# Piezoelectric bimorphs for laser shutter systems: optimization of dynamic characteristics

**V. Jurenas*, R. Bansevicius**, S. Navickaite*****
**Kaunas University of Technology, Kęstučio 27, 44312 Kaunas, Lithuania, E-mail: vytautas.jurenas@ktu.lt*
***Kaunas University of Technology, Kęstučio 27, 44312 Kaunas, Lithuania, E-mail: ramutis.bansevicius@ktu.lt*
****Kaunas University of Technology, Kęstučio 27, 44312 Kaunas, Lithuania, E-mail: sigita.navickaite@stud.ktu.lt*

## 1. Introduction

Since the piezoelectric effect was first discovered in 1880 by the French scientists Pierre and Paul-Jacques Curie, the use of piezoelectric materials has really increased in modern engineering applications, especially in the field of smart structures, where they are used as actuators and/or sensors. Although the magnitudes displacements and/or voltages are small, piezoelectric materials have been adapted to an impressive range of applications. An interesting application in laser technology devices is controlling the intensity of laser beam power up to zero, realized by various laser beam shutters for safety and beam control applications.

Piezoelectric bending actuators are designed as double layer elements. In operation, one of the layers extends while the other compresses. As a result, it courses the element to bend. Piezo bimorphs is a class of electromechanical transducers converting an electrical voltage into a mechanical displacement and vice versa. These types of actuators provide the value of a bending displacement much more than planar ones [1]. The paper considers optimal design problems in the context of piezoelectric bimorph actuator dynamics. The width profile of a piezoelectric bimorph actuator is optimized. The study utilized by the finite element method (FEM) to optimize the width profile of the cantilever beam in order to determine the resonance frequencies of the bimorph. The optimal form of actuator was found considering to theoretical calculations and experiment results. More specifically, we are interested in controlling the tip-deflection of a cantilever beam subjected to a static and time-harmonic loading on its free extreme [2].

The problem of establishing optimal piezoelectric transducer's geometrical form has been studied by many authors, but since these approaches usually assume that size, shape and number of actuators are given a priori, they may lead to suboptimal solutions. It is also interesting to optimize both structural and control parameters at the same time. One of the first works in this area was given in [1] which used fixed number and position of actuators for actively controlled beam structures [3].

Recently, some authors have begun to apply topology optimization to find optimal piezoelectric actuators' distribution on plates and shells in the static case and beams in the dynamic case, assuming constant thickness or width in all of them. Some interesting results are obtained by using shape optimization techniques. In [3] an iterative technique to optimize the shape of piezoelectric actuators over beams and plates is used in order to achieve desired shapes of the structure.

The second design problem deals with finding the optimal distribution of piezo-actuator width along the structure under the same loading conditions, but keeping constant the thickness [3].

## 2. The layout of investigated laser beam shutter and working principle

Investigated piezoelectric laser beam shutter consists of the bimorph type piezoelectric actuator *1*, special plate for the beam shutting *2* and holder of bimorph *3*. It's design is illustrated by view from the top and the view from the front (Fig. 1). Bending deformations of bimorph *1* can be actuated by the piezoelectric effect. The direction of deformation and deformation rate depend on materials used in actuator, polarization direction and electric field that depend on supply voltage. Laser beam *4* is blocked if electricity doesn't influence piezo actuator, but in that case if actuator is acted by supply voltage, bimorph actuator is bended by amplitude *A* (Fig. 1, b) and laser beam *4* goes without disturbing through laser shutter system [2].

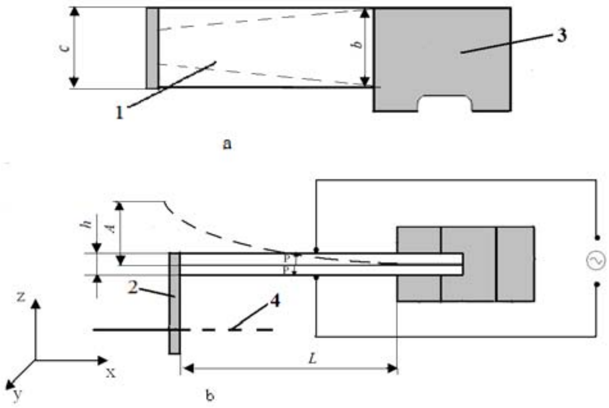

Fig. 1 The scheme of piezoelectric laser beam shutter: a – view from the top, b – view from the front: *b* and *c* - width of piezoelectric actuator ends, *h* - height, *L* - length of piezo ceramic plate, *P* - direction of polarization, *A* - amplitude

## 3. Bimorphs used in design of laser beam shutting system

The piezoelectric bimorph actuator (Fig. 1) is a beam made of two uniaxial piezoelectric layers, laminated together with opposite polarities.

Therefore, the piezoelectric elements are electrically connected in series as shown in Fig. 1, b, in which two piezoelectric elements with opposite poling directions are directly bonded, and then covered by electrodes. The application of an electric field across the two layers of the bimorph causes one layer to expand, while the other layer contracts.

When an external voltage is applied, the induced strain generates moments that bend the bimorph beam. The calculated static deflection of the beam is compared with the analytical solution, described hereafter and with the finite element modeling and experimental results.

The piezoelectric material used for the bimorph is PZT (lead zirconate titanate). The material properties of PZT (type CTS-23) are shown in Table 1.

Table 1

Properties of the PZT material CTS-23

| Property | Values |
|---|---|
| Density, kg m$^{-3}$ | $7.4 \times 10^3$ |
| Dielectric constant | 1200 |
| Coupling factor | 0.42 |
| charge constant $d_{31}$, mV$^{-1}$ | $-140 \times 10^{-12}$ |
| Young's modulus, Pa | $70 \times 10^9$ |
| Mechanical quality factor | 200 |

The external surfaces of the piezo bimorph are plated with a uniform layer of nickel electrodes, approximately 2 μm thick. The bimorph shown in Fig. 1 is driven into bending vibration by applying an AC voltage across the electrodes (peak to peak amplitude is 19 V).

The purpose of this investigation is to find optimal geometrical parameters of bimorph transducer with the aim to reach operating frequency bandwidth as wide as possible. Bandwidth depends on resonant frequency of the first bending form of actuator, so it is very important to relate actuator's geometric parameters with the first resonant frequency and specified amplitude of oscillation. In that case the design of piezoelectric shutter would be rational and consistent with the technical characteristics of the system.

Calculations and experiments were made for three cases: when ratios of the width of ends of the actuator were 1:1 ($b = c$), 1:2 ($b = c/2$) and 1:3 ($b = c/3$). Their dimensions are shown in Table 2.

Table 2

| PZT material | CTS-23 | | |
|---|---|---|---|
| Width ratio | $b = c$ | $b = c/2$ | $b = c/3$ |
| Length $L$, m | 0.055 | 0.055 | 0.055 |
| Width $b$, m | 0.01 | 0.01 | 0.01 |
| Width $a$, m | 0.01 | 0.005 | 0.0033 |
| Height $h$, m | 0.002 | 0.002 | 0.002 |

## 4. Theoretical analysis

The static analysis of piezoelectric cantilever actuators is typically performed using an approach employed by Timoshenko for calculating the deflection of a thermal bimorph [4]. In Timoshenko's analysis, the principal of strain compatibility is employed between two cantilever beams joined along the bending axis. The deflection of the two-layer structure due to forces generated by one or both of the layers is then determined from static equilibrium. For the case of a piezoelectric heterogeneous bimorph, the structure of interest consists of a piezoelectric layer bonded to a purely elastic layer. The purpose of the elastic layer is, in essence, to offset the neutral axis of the two-layer system so that a lateral strain produced by piezoelectric effect is translated into an applied moment on the bimorph. Such structures are commonly used in macroscale applications such as active structural damping and precision positioning systems. For these macrodevices, the two-layer Timoshenko model (bimorph model) is sufficient for determining the quasi-static behavior of the system since any additional (e.g., bonding) layers are relatively thin and can be ignored.

To design and use bimorphs rationally, it is crucial to understand their coupled electromechanical behavior using modeling. Generally, a bimorph actuator consists of two ceramic plates bonded together, with the negligible bonding layer (Fig. 2) and driven with opposite electrical fields.

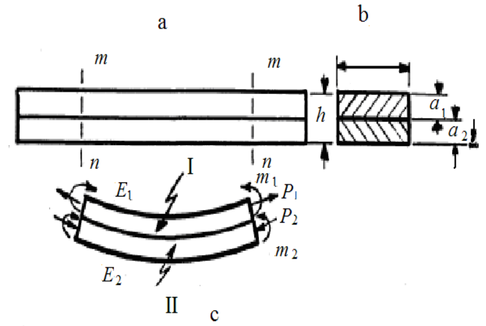

Fig. 2 Deflection of piezoelectric bimorph: a - piezoelectric bimorph, b - cross section of bimorph, c - deflection

Linear piezoelectric effect of piezoelectric bimorph can be expressed as

$$\varepsilon_{3Piezo} = d_{31}E_1 \tag{1}$$

where $d_{31}$ is charge constant, depends on used material, m V$^{-1}$; $E_1$ is Young's modulus, Pa.

Curvature of piezoelectric bimorph is given by

$$\frac{1}{\rho} = \frac{6(d_{31\_2}E_{1\_2} - d_{31\_1}E_{1\_1})(1+m)^2}{h\left[\left(m^2 + \frac{1}{nm}\right)\right](1+nm) + 3(1+m)^2} \tag{2}$$

where the thickness of piezoelectric bimorph is $h$; in our case $m = 1$ and $n = 1$.

Ratio of thickness is

$$m = \frac{a_1}{a_2} \tag{3}$$

Ratio of Young's modulus, if piezo materials of bimorph layers are different

$$n = \frac{E_1}{E_1} \tag{4}$$

Often, in a bimorph, we use the same material on both layers, but apply an opposite potential to each

$$V_1 = -V_2 = -V \tag{5}$$

This leads to

$$\frac{1}{\rho} = \frac{6d_{31}V}{h^2} \tag{6}$$

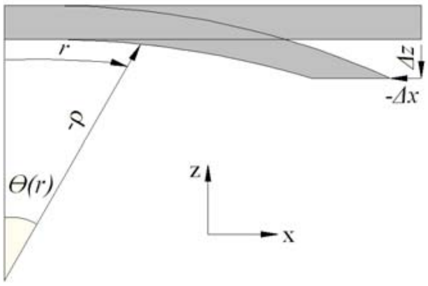

Fig. 3 Displacements of piezoelectric bimorph: $\Delta z$ – vertical displacement, $\Delta x$ – horizontal displacement, $\rho$ – curvature of piezoelectric bimorph, $r$ – arc of piezoelectric bimorph.

Displacements of piezoelectric bimorph in z and x directions can be calculated as

$$\Delta z(r) \approx \frac{r^2}{2\rho} - \frac{r^4}{24\rho^3} \tag{7}$$

$$\Delta x(r) \approx -\frac{r^3}{6\rho^2} + \frac{r^3}{120\rho^4} \tag{8}$$

The fundamental resonance frequency of a cantilever beam of length $L$, thickness $h$ and uniform width is given by

$$f = \frac{\lambda_1^2}{2\pi L^2}\sqrt{\frac{Eh^2}{12\rho_d}} \tag{9}$$

where $\rho_d$ is the material density, $E$ is Young's modulus and $\lambda_1 = 1.875$ is a constant resulting from the fixed-free boundary conditions of the cantilever beam [5].

## 5. Harmonic analysis

Harmonic analysis of piezoelectric actuator was made by using finite element method and also with experiments [6-8].

The dimensions of piezoelectric actuator model were chosen as it is shown in Table 2. Common FE model for numerical calculations are shown in Fig. 4 [9].

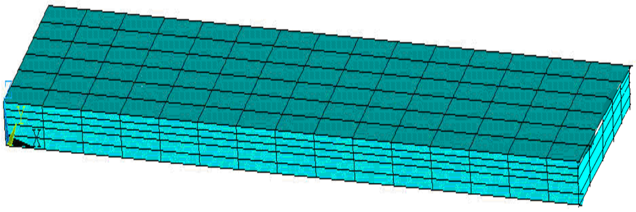

Fig. 4 Common FE model of piezoelectric actuator

As a result of calculations and experiments with bimorph piezoelectric transducers, we obtained amplitude-frequency characteristics. Resonant frequencies are shown in Table 3.

Table 3

| Width ratio | Resonant frequency, Hz | |
|---|---|---|
| | Numerical results by FEM | Experimental results |
| $c/b = 1$ | 310 | 307 |
| $c/b = 0.5$ | 380 | 379 |
| $c/b = 0.33$ | 420 | 419 |

## 6. Displacements of piezoelectric laser beam shutter

In order to compare the theoretical deflection model of a bimorphs with experimental results, three 55 mm long bimorphs with variable width ratio of ends $a/b$ were actuated by applying a dc voltage between the upper and lower electrodes and measuring the deflection at the tip [10]. The geometric parameters for a bimorph cantilever beams are shown in Table 2.

Fig. 5 Experimental set up

Displacements of piezoelectric bimorph were measured by experimental set up is shown in Fig. 5. It consists of: : *1* – power amplifier EPA-104; *2* – signal generator Agilent 33220A; *3* –analog digital converter (ADC) "PicoScope-3424"; *4* – laser displacement sensor LK-G82; *5* – laser sensor controller LK-G3001PV; *6* - Polytec OFV-5000 vibrometer controller; *7* - Polytec OFV-512 fiber interferometer; *8* - Polytec OFV-130-3 micro-spot sensor head; *9* - Polytec computer; *10* – computer; *11* – piezoelectric bimorph actuator.

Experimental and theoretical results of displacements are shown in Fig. 6.

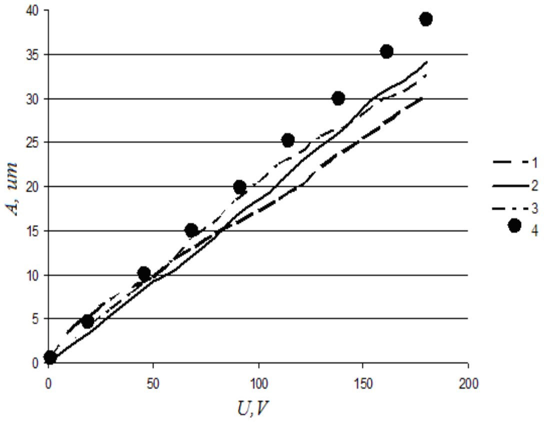

Fig. 6 Experimental displacements of bimorphs with variable width ratio of ends $c/b$: *1* – ($c/b$ = 1); *2* – ($c/b$ = = 0.5); *3* – ($c/b$ = 0.33); *4* – theoretical results

## 7. Conclusions

The design and analysis of the piezoelectric bimorph actuator for the laser beam shutter systems was presented. Influence of the geometric parameters and form of the piezoelectric bimorph on the resonant frequency of the actuator was determined. Modal frequency and harmonic response analysis based on FEM and experimental studies of the actuator have been carried out. Both the finite element computation and experimental results confirmed that bimorph with width ratio of ends $c/b = 0.33$ had a 30% higher resonant frequency of the bending vibrations, than that with $c/b = 1$. Experimental results showed that bimorph actuators with width ratio of ends $c/b = 0.33$ had not only higher resonant frequency, but almost the same displacement output.

## Acknowledgement

The work was supported by the Lithuanian State Science and Studies Foundation, Project No B-43/2009.

## References

1. **Bendsøe, M.P., Olhoff, N., Taylor, J.E.** On the design of structure and controls for optimal performance of actively controlled flexible structures.-Mech. Struct. & Mach., v.15, N.3, 1987, p.265-295.
2. Fast Laser Shutters With Low Vibratory Disturbances, NASA's Jet Propulsion Labratory, USA, February 2005.
3. **Donoso, A., Sigmund, O.** Optimization of piezoelectric bimorph actuators with active damping for static and dynamic loads, E.T.S. Ingenieros Industriales Universidad de Castilla - La Mancha, 13071 Ciudad Real, March 2007.
4. **Timoshenko, S.P., Yong, D.H., Weaver, W.** Vibration Problems in Engineering (4th Ed). -New York: Wiley, 1974.
5. **Rao, S. S.** Mechanical Vibrations. 2nd edn (Reading, MA: Addison-Wesley, 1990, p.397-8.
6. **Tao, W., Paul, I.R.** Dynamic peak amplitude analysis and bonding layer effects of piezoelectric bimorph cantilevers.-Smart Mater. Struct., 13, 2004, p.203-210.
7. **Kargaudas, V., Žmuida, M.** Forced vibrations of two plates in fluid and limit eigenmodes. -Mechanika. -Kaunas: Technologija, 2008, Nr.2(70), p.27-31.
8. **Mažeika, D., Bansevičius, R.P.** Study of resonant vibrations shapes of the beam type piezoelectric actuator with preloaded mass. -Mechanika. -Kaunas: Technologija, 2009, Nr.2(76), p.33-37.
9. **Hwang, W. S. and Park, H.C.** Finite element modeling of piezoelectric sensors and actuators.-AIAA Journal, 1993, 31(5), p.930-937.
10. **Bubulis, A., Jūrėnas, V., Minchenya, V.T., Valaika, M.** Experimental investigation of ultrasound vibrations of a flexible waveguide.-Journal of Vibroengineering / Vibromechanika. -Vilnius: Vibromechanika, 2008, v.10, no.1, p.74-78.

V. Jurėnas, R. Bansevičius, S. Navickaitė

## PIEZOELEKTRINĖSE LAZERIO SPINDULIO SKLENDĖSE NAUDOJAMŲ BIMORFŲ DINAMINIŲ PARAMETRŲ OPTIMIZACIJA

### Reziumė

Straipsnyje pateikiami tyrimų, skirtų lazerio spindulio sklendžių greitaeigingumui didinti, rezultatai. Parodyta, kad egzistuoja bimorfinio pjezoelektrinio keitiklio optimali forma, užtikrinanti maksimalų keitiklio rezonansinį dažnį, esant iš anksto užduotai jo virpesių amplitudei. Palyginami teoriniai skaičiuotieji ir eksperimentinių tyrimų metu gauti rezultatai. Pagal nustatytąjį įtaiso darbo diapazoną, eksperimentiškai ir teoriškai nustatomi bimorfo atsilenkimai.

V. Jurenas, R. Bansevicius, S. Navickaite

## PIEZOELECTRIC BIMORPHS FOR LASER SHUTTER SYSTEMS: OPTIMIZATION OF DYNAMIC CHARACTERISTICS

### Summary

The paper considers optimal design problems in the context of piezoelectric bimorph actuator dynamics. The width profile of a piezoelectric bimorph actuator is optimized. The study utilized the finite element method to optimize the width profile of the cantilever beam in order to determine the resonance frequencies of the bimorph. The optimal form of actuator was found considering to theoretical calculations and experiment results. The calculation method and experimental measurements of displacements of piezoelectric bimorphs are presented.

В. Юренас, Р. Бансявичюс, С. Навицкайте

## ОПТИМИЗАЦИЯ ДИНАМИЧЕСКИХ ХАРАКТЕРИСТИК ПЬЕЗОЭЛЕКТРИЧЕСКОГО БИМОРФА ИССПОЛЬЗУЕМОГО В ЗАТВОРАХ ЛАЗЕРНОГО ЛУЧА

### Резюме

В статье представленны результаты исследования динамики затвора лазерного луча, выполненного в виде пьезоэлектрического биморфа.Определен оптимальнй профиль ширины пьезоэлектрического преобразователя биморфного типа, обеспечивающий максимальную резонансную частоту преобразователя при определенной амплитуде вибраций. Применяя результаты теоретических и экспериментальных исследований получена оптимальная форма преобразователя. Представленны методика рассчета и экспериментальные измерения изгибных деформаций пьезобиморфа.

Received May 06, 2010
Accepted September 27, 2010