupling structure bonded to the piezoceramics, which is related to the coupling structure topology. The main difficulty is to reduce the movement coupling among piezoceramics, otherwise movements in undesired directions may appear when a piezoceramic is actuated. Therefore, the problem of designing a multi-actuated piezoelectric device is posed as the design of a flexible structure coupled to the piezoceramics that maximizes different output displacements (or grabbing forces) in different specified directions and points of the domain, for different excited piezoceramics, including a coupling constraint among actuated displacements. The flexible structure must be designed together with the attached piezoceramics to take into account their mechanical impedance, otherwise the optimality of the flexible structure design will be compromised (Carbonari et al., 2004). A linear behavior of piezoceramics is considered.

Examples presented herein are limited to two-dimensional (2D plane stress), because they aim mainly micro-tools and MEMS applications and they are easier to manufacture, however, the proposed method is general and can be applied to three-dimensional (3D) models.

Figure 3 illustrates the topology optimization procedure to design a multi-actuator piezoelectric device. First, an initial design domain is defined limited by the device boundary conditions such as regions where there are restraints and applied loads. This domain is discretized into finite elements and it will be an input to the topology optimization software. The software gives as a result an optimized material distribution in the design domain which represents a digital image of coupling structure design. This digital image must be interpreted and a final FEM analysis is usually performed to verify the final design.

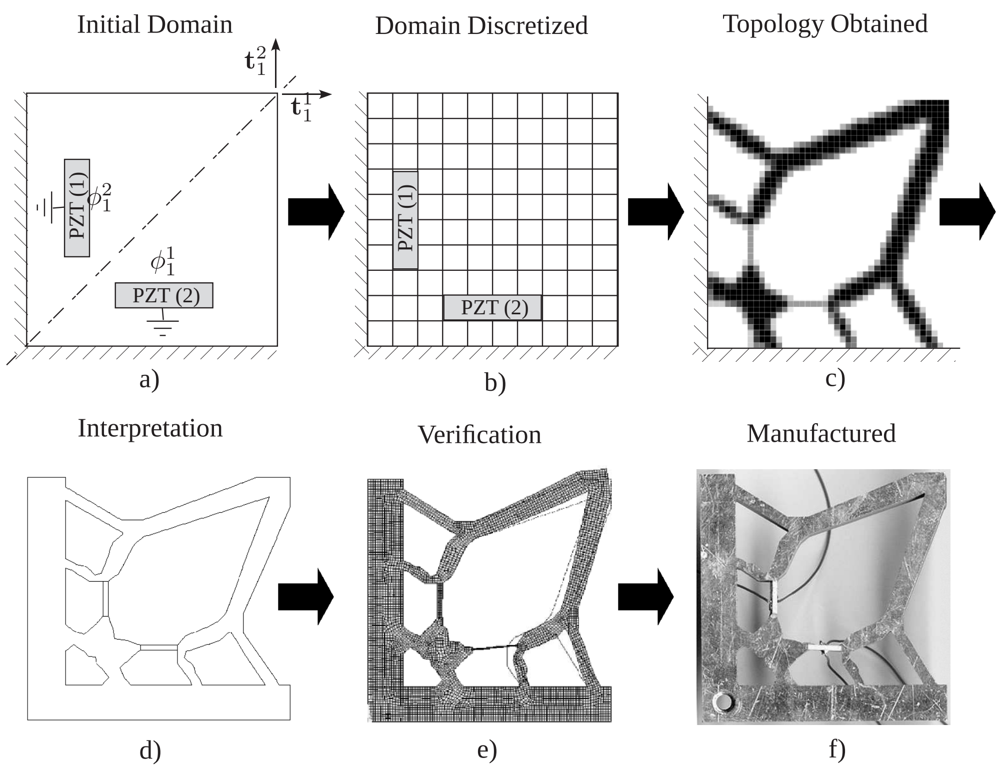
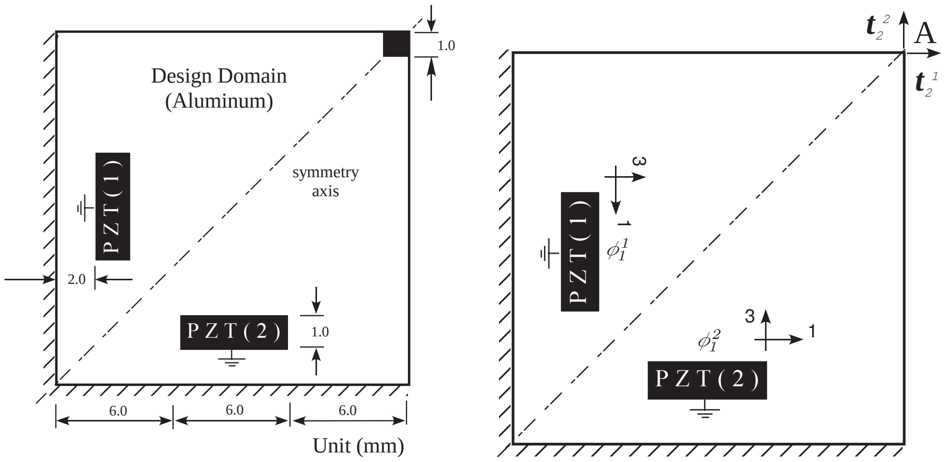


Figure 3. Topology optimization procedure for designing piezoelectric mechanisms. $\triangle u$ is the desired output displacement.

The piezoelectric mechanisms characterized in this work were obtained by considering the design domain shown in

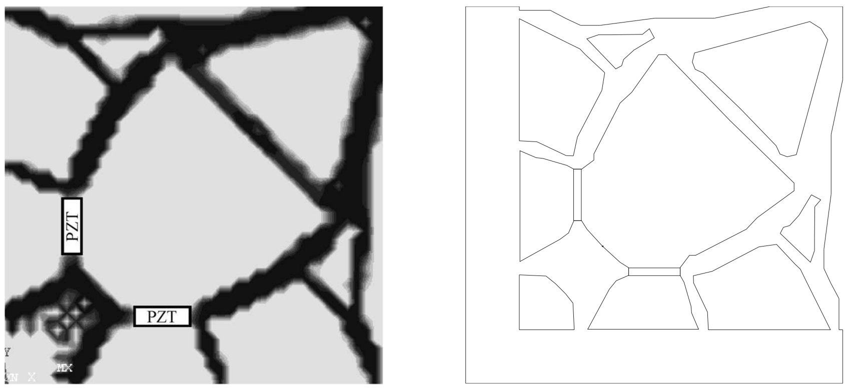
Figure 4. The devices shown in Figure 2 are a XY piezoelectric nanopositioner (Chang et al., 1999) actuated by two piezoceramics. The XY05b nanopositioner is designed by minimizing coupling while in the design of nanopositioner XY05 and XY08 the coupling minimization is not taking into account.



a) b)

Figure 4. a) Initial Design domain; b) Design specifications for XY nanopositioners.

The topology optimization results and corresponding interpretations that generated the final designs of these devices are described in Figures 5, 6, and 7. Based on these final designs some prototypes were manufactured to verify their behavior. They are described in Figure 2 and their dimensions are illustrated in Figure 4.



a) b)

Figure 5. a) Topology optimization result for actuator XY05b; b) Corresponding interpretation (CAD design).

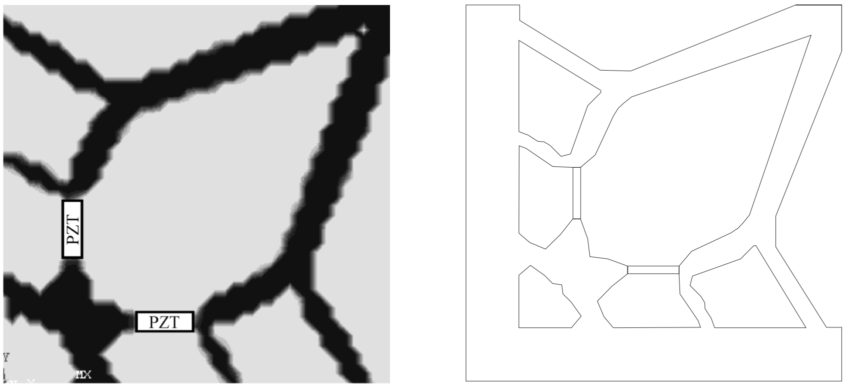
The prototypes are composed of aluminum structures, manufactured by using a wire EDM machine, which are bonded to rectangular PZT5A piezoceramic blocks by using a thin film of epoxy resin (Araldite 502/956). Dimensions of block piezoceramics are shown in Figure 4. These piezoceramics are polarized in the 3-direction and the electrode surfaces are normal to this direction.

3. FINITE ELEMENT ANALYSIS

The manufactured XY piezoelectric devices are modeled by finite element using the software ANSYS^{TM}. Since the devices have a prismatic shape, 2D FEM models were built. Once the depth of actuators is small in relation to their other dimensions the plane stress assumption is adopted. These FEM models are shown in Figure 8. The applied electromechanical boundary conditions and piezoceramic poling directions are the same as described in Figure 4.

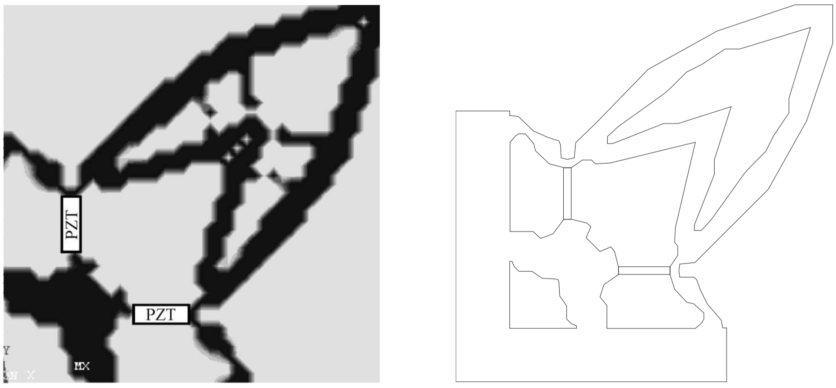
Material properties of piezoelectric ceramic PZT5A and Aluminum are shown in Table 1. The Young modulus and Poisson's ratio of Aluminum are equal to $70\ GPa$ and 0.33, respectively.

Figure 9 shows the Von Mises stress distribution for all XY nanopositioners obtained by using FEM. The maximum stress values occur at the connections between the piezoceramics and the aluminum structure, as expected. For example, considering a voltage applied to the electrodes equal to 100V, the maximum stress value is equal to 1.81 MPa, 1.49 MPa, and 1.39 MPa for XY nanopositioner XY05, XY05b and XY08, respectively.



a) b)

Figure 6. a) Topology optimization result for actuator XY05; b) Corresponding interpretation (CAD design).



a) b)

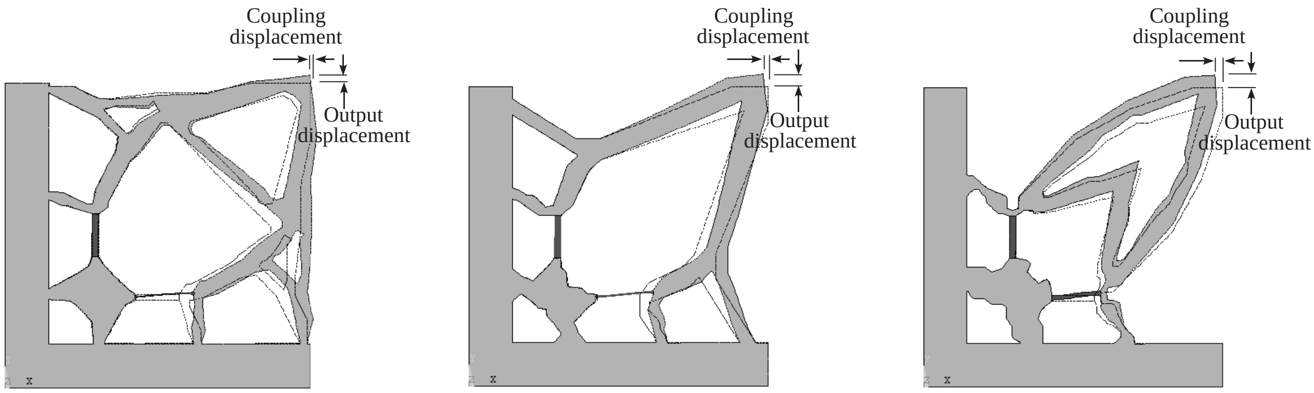
Figure 7. a) Topology optimization result for actuator XY08; b) Corresponding interpretation (CAD design).

4. LASER INTERFEROMETRY

Multi-actuator piezoelectric device displacements are measured by using laser interferometry since it allows us to perform dynamic measurements (static and harmonic) in the kHz range which is the order of the first resonance frequency of these piezomechanisms. The interferometric system setup used is a low cost and very precise to perform these measurements allowing us to measure displacement amplitudes in nanometric range. In this section, the interferometer setup and the laser interferometry principle are described.

Among several interferometric techniques applied to measure displacements of piezoelectric transducers (Monchalin, 1986; Scruby and Drain, 1990) laser interferometry has more precision and resolution (Royer and Dieulesaint, 1986). The principle of laser interferometry used in this work is to measure displacements from a phase shift of an optical wave due to the movement of a sample (Scruby and Drain, 1990; Pan et al., 1990). The displacement of the sample is obtained in terms of the known laser wavelength (λ). A phase difference of π corresponds to a displacement of $\lambda/4$. This is a sensitive and efficient method to measure small displacements and deformations and it was used to obtain dynamic displacement measurements.

A Michelson-type quadrature interferometer, as shown in Figure 10, is applied to measure quasi-static displacement response of piezoactuators in one single point. It uses a He-Ne laser source (λ = 632.8 nm). A half-wave plate (λ/2) is used to control the intensity ratio to reference mirror (R) and sample analyzed (S), which are reflected and transmitted by a polarizing beam splitter (PBS). The convergent lens L1 is applied to focus the laser beam in the reference mirror and sample surface. Between the two beam splitters (BS1 and BS2) there is no interference, because the reflected light from R and S are orthogonal polarized. After the polarizer A1 (at 45^o), the reference and sample lights are in the same polarization, then, there is interference. The light reflected by BS2 passes through a quarter-wave plate (λ/4) at 45^o, which is the π/2 phase shifter, in this application. After the quarter-wave plate the light passes through a polarizer A2 at (at -45^o). The interference patterns acquired by amplified and balanced photo-diodes (PDA1 and PDA2), are shifted by π/2. A convergent lens L2 is applied to expand the laser beam and enlarge the interference pattern on PDA1 and PDA2. The main advantage of the quadrature interferometer is that it is a non-stabilized interferometer less subjected to the environmental vibrations (Scruby and Drain, 1990; Pan et al., 1990).



a) b) c)

Figure 8. Displacement of XY nanopositioner obtained by FEM. a) XY05b, b) XY05, and c) XY08.

Table 1. PZT-5A properties used in software ANSYS.

elastic constant	c_{11}^E	12.10	$\times 10^{10}$N.m^{-2}
	c_{12}^E	7.52	$\times 10^{10}$N.m^{-2}
	c_{13}^E	7.51	$\times 10^{10}$N.m^{-2}
	c_{33}^E	11.10	$\times 10^{10}$N.m^{-2}
	c_{44}^E	2.105	$\times 10^{10}$N.m^{-2}
	c_{66}^E	2.24	$\times 10^{10}$N.m^{-2}
piezoelectric constant	e_{31}	-5.35	C.m^{-2}
	e_{33}	15.8	C.m^{-2}
	e_{15}	12.3	C.m^{-2}
relative dielectric constant*	$\epsilon_{11}^S/\epsilon_0$	916	
	$\epsilon_{22}^S/\epsilon_0$	916	
	$\epsilon_{33}^S/\epsilon_0$	830	
density	ρ	7750	kg.m^{-3}

(*) ϵ_0=8.85$\times 10^{-12}$F.m^{-1}

The electronic apparatus is composed by a digital oscilloscope and a computer, which acquires the signals from channel 1 and 2 from de oscilloscope by a GPIB interface. The piezoactuators are excited by an harmonic 60 Hz cycle sine from 10 V to 220 V (RMS) obtained form electric power net.

5. EXPERIMENTAL AND SIMULATED RESULTS

Since the laser interferometer can only measure displacements and the actuator operate in a static mode, displacement measurements are done considering quasi-static excitation, by applying an harmonic sinusoidal excitation (continuous mode) at 60 Hz. The objective is to compare experimental and numerical displacement in X and Y direction, by considering generated displacement and coupled displacement.

The displacements are obtained from 10 V to 200 V RMS, which gives an amplitude between approximately 14 V to 311 V. This procedure was conducted to determine the linearity displacement response by electric potential. Results are shown normalized at 100 V/mm, because all multiactuators have linear response to displacement. In Table 2 and Table 3 are illustrated experimental and numerical displacements results, respectively.

Table 2. Experimental displacement and coupling results normalized for 100 V/mm.

microactuator	**experimental generated displacement (nm)**	**experimental coupled displacement (nm)**	**coupling rate**
XY05	102	54	53%
XY05b	40	8	20%
XY08	226	123	54%

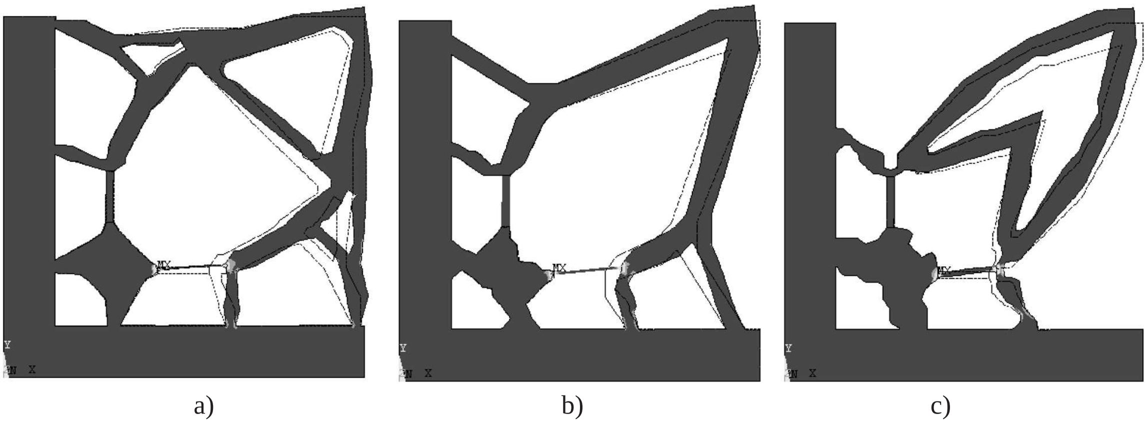


Figure 9. Von Mises stress distribution of XY nanopositioner obtained by FEM. a) XY05b, b) XY05, and c) XY08.

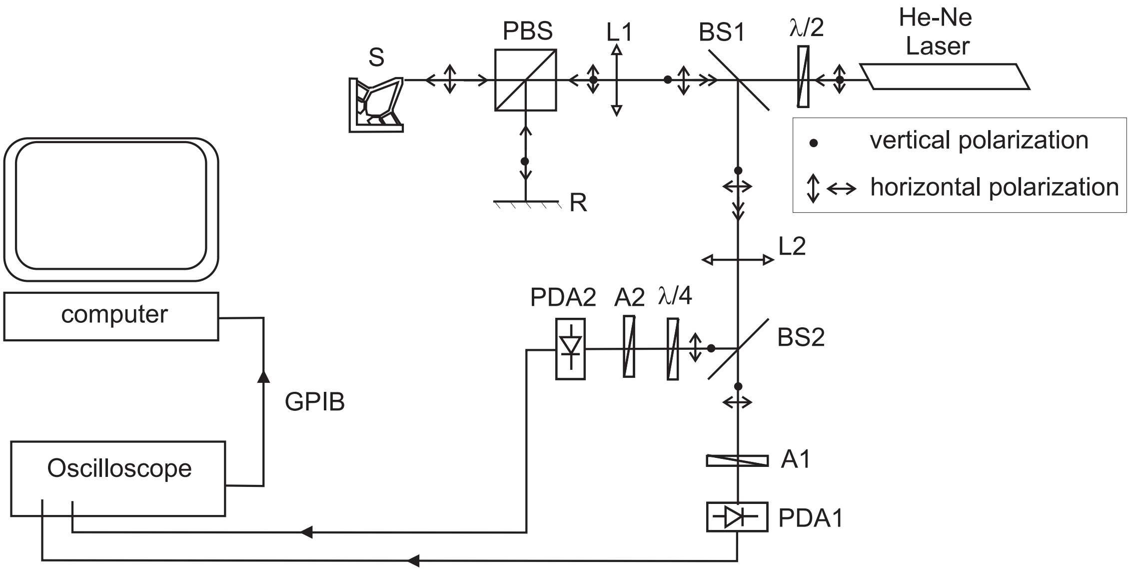


Figure 10. Experimental setup of Michelson-type quadrature interferometer. L1, L2 - convergent lens; BS1, BS2 - beam splitter; PBS - polarizing beam splitter; R - reference mirror; S - sample; $\lambda/2$ - half-wave plate; $\lambda/4$ - quarter-wave plate at 45^o; A1, A2 - polarizing at 45^o; PDA1, PDA2 - amplified photo-diode, GPIB - communication protocol.

These results shown a good agreement between XY05 experimental and numerical generated displacement. However the experimental coupled displacement for same nanopositioner is approximately 100% larger than numerical.

Nanopositioner XY05b, which is designed for low coupled displacement. This nanopositioner shows an good agreement between experimental and numerical results for generated and coupled displacement, as shown in Tables 2 and 3, and also for coupling rate.

Best responses are obtained for nanopositioner XY08. Generated and coupled experimental displacements results are approximately equals to numerical results. However, coupling rate shown an agreement.

Some differences between experimental and numerical results can be dependent of nanopositioner holder. In a future work, new analysis will be conducted to verify the influence of mechanical holder in the microactuators behavior.

Thus, a qualitative analysis for coupling rate for each nanopositioner shows that these devices have the expected behavior as designed by topology optimization.

6. CONCLUSIONS

Novel designs of multi-actuator flextensional piezoelectric devices were successfully manufactured and characterized by using laser interferometer. A low cost Michelson interferometer was used to perform the experimental verification of amplification rate of prototypes. Quasi-static measurements were conducted to characterize piezomechanism behavior. From the results obtained experimental and simulated results matched well showing that FEM models were able to represent the multi-actuator behavior, and that multi-actuator piezoelectric devices designed by topology optimization (which

Table 3. Numerical displacement and coupling results normalized for 100 V/mm.

microactuator	numerical generated displacement (nm)	numerical coupled displacement (nm)	coupling rate
XY05	99.0	27.5	27.8%
XY05b	51.9	8.5	16.4%
XY08	228.9	123.0	53.7%

is based on FEM) perform as predicted in the initial design specifications.

7. Acknowledgments

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8. References

Bendsøe, M. and Sigmund, O. (2003). *Topology Optimization - Theory, Methods and Applications*. Springer, New York, EUA.

Carbonari, R. C., Silva, E., and Nishiwaki, S. (2004). Topology optimization applied to the design of multi-actuated piezoelectric micro-tools. In *Proceedings of Modeling, Signal Processing and Control – 11th SPIE (Annual International Symposium on Smart Structures and Materials)*, volume 5383, pages 277–288.

Chang, S., Tseng, C. K., and Chien, H. (1999). An ultra-precision $xy\theta_Z$ piezo-micropositioner part ii: Experiment and performance. *IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control*, 46(4):906–912.

Claeyssen, F., Letty, R. L., Barillot, F., Lhermet, N., Fabbro, H., Guay, P., Yorck, M., and Bouchilloux, P. (2001). Mechanisms based on piezo actuators. In *Proceedings on Industrial and Commercial Applications of Smart Structures Technologies of 8th SPIE (Annual International Symposium on Smart Structures and Materials)*, volume 4332, pages 225–233.

Howell, L. (2001). *Compliant Mechanisms*. John Wiley & Sons, Inc., New York, USA.

Ishihara, H., Arai, F., and Fukuda, T. (1996). Micro mechatronics and micro actuators. *IEEE/ASME Transactions on Mechatronics*, 1(1):68–79.

Kohnke, P. (2003). *ANSYS 6.1 Help*. On line Manual, Pittsburgh, USA.

Ku, S., Pinsopon, U., Cetinkunt, S., and Nakajima, S. (2000). Design, fabrication, and real-time neural network control of a three-degrees-of-freedom nanopositioner. *IEEE/ASME Transactions on Mechatronics*, 5(3):273–279.

Monchalin, J. (1986). Optical detection of ultrasound. *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, 33(5):485 – 499.

Pan, W. Y., Wang, H., and Cross, L. E. (1990). Laser interferometry for studying phase delay of piezoelectric response. *Japanese Journal of Applied Physics*, 29(8):1570–1573.

Reynaerts, D., Peirs, J., and Brussel, H. (1998). A mechatronic approach to microsystem design. *IEEE/ASME Transactions on Mechatronics*, 3(1):24–33.

Royer, D. and Dieulesaint, E. (1986). Optical detection of sub-angstrom transient mechanical displacements. In *IEEE Ultrasonic Symposium Proceeding*, pages 527–530.

Scruby, C. B. and Drain, L. E. (1990). *Laser Ultrasonics, Techniques and Applications*. Adam Hilger, EUA.

Smith, S. and Chetwynd, D. (1992). *Foundations of Ultraprecision Mechanism Design*, volume 2. Developments in Nanotechnology; Gordon and Breach Science Publishers, Netherlands.