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Development and Characterization of a Unimorph-type Piezoelectric Actuator Applied to a Michelson Interferometer

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Abstract. *A single piezoceramic generates nanometer displacements when a electrical voltage is applied. A way to amplify these displacements is to build a unimorph piezoactuator. Unimorphs are applied to sensors, actuators and hydrophones. In this work, a unimorph-type piezoactuator is developed and characterized. This unimorph consists of a thin glass plate (mirror) bonded on the center of the piezoceramic surface using epoxy resin. The piezoceramic is bonded on its ends to an aluminum block. The transducer developed has different characteristics than a default unimorph once the plate has a lower dimension than the piezoceramic. The actuator development is conducted by combining computational simulation and experimental techniques. First, the proposed prototype is simulated using Finite Element Method (FEM) by considering several ratios between piezoceramic and glass plate length to find the best rate. Modal and harmonic analysis are performed. Experimental verifications are performed measuring prototype displacements by using a laser interferometer considering harmonic excitation. Resonance frequencies are measured by using an impedance analyzer. From these results is determined that if the size of the mirror is increased, the displacement is decreased. The best rate obtained corresponds to a glass plate length equal to 1/3 of piezoceramic length.*

Keywords: *Laser interferometry, piezoactuator, unimorph, finite element method*

1. Introduction

Unimorphs are used as high displacement piezoelectric actuators. Unimorphs are manufactured by bonding a piezoceramic to a non-piezoelectric layer (usually metal), as showed in Fig. (1a). Unimorph maximum displacement is obtained at center of actuator, as showed in Fig. (1b) due to non-piezoelectric layer bonded on piezoceramic. This kind of piezoactuator is often applied to laser interferometer mirrors for environment vibration control (Abe *et al.*, 1982, Ellis, 1999) and liquid viscosity and density measurement (Shih *et al.*, 2001). They have been developed in the past few years by many authors (Idogake *et al.*, 1996, Wang *et al.*, 1999, Yi *et al.*, 2002). Usually a non-piezoelectric layer length is larger than the piezoceramic length. However, in this work it was realized that a non-piezoelectric layer smaller than piezoceramic also generates the same effect. The actuator bends where the layer is fixed, and amplitude displacement is higher than a piezoceramic without layer.

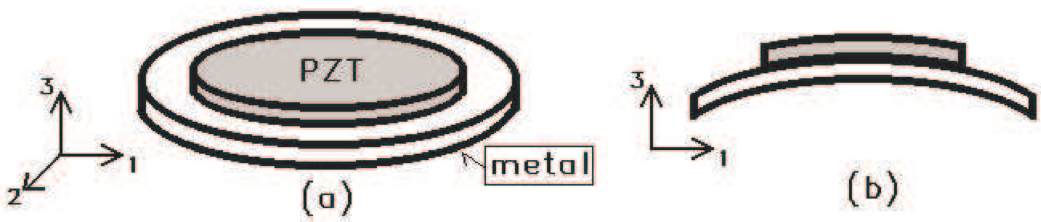
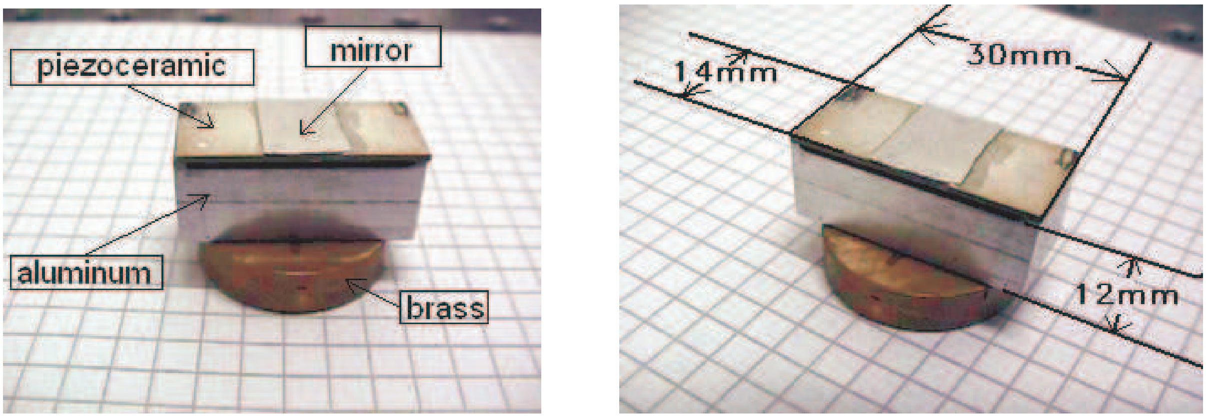


Figure 1. Unimorph piezoactuator: (a) frontal view; (b) excited condition.

The unimorph-type piezoactuator developed and characterized in this work is shown in Fig. (2). The non-piezoelectric layer consists of a tiny mirror (100 μm thickness). It is designed to be applied as a mechanical vibration control in reference mirror of Michelson interferometer as described in Sec. (4). Also, through detailed numerical and experimental analysis, it is shown how to characterize and optimize the actuator.



(a) (b)

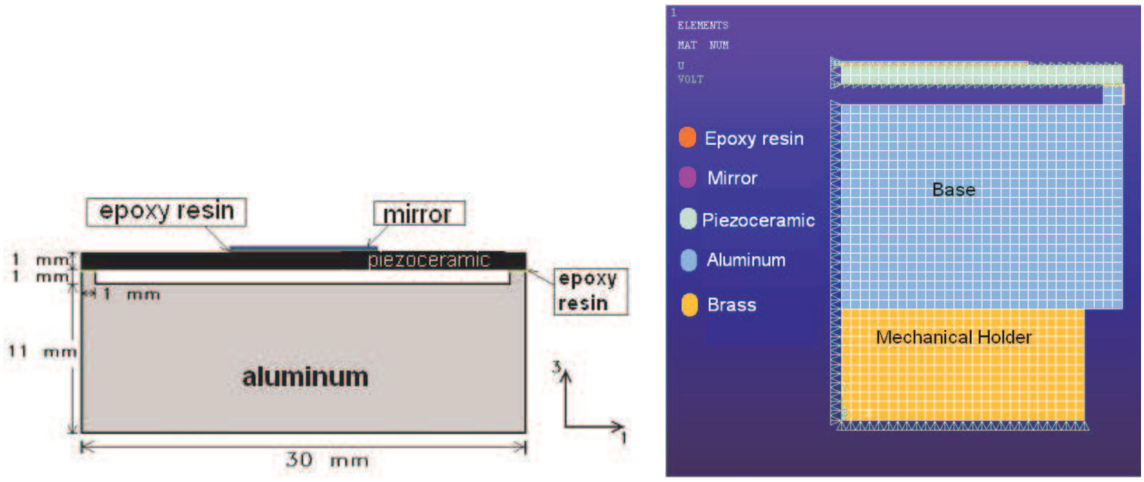
Figure 2. Assembled actuator: (a) components and (b) dimensions.

Application of optical and numerical techniques simultaneously allows us to determine piezoceramic behavior, the importance of the piezoceramic boundary conditions and how to consider and implement them in computational simulations (Nader *et al.*, 2003_A). Then, by aiming to manufacture an actuator with high displacement amplitude at center, four different mirror dimensions (10, 20, 30 and 40 mm) and the way of holding piezoceramic are simulated by finite element method (FEM). Experimental dynamic displacement measurements are done using laser interferometry. These data are compared with numerical results obtained by FEM.

This paper is organized as follows. In section 2, FEM model of unimorph actuator is described. In section 3, interferometric optical principle applied to measure piezoceramic displacements is presented. In section 4, it is discussed how these two methods were combined to evolve the unimorph design. In section 5, the results obtained are shown. Finally, in section 6, some conclusions are given.

2. Finite element method

The unimorph piezoactuator is modeled by finite element using the software ANSYS™. Since the actuator has a prismatic shape, 2D FEM models were built. Once the depth of actuators is small in relation to their other dimensions [Fig. (2b)], the plane stress assumption should be adopted. Complete CAD model is shown in Fig. (3a). The model is built using the actuator symmetry [Fig. (3b)] to reduce computational effort. Electrodes are on both surfaces normal to the *3-direction* (poling direction). Also, brass mechanical holder that restrains the movement in the same direction is considered. Fixed in this holder, there is an aluminum block in which ends the piezoceramic is bonded with epoxy resin. Model built in ANSYS™ software and loads applied are presented in Fig. (3b). In this case, a mirror is covering two thirds of the unimorph surface. All models in this work show the right part of a symetric mechanism.



(a) (b)
(b)

Figure 3. Models used in Finite Element Analysis: (a) 2D 10mm mirror model; (b) Ansys 20mm mirror model.

Material properties used in ANSYS™ of piezoceramic PZT5A, aluminum, brass and epoxy resin are shown in Tab. (1). Damping materials showed in Tab. (1) are determined by technique developed in a previous work (Nader *et al.*, 2003_B).

Table 1. Material Properties of PZT5A, aluminum, brass and epoxy resin used in FEM.

PZT5A	
elastic constants	(10^{10} N.m^{-2})
c_{11}^E	12.1
c_{12}^E	7.54
c_{13}^E	7.52
c_{33}^E	11.1
c_{44}^E	2.11
c_{66}^E	2.26
piezoelectric constants	(C.m^{-2})
e_{31}	-5.4
e_{33}	15.8
e_{51}	12.3
ε^S: dielectric constants	
$\varepsilon^S_{11}/\varepsilon_0$	916
$\varepsilon^S_{33}/\varepsilon_0$	830
density (ρ)	7750 kg.m^{-3}
damping	4.9 x 10^{-8}

aluminum	
Young's modulus (E)	71 x 10^9 N.m^{-2}
density (ρ)	2700 kg.m^{-3}
damping (β)	15 x 10^{-8}
Poisson's ratio (σ)	0.33

brass	
Young's modulus (E)	100.00 x 10^9 N.m^{-2}
density (ρ)	8400 kg.m^{-3}
damping (β)	15 x 10^{-8}
Poisson's ratio (σ)	0.34

epoxy resin	
Young's modulus (E)	4.25 x 10^9 N.m^{-2}
density (ρ)	1160 kg.m^{-3}
damping (β)	40 x 10^{-8}
Poisson's ratio (σ)	0.38

4. Laser interferometry

Optical techniques are measurement tools more and more applied in precision engineering due to its high resolution, precision, accuracy and sensitivity. Laser interferometry is an optical technique that allows us to measure displacements in a range between subangströms (Vilkomerson, 1976, Royer and Dieulesant, 1986) up to a set of ten meters (Scruby and Drain, 1990, Royer, 1997) without mechanical contact.

Unimorph piezoactuator displacements are measured using laser interferometry since it is capable of performing dynamic harmonic measurements. In this work measurements are done in a range of 100 Hz to 6000 Hz, because first resonance frequency of unimorph piezoactuator is close to 3400 Hz. The interferometric system setup used is a low cost and very precise one that allows us to perform measurements of displacement amplitudes from nanometric range to micrometric range. In this section, the interferometer setup and the laser interferometry principle are described.

Interferometer setup shown in Fig. (4) is a Michelson-type interferometer (Djelouah and Baboux, 1992). It uses a He-Ne laser source (λ = 632.8 nm). A beam-splitter (BS), with ratio between transmission and reflection (R/T) equal to 50/50, splits the light laser into two beams with same intensity. These two beams are directed along orthogonal paths, usually called arms of the interferometer, where they strike two mirrors, the reference mirror (R) and the sample mirror (S), both at the same distance to the BS to satisfy temporal laser coherence. These beams return to the beam splitter where they interfere on the way to an amplified photo-diode (PD-A). A convergent lens (L) is applied to expand the laser beam and enlarge the interference pattern on the PD-A, increasing the laser interferometer sensitivity.

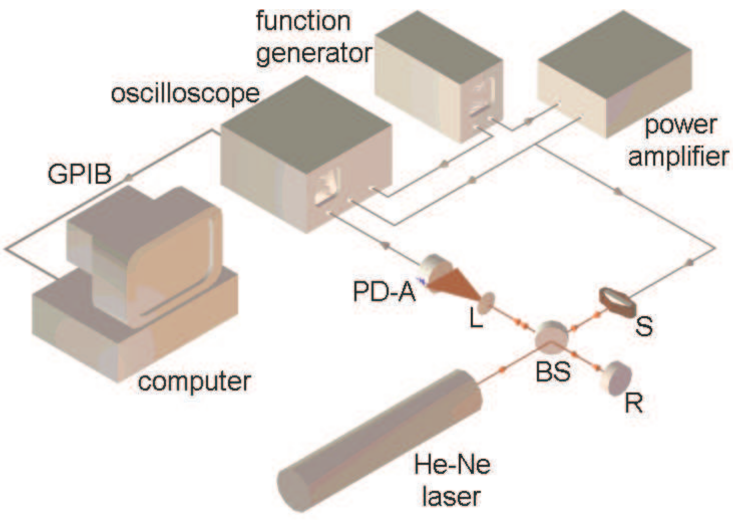


Figure 4. Experimental setup of the Michelson interferometer.

The interferometric technique applied measures a one-point displacement of the actuator surface (Royer and Casula 1994) through phase measurement technique, which consists of measuring the intensity variation of an interference pattern, as illustrated in Fig. (5). Mathematical treatment of light interference is given by wave superposition principle (Born and Wolf, 1980). Light is an electromagnetic wave. Electric and magnetic fields have identical behavior, thus, the mathematical treatment is done considering the light as monochromatic polarized electric field and in a range which the light laser has temporal coherence for sake of simplicity. Thus, electric fields from reference and sample mirrors are:

$$\vec{E}_R = \vec{a}\exp[i(\omega t - \vec{k}.\vec{u}_R)], \qquad \vec{E}_S = \vec{b}\exp[i(\omega t - \vec{k}.\vec{u}_S)], \tag{1}$$

where $|\vec{k}| = 2\pi/\lambda$ is the wave vector and $\omega = 2\pi\nu$ is the angular frequency of the light. λ and ν are the laser wavelength and frequency, respectively. $\vec{u}_R$ and $\vec{u}_S$ are the optical paths of light after beam-spliter to reference and sample mirrors, respectively. These optical paths are equal to $2L_R$ and $2L_S$, which means twice the interferometer arms. For simplicity, it will be considered amplitude a equals to b.

When interference occurs, the electric field resultant is:

$$\vec{E} = \vec{E}_R + \vec{E}_S\,. \tag{2}$$

Once the measurement is done through intensity, it is reasonable to write Eq. (2) in intensity form:

$$\begin{aligned} I &= |\vec{E}^2| = |\vec{E}_R^2| + |\vec{E}_S^2| + 2|(\vec{E}_R.\vec{E}_S)|, \\ I &= |I_R| + |I_S| + 2|(\vec{E}_R.\vec{E}_S)|, \end{aligned} \tag{3}$$

where I = the light intensity on the photo-diode (PD-A); I_R = reference beam intensity (reflected from mirror R); I_S = sample beam intensity (reflected from mirror S).

From real part of third term of Eq. (3):

$$2|(\vec{E}_R.\vec{E}_S)| = \Re\{\vec{E}_R.\vec{E}_S^*\} = ab\cos(ku_R - ku_S)\,, \tag{4}$$

where * denotes complex conjugated. However, from Eq. (3) I_R and I_S can be written in the following form:

$$\begin{aligned} I_R &= |E_R^2| = \frac{1}{2}\Re\{\vec{E}_R.\vec{E}_R^*\} = \frac{a^2}{2} \\ I_S &= |E_S^2| = \frac{1}{2}\Re\{\vec{E}_S.\vec{E}_S^*\} = \frac{b^2}{2} \end{aligned}\,, \tag{5}$$

and consequently Eq. (4) is:

$$2|(\vec{E}_R.\vec{E}_S)| = ab\cos(ku_R - ku_S) = 2\sqrt{I_R I_S}\,\cos(\phi)\,, \tag{6}$$

where $\phi = ku_R - ku_S$. Finally, intensity equation can be written as:

$$I = I_R + I_S + 2\sqrt{I_R I_S}\cos\phi\,. \tag{7}$$

Since with $u_R = 2L_R$ and $u_S = 2L_S$:

$$\phi = \frac{4\pi}{\lambda}(L_R - L_S) = \frac{4\pi}{\lambda}\delta\,, \tag{8}$$

where the phase variation ϕ is proportional to the displacement amplitude δ.

Thus, maximum intensity is obtained when $\phi = \pm 2n\pi$, for n integer:

$$I_{MAX} = I_R + I_S + 2\sqrt{I_R I_S}\,, \tag{9}$$

and minimum intensity is obtained when $\phi = \pm(2n-1)\pi$, for n integer:

$$I_{MIN} = I_R + I_S - 2\sqrt{I_R I_S} \ , \tag{10}$$

as shown in Fig. (5).

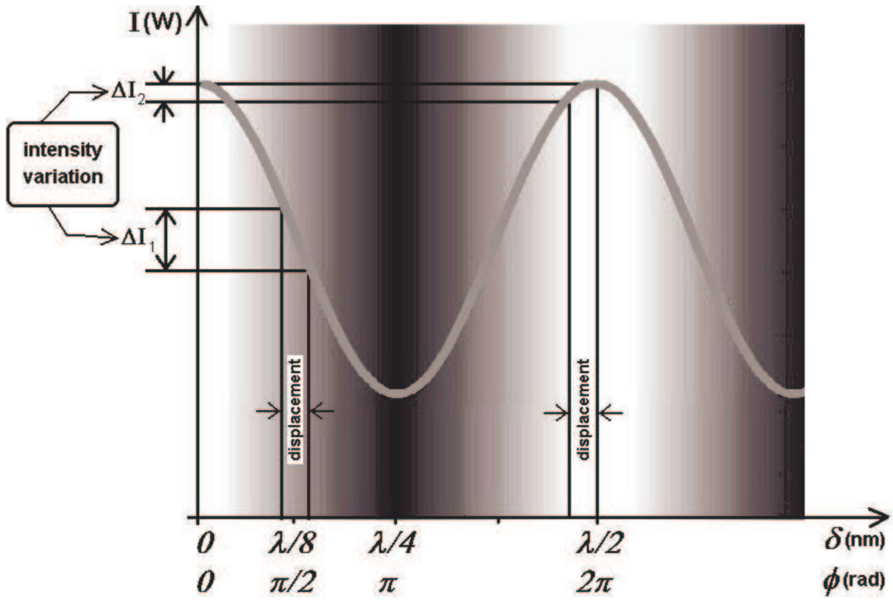


Figure 5. Transfer function of light interference pattern.

Notice from Fig. (5) that the difference between a maximum intensity (crest) and a minimum intensity (trough) is equal to a phase difference of π. From Eq. (8), this phase difference occurs when the optical path difference changes by λ/4. However, in this method, it is necessary to remain in the linear region of the light interference pattern where the sensitivity is maximum, as illustrated in Fig. (5). This linear part is obtained by considering a small region around an inflection point of Eq. (10) given by:

$$\frac{d^2 I}{d\phi^2} = -2\sqrt{I_R I_S}\cos\phi = 0 \ . \tag{11}$$

Eq. (11) is null when $\phi = (n+\pi/2)$, for n integer. The intensity variation is periodic, then considering $n=0$ for all assumption, the ideal phase difference to obtain the response signal is $\phi=\pi/2$ and from Eq.(8) this corresponds to region close to λ/8, as shown in Fig. (5). Due to small piezoceramic displacements in 3-direction, it was chosen to work only in the interference pattern linear range, which allows us to measure displacements amplitudes up to 10 nm (Scruby and Drain, 1990). Thus, to guarantee that generated displacements will remain in this linear region, unimorph piezoactuator is excited with voltages in a range from 0.1 to 10V.

The electronic apparatus consists of a function generator [see Fig. (4)], which sends a harmonic sinusoidal signal or one sine cycle (burst) to a power amplifier, exciting the piezoelectric transducer (S). A digital oscilloscope monitors and acquires the response signal from PD-A and the attenuated output signal of the power amplifier.

This interferometric system does not use vibration control and the ambient noise is periodic in approximately 250 Hz. Because of this, the intensity response signal changes continuously between maximum and minimum intensities. Fig. (5) shows same displacement value close to λ/8 where the light intensity variation (ΔI_1) is a maximum and close to λ/2 where the variation moves to a minimum. The response signal is acquired when the sensitivity is a maximum.

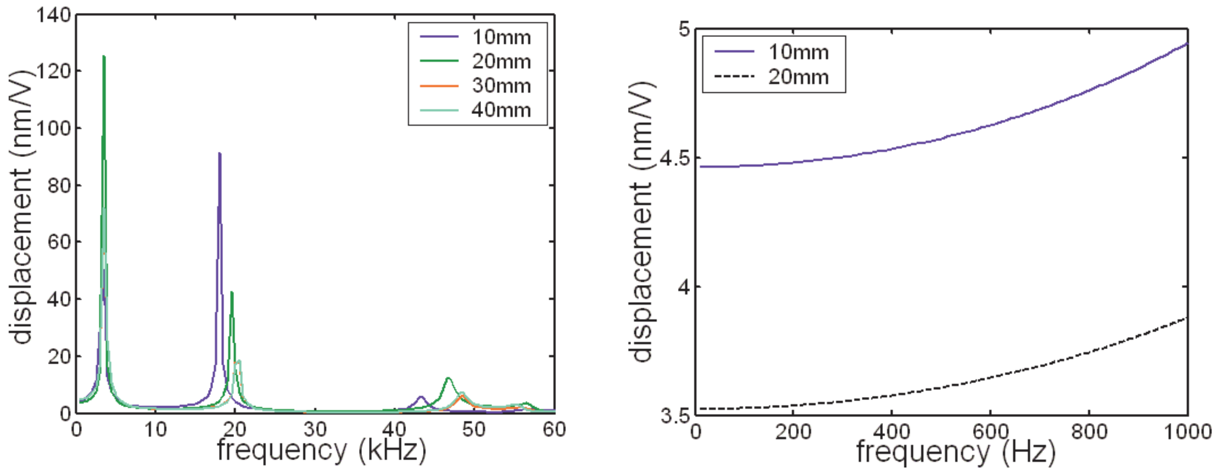
The calibration of this system is obtained by making the piezoelectric sample vibrate with amplitude larger than λ/4. The interference pattern is not very stable, therefore the calibration is performed frequently. Care must be taken to keep minimum vibrations on the assembly.

The unimorph presented in this work was designed to stabilize the Michelson Interferometer. In a previous work (Shirahige *et al.*, 2002) a bimorph piezoactuator was characterized to mechanical stabilization of the Michelson interferometer. Therefore, the bimorph first resonance frequency was too low, in the order of 400 Hz (Shirahige *et al.*, 2002). This fact severely difficults mechanical control. Unimorph is expected to have a higher first resonance frequency, close to 3.5 kHz. Allied to the fact that unimorphs generally present good frequency responses, this kind of actuator is selected.

5. Results

Based on the numerical results it was determined how mirror length influences piezoceramic bending. Four models were simulated considering different mirror lengths bonded to piezoceramic surface. The mirrors lengths were 10 mm, 20 mm, 30 mm and 40 mm. These numerical analyses were necessary to analyze unimorph behavior and to predict the best solution of mirror length. After determining this length, a physical unimorph piezoactuator was manufactured with the characteristics of the model. Then, experimental test were conducted to verify and validate the prototype manufactured. In simulations the best way to hold the unimorph was verified.

Figure (6a) shows numerical results of displacement frequency response of unimorphs modeled by using FEM. The frequency range is from 100 Hz to 60 kHz and modeled unimorphs had mirrors bonded with length 10 mm, 20 mm, 30 mm, and 40 mm. Figure (6b) shows the comparison between amplitude displacements of 10 mm and 20 mm mirrors lengths bonded on piezoceramics, considering a frequency range from 0 to 1 kHz. Notice that, before first resonance frequency, best displacement response per voltage applied is obtained with 10 mm mirror length bonded on piezoceramic. Due to application reasons, the frequency range of interest is less than 1 kHz.



(a) (b)

Figure 6. Displacements produced with four different mirror sizes. a) 0 to 100 kHz; b) 0 to 1 kHz.

From Figure (6a), it can be noticed that unimorph first resonance coincides for all mirrors length bonded, but second and third resonance frequencies are slighly different. Figure (7) describes von Mises stresses obtained for unimorph with 10 mm mirror length bonded, at first resonance frequency. The maximum stress occurs in the contact point between piezoceramic and aluminum holder.

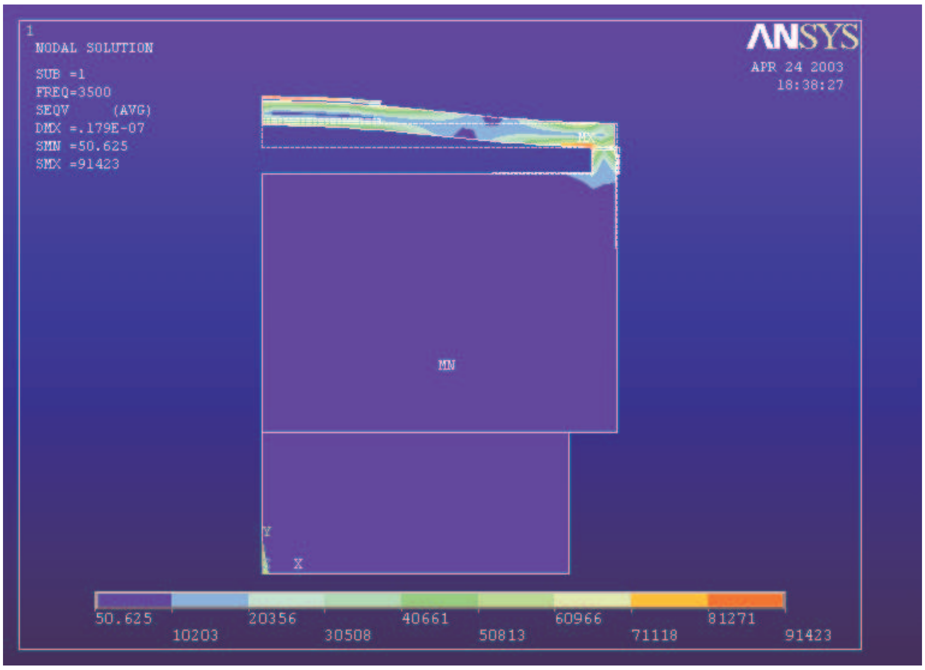
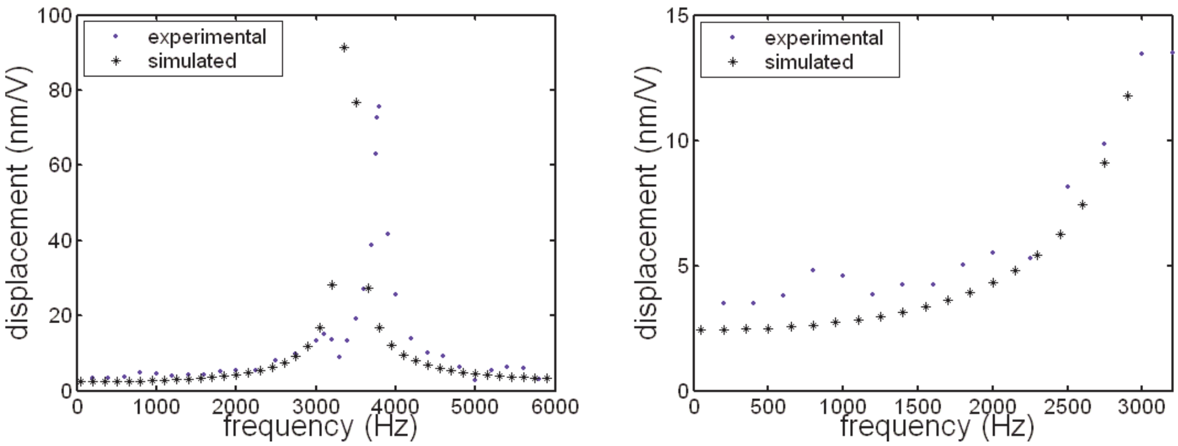


Figure 7. Von Mises stresses at resonance frequency of 10 mm mirror model.

The 10 mm mirror length was selected as the unimorph-type actuator. During the unimorph manufacturing, the piezoceramic suffered a small wear in the region of the tiny mirror, which may have caused small variations on its behavior. To consider this variation, computational simulations were performed with 100 μm depth cavity, which approximately represents the physical wear of the piezoceramic.

Experimental and numerical results of unimorph piezoactuator with 10 mm length mirror bonded are shown in Fig. (8). Figure (8a) shows experimental and numerical displacement frequency response from 100 Hz to 6 kHz. Figure (8b) shows experimental and numerical results from 100 Hz to 3 kHz, which is the range of interest for applying this unimorph as a mechanical control in a Michelson interferometer. The difference between experimental and numerical results is in the order of 20%, which occurs probably due to the difficulty of obtaining accurate values of piezoceramic properties, and the wear size in the piezoceramic geometry.



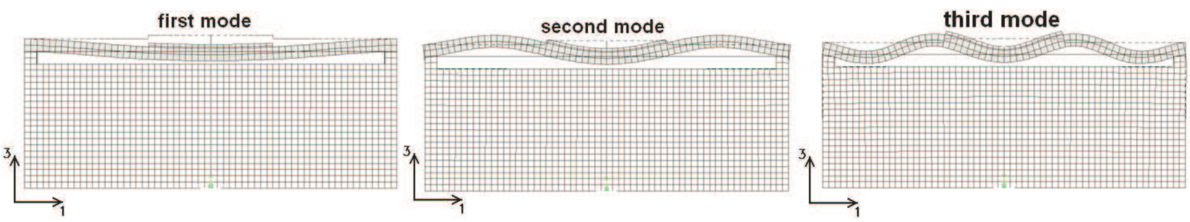
(a) (b)

Figure 8. Experimental and numerical displacement results: (a) from 100 Hz to 6 kHz and (b) from 100 Hz to 3 kHz, before first resonance frequency.

Experimental resonance frequencies of unimorph piezoactuator were obtained by electrical admittance analysis by using a HP4194A. Numerical resonance frequencies were obtained by modal analysis. These results are shown in Tab. (2). Notice that deviations between experimental and numerical resonance frequency are lower than 10%. The mode shapes of these three resonance frequencies are showed in Fig. (9), which is obtained by modal analysis. These results are enough to validate the FEM to model in predicting the actuator behavior.

Table 2. Unimorph piezoactuator resonance frequencies.

	Experimental (kHz)	Numerical (kHz)	Deviation (%)
first	3.7	3.4	8.1
second	19.3	18.4	4.7
third	43.9	43.4	1.1



(a) (b) (c)

Figure 9. Mode shapes: (a) First mode at 3.4 kHz; (b) Second mode at 18.4 kHz; (c) Third mode at 43.4 kHz.

6. Conclusions

Experimental analysis and Finite element method was successfully applied to develop a unimorph actuator. Through numerical analyses it was possible to simulate the actuator behavior considering different mirrors length bonded on piezoceramic. It was verified that bonding a tiny mirror with 10 mm length on piezoceramic center surface, the piezoceramic bending is larger than the condition to bonding 40 mm length mirror. It is a novel concept in relation to conventional unimorph actuators where usually the non-piezoelectric layer length is larger than piezoceramic length. From all analysis, the actuator with higher bending could be selected. Therefore, a physical unimorph piezoactuator was manufactured with a 10 mm length mirror bonded in a center of piezoceramic surface. The difference between experimental and numerical displacement frequency results are in the order of 20%, for frequency range from 100 Hz to 3 kHz, which is satisfactory, due to difficulty to determiner accurate piezoceramic properties, and the wear size in the piezoceramic geometry.

This actuator proved to be capable to generate displacement amplitude up to ten times the displacement produced by a single piezoceramic. Thus, as a future work, it may be used as a vibration mechanical controller in the reference mirror of a Michelson interferometer.

7. Acknowledgement

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