589. Investigation of motion control of piezoelectric unimorph for laser shutter systems

A. Bubulis[1], V. Jurenas[2], S. Navickaite[3], V. Rugaityte[4]
Kaunas University of Technology, Kaunas, Lithuania
e-mail: *algimantas.bubulis@ktu.lt*[1] *vytautas.jurenas@ktu.lt*[2]
sigita.navickaite@stud.ktu.lt[3] *viktorija.rugaityte@stud.ktu.lt*[4]

(Received 30 September 2010; accepted 9 December 2010)

Abstract. This paper presents the design and testing of a resonance frequency-tunable piezoelectric unimorph chopper and shutter that employ a magnetic force technique and magnetorheological fluid (MRF). This technique enabled to increase the frequency of the resonance up to 110% of the untuned resonant frequency. A piezoelectric unimorph cantilever with a natural frequency of 126 Hz is used as the laser beam chopper or shutter, which is successfully tuned in a frequency range of 126 - 270 Hz thereby enabling continuous control of the laser beam over the entire frequency range tested. A theoretical model based on variable magnetic field strength and MRF damping is presented. The magnetic force and MRF applied for damping of transient vibrations of the piezoelectric unimorph shutter have been experimentally determined.

Keywords: vibrations, bimorph, piezo materials, laser shutter, position control, magneto rheological fluids.

Introduction

Nowadays laser technologies are widely used in modern equipment. Laser shutting or chopping systems are used for laser beam control. Laser beam goes without disturbances through laser shutter system if the shutter is opened, but if the shutter is fully or partially closed, laser beam power is fully or partially blocked.

Lately in development of high-tech products there is observed an increasing tendency to apply smart materials or materials with controllable properties (piezoactive and shape-memory materials, suspensions with controllable rheology – electro- or magneto-rheological fluids (ERF and MRF), artificial muscles, etc.). In this paper authors investigate position control of piezoelectric unimorph for laser shutting system using MRF and magnetic forces.

Most laser beam choppers or shutters developed to date are single resonance frequency based, and while recent efforts have been made to broaden the frequency range of laser beam choppers, what is lacking is a robust tunable frequency technique of the chopper. Shutters differ from choppers in that they are not limited to a simple periodic on-off cycle but will follow an arbitrary, varying pattern of openings and closings. Optical shutters are useful for low frequency chopping, particularly when slow or non-periodic behavior is needed.

The scheme of the investigated laser beam shutter and its working principle

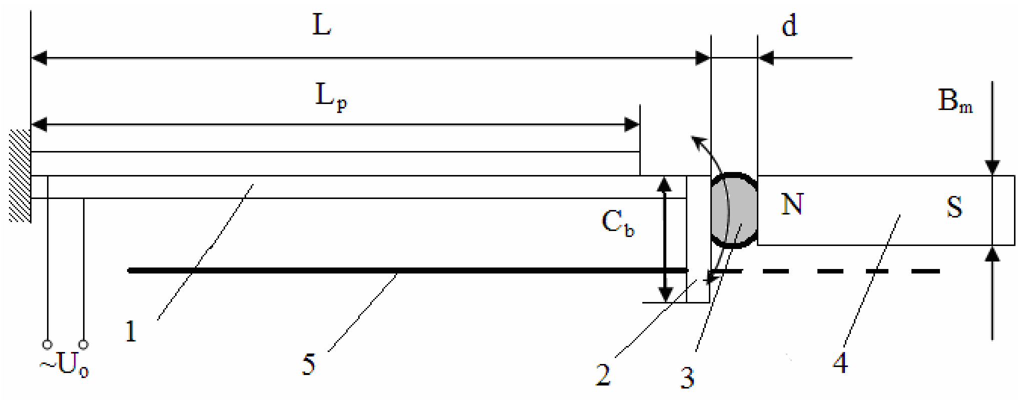


Fig. 1. The scheme of the piezoelectric laser shutting system: L_p– length of piezoelectric plate, L – length of piezoelectric unimorph 1, C_b – length of special plate 2 for the laser beam 5 shutting, d – distance between the end of unimorph 1 and permanent magnet 4, B_m – thickness of permanent magnet 4, 3 - MRF

Investigated piezoelectric laser beam shutter consists of piezoelectric unimorph actuator 1 and special ferromagnetic plate 2 for the laser beam shutting. Its design is illustrated in Fig. 1. Bending deformations of unimorph 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 5 is blocked if electricity does not influence piezoactuator, but in the case when actuator is powered, unimorph actuator is bended by and laser beam 5 goes without obstruction through laser shutter system [2]. The motion of the unimorph 1 is controlled using MRF 3. Permanent magnet 4 is used in order to generate magnetic force and magnetic field that changes viscosity of MRF 3. Magnetic force and MRF that increase the stiffness and damps vibrations of the cantilever unimorph 1 depends on distance between the tip of unimorph and permanent magnet 4.

In the present approach a magnetic force is used to alter the overall stiffness of the piezo unimorph cantilever. This enables one to increase the overall stiffness of the device using magnetic force and to change the natural frequency of the device. Here, attractive magnetic force is used to shift the beam natural frequency to higher frequencies with respect to the original resonant frequency (with no magnetic force present).

Unimorph and MRF used in design of investigated laser beam shutting system

A standard rectangular shape unimorph actuator under activation is illustrated in Fig. 1. The actuator consists of a single piezoelectric layer, with length L_p, bonded to a purely elastic layer, with length L. Ferromagnetic steel is chosen for the elastic layer. When a voltage U is applied across the thickness of the piezoelectric layer, longitudinal and transverse strain is induced. The elastic layer opposes the transverse strain which leads to a bending deformation [1].

The piezoelectric material used for the unimorph is PZT of type PZ26 (Noliac company). Ferromagnetic steel is used as elastic layer. The properties of materials are listed in Table 1.

Table 1. Properties of the PZT material Pz26 and steel

Property	Values of PZT	Values of steel	Unit
Density	7.7×10^3	7.872×10^3	kg m^{-3}
Dielectric constant	1300		
Coupling factor	0.47		
d_{31} charge constant	-130×10^{-12}		m V^{-1}
Young's modulus	70×10^9	193×10^9	Pa
Mechanical quality factor	1000		

The outer surfaces of the piezo unimorph are plated with a layer of nickel electrodes, approximately 2 μm thick. The unimorph shown in Fig. 1. is driven into bending vibration by applying an AC voltage U across the electrodes, whose peak to peak amplitude is 6 V. Geometrical parameters of the laser shutting system with the piezoelectric unimorph and permanent magnet (Neodymium magnet, flux density B=1,2 T) are shown in Table 2.

Table 2. Geometric parameters of the unimorph

L, mm	L_p, mm	B_m, mm	C_b, mm	d, mm
31	25	3.5	3.5	1…15

In this paper authors investigate position control of piezoelectric unimorph for laser shutting system using MRF and magnetic forces.

Table 3. Specification of MRF used in experimental study [3]

MRF	MRF-140CG	MRF-122EG
Appearance	Dark Gray Liquid	Dark Gray Liquid
Viscosity, Pa-s @ 40°C (104°F), Calculated as slope 800-1200 sec^{-1}	0.280 ± 0.070	0.042 ± 0.020
Density g/cm3	3.54-3.74	2.28-2.48
Solids Content by Weight, %	85.44	72
Flash Point, °C (°F)	>150 (>302)	>150 (>302)
Operating Temperature, °C (°F)	-40 to +130 (-40 to +266)	-40 to +130 (-40 to +266)

Theoretical analysis

For effective design of the unimorphs it is crucial to understand their coupled electromechanical behavior through application of mathematical modeling [4,5]. There are two crucial parameters describing a piezoelectric unimorph actuator:

- *Blocking force F_b*: representing the external force to be applied so that no displacement occurs when an external voltage U_0 is applied.
- *Free displacement δ_{dc}*: representing the displacement caused by an applied voltage U_0 when no external force is exerted at the tip of the actuator.

A third fundamental parameter, mechanical stiffness, is then readily derived: $k = F_b/\delta_{dc}$. Theoretical formulas that link blocking force and free displacement to geometrical dimensions as well as piezoelectric and mechanical properties of the actuator can be found in [6]:

$$\begin{cases} \delta_{dc} = \dfrac{3L^2 AB(B+1)}{h_p^2 D} d_{31} U_0 \\ F_b = \dfrac{3h_p WAB(B+1)}{4s_p(AB+1)} d_{31} U_0 \\ k = \dfrac{F_b}{\delta_{dc}} = \dfrac{Wh_p^3 D}{4s_p L^3 (BA+1)} \end{cases} \tag{1}$$

where $A = s_p/s_s = Ys/Yp$, $B = hs/hp$, $C = \rho s/\rho p$, $D = A^2B^4 + 2A(2B + 3B^2 + 2B^3) + 1$. Here, L is the unimorph length, W is the width, U_0 is the applied voltage, d_{31} is the transverse piezoelectric coefficient. Subscripts p and s refer to, respectively, the piezoelectric layer and to the steel one. s_p and s_s are the elastic compliances, h_p and h_s are the thicknesses, Y_p and Y_s are the Young's moduli, and ρ_p and ρ_s are the densities of the piezoelectric and steel layers respectively.

To calculate the amplitude of the cantilever deflection in the presence of the magnetic coupling force in z direction, we use a modified version of the standard spring–mass model. The model parameters are shown schematically in Fig. 2.

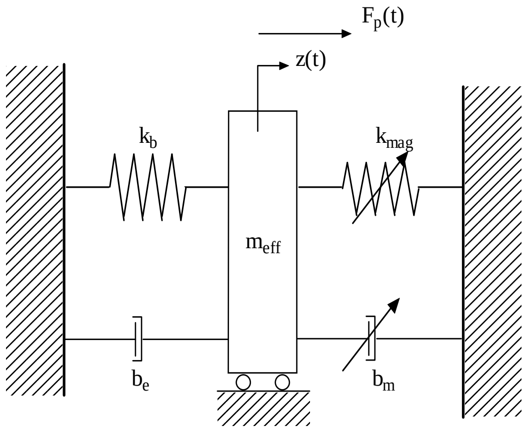


Fig. 2. Lumped model of the laser shutting system

The cantilever is represented by a one-dimensional spring–mass system, where m_{eff} is the effective mass of the cantilever beam, k_b is the spring constant (cantilever beam stiffness), k_{mag} - stiffness introduced via application of the magnetic force. The cantilever deflection, $z(t)$, is driven by a piezoelectric force F_p, which excites sinusoidal bending oscillations of the cantilever with an angular frequency ω. Electrical and mechanical damping are described by the coefficients b_e and b_m respectively and are determined experimentally. To minimize the complexity of the problem, the magnetic coupling force F_{mag} is considered to be one-dimensional, acting only in the z-direction, and the magnetic force in the axial direction is ignored (justification for this approximation is provided in [7]).

In general, the magnetic coupling force F_{mag} is a complicated non-linear function of the deflection z and the magnet/cantilever tip separation distance d.

As described in [7], the experimentally determined magnetic force values are fit to an empirically determined analytical expression for $F_{mag}(z, d)$:

$$F_{\mathrm{mag(z,d)}} = \frac{az}{b + cz^4} \tag{2}$$

where a, b, and c are experimentally obtained parameters [7].

When peak to peak bending amplitude of the cantilever is smaller than the radius of the magnet, the F_{mag} can be written as:

$$F_{mag} = az/b = k_{mag} z, \tag{3}$$

Where k_{mag} – stiffness introduced via application of the magnetic force F_{mag}.

In the case of no magnetic force, the effective stiffness of a multilayered (through the thickness) cantilevered beam can be written as [8]:

$$k_b = \frac{W}{4L^3(\sum_{i=1}^{n_1} n_i E_i h_i^3 + \sum_{j=1}^{n_2} n_j E_j h_j^3)} \tag{4}$$

where W is the width of the beam, n_1 and n_2 are the numbers of piezoelectric and elastic layers, respectively, E_i and h_i are the Young's modulus and height of each piezoelectric layer, and E_j and h_j are the Young's modulus and height of each elastic layer. The effective mass of a multilayered cantilever beam with a tip mass can be approximated as:

$$m_{eff} = m_t + 0{,}23bL(\sum_{i=1}^{n_1} n_i \rho_i h_i^3 + \sum_{j=1}^{n_2} n_j \rho_j h_j^3) \tag{5}$$

where ρ_i and ρ_j are the densities of the piezoelectric and elastic layer and m_t is the tip mass. From this the corresponding natural frequency of the multilayered cantilevered beam is given as:

$$\omega_b = \sqrt{\frac{k_b}{m_{eff}}} \tag{6}$$

In the case of the magnetic force, one can substitute equation (7) into $k_{eff} = k_b + k_{mag}$ to calculate the required applied magnetic stiffness to tune the vibrating beam from an original resonance frequency ω_b to the desired tuned resonance frequency ω_t:

$$\mathrm{k}_{\mathrm{mag}} = m_{eff}\,\omega_t^2 - k_b = m_{eff}(\omega_1^2 - \omega_b) \tag{7}$$

The cantilever deflection $z(t)$ can then be determined by solving the differential equation for a one-dimensional forced harmonic oscillator. According to equations (3-7) the equation can be written as:

$$\ddot{z}(t) + \frac{b_{eff}}{m}\dot{z}(t) + \frac{k_{eff}}{m}z(t) = \frac{F_p(t)}{m} \tag{8}$$

where $b_{eff}=b_e+b_m$ – total effective damping of the system; $k_{eff} = k_b+k_{mag}$ - total effective stiffness of the system, F_p - piezoelectric force can be calculated by equation (1) as F_b.

The induced stiffness from the applied magnetic force and MRF also induces a certain amount of additional damping within the device. It is observed that the damping increases with the increase in induced stiffness required for resonance frequency tuning. The damping is determined by first tuning the resonance frequency via the magnetic stiffness approach, and then performing a bump test to obtain an amplitude decay plot with time. From this amplitude decay plot the damping b_{eff} is calculated using the relationship:

$$b_{eff} = \frac{1}{2\pi} ln(\frac{z_1}{z_2}) \tag{9}$$

where z_1 and z_2 are consecutive amplitudes.
The piezoelectric cantilever can be approximated with 1 degree-of-freedom harmonic oscillator (Fig. 2), whose response to a modulated applied force is characterized by its transfer function:

$$z(t) = \frac{F_p(t)}{m_{eff}\sqrt{(\omega_0^2 - \omega^2)^2 + b_{eff}^2\omega^2}} \tag{10}$$

$$tan\,\alpha = \frac{b_{eff}\,\omega}{\omega_0^2 - \omega^2} \tag{11}$$

where ω is the applied force frequency, ω_0 the oscillator resonant frequency and b_{eff} the system damping factor. Equation (10) gives the cantilever oscillation amplitude when a modulated force $F_p(t)$ is applied. Equation (11) gives the phase lag of the cantilever oscillation with respect to the applied force.

Experiments of piezoelectric unimorph motion control for laser beam shutter

The experimental setup is illustrated in Fig. 3. It consists of: 1 – piezoelectric unimorph actuator, 2 – permanent magnet, 3 – ferromagnetic plate for laser beam shutting, 4 – laser sensor head LK-82G with controller LK-G3001PV, 5 – laser beam of laser sensor head, 6 – analog digital converter (ADC) “PicoScope-3424”, 7 – computer, 8 – MRF.

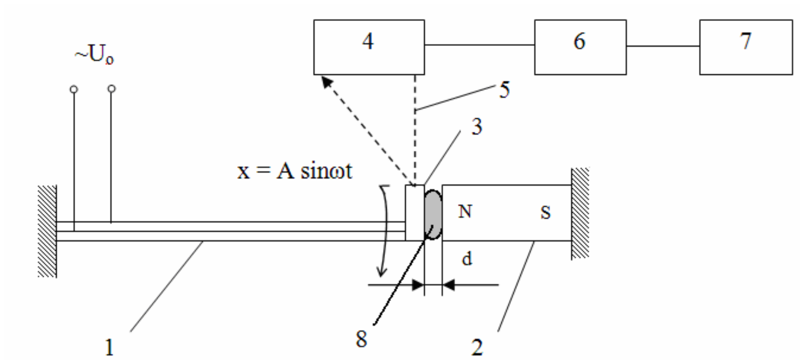
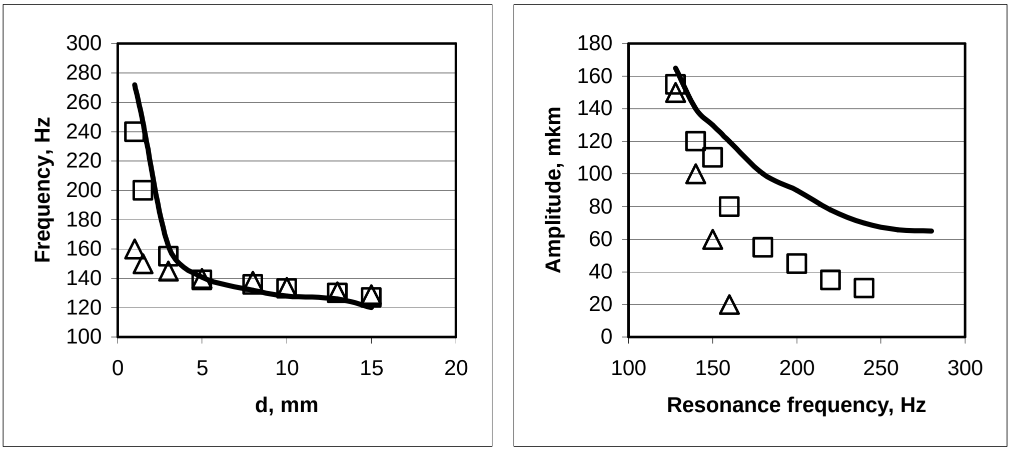


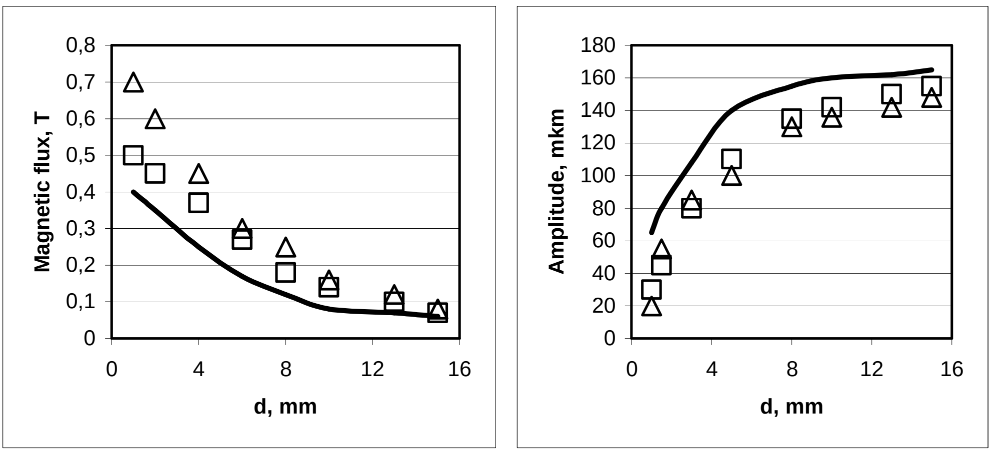
Fig. 3. Layout of the experimental setup for the evaluation of dynamics of the piezoelectric unimorph.

A non-contact laser displacement device Keyence LK-82G was used for measuring frequency response of the piezoelectric unimorph actuator. Permanent Niodymium magnet with the residual flux density B=1,2 T is applied for tuning resonance frequency of the cantilevered unimorph. The change of the separation distance d in range from 1 mm to 15 mm between a tip of cantilever and magnet was performed by means of the precision micro-screw drive. For the additional improve the effect of the magnetic force, two types of the MR fluids (MRF-122EG, MRF-140CG) was placed in the separation gap between the cantilever tip and magnet. A sinusoidal voltage U_0=6 V is used to excite the piezoelectric unimorph resonant frequencies of the bending vibrations. As a result of experiments we have curves of resonance frequency responses versus separation distance *d* between tip of the cantilever beam and the cylindrical magnet and the corresponding applied magnetic force shown in Fig. 4 a. The resonant amplitudes of the cantilever at the corresponding resonance frequencies and applied MRF are presented in Fig. 4 b.



a) b)

Fig. 4. Resonace characteristics of the cantilever; a - resonance frequency of the resonant cantilever versus separation distance *d* between tip of the cantilever beam and the cylindrical magnet; b – amplitude of the cantilever vibrations at the resonant frequencies : ___ - without MRF; □ - with MRF-122EG ; Δ – with MRF -140CG



a) b)

Fig. 5. Magnetic flux (a) and amplitude of the cantilever at the resonance frequencies (b) versus separation distance *d* between tip of the cantilever beam and the cylindrical magnet: ___ - without MRF; □ - with MRF-122EG ; Δ – with MRF -140CG

Magnetic flux in the gap between the cantilever ferromagnetic tip and permanent magnet is measured with magnetic flux meter SH1-8 and its dependence on distance *d* between tip of the cantilever beam and the cylindrical magnet is given in Fig. 5 a. The amplitude of the cantilever at the resonance frequencies versus separation distance *d* between tip of the cantilever beam and the cylindrical magnet is provided in Fig. 5 b. The results indicate that in the cases of high density MRF-140CG the increase of the viscosity and the vibration damping at the small *d* values eliminate the effect of the resonance frequency tunability. MRF-122EG can be applied as a damper for the suppression of the shutter-induced transient vibrations, when piezoelectric unimorph shutter is driven by TTL impulse.

A magnetic force technique (without MRF) enabled to increase the frequency of the resonance up to 110% of the untuned resonant frequency. A piezoelectric unimorph cantilever with a natural frequency of 126 Hz is used as the laser beam chopper or shutter, which is successfully tuned in a frequency range of 126 - 270 Hz to enable a continuous control of the laser over the entire frequency range.

Conclusions

This paper reports the design and testing of a resonance frequency-tunable piezoelectric unimorph chopper and shutter, which operation is based on magnetic force technique and application of magnetorheological fluid. A methodology is presented for the analysis and design optimization of piezoelectric unimorph actuator used for laser beam shutting systems. The magnetically-coupled piezoelectric unimorph cantilever motion is analyzed by means of a simple harmonic oscillator model with a non-linear magnetic force term. The results reveal that magnetic coupling can be used to increase the frequency of the resonance up to 110% of the untuned resonant frequency. Magnetic forces and MRF damping effect of transient vibrations of the piezoelectric unimorph shutter were experimentally evaluated.

Acknowledgment

This research was funded by a grant AUT-09/2010 and TPA-32/2010 from the Research Council of Lithuania

References

[1] **Sitti M, Campolo D, Yan J, Fearing R.** Development of PZT and PZN-PT Based Unimorph Actuators for Micromechanical Flapping Mechanisms Constant magnet motors. USA, 2001.

[2] **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.

[3] **Riesch C, Reichel E, Keplinger F, Jakoby B.** Characterizing Vibrating Cantilevers for Liquid Viscosity and Density Sensing, Hindawi Publishing CorporationJournal of SensorsVolume 2008, Article ID 697062, 9 pages doi:10.1155/2008/697062

[4] **Smits G, Ballato A.** Dynamic admittance matrix of piezoelectric cantilever bimorphs J. Micro-electromech. Syst.3(1994), P. 105–12

[5] **Tao W, Paul I.** Dynamic peak amplitude analysis and bonding layer effects of piezoelectric bimorph cantilevers, Smart Mater. Struct. 13 (2004) 203–210

[6] **Q. Wang, X. Du, B. Xu, and L. Cross.** "Electromechanical coupling and output efficiency of piezoelectric bending actuators" *IEEE Trans. on Ultrasonics, Ferro. and Freq. Control,* vol.46, pp. 638-646, May 1999.

[7] **Lin J-T, Barclay Lee, Alphenaar B.** The magnetic coupling of piezoelectric cantilever for enhanced energy harvesting efficiencys. Smart Mater. Struct. 19 (2010) 045012.

[8] **Vinod R. Challa, Prasad M. G., Yong Shi and Frank T. Fisher.** A vibration energy harvesting device with bidirectional resonance frequency tunability. Smart Mater. Struct. 17 (2008) 015035.