573. Development and investigation of novel design piezo-actuated laser beam shutting system

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Abstract. In this paper authors investigate the developed laser beam shutting system of a new design. The scheme of considered laser beam shutter and working principle are explained. Numerical analysis and experiments were performed for the laser beam shutting system. A finite element (FE) model of thin plate was constructed for numerical analysis. The model was solved by means of COMSOL nonlinear buckling analysis of the thin plate and using solid stress-strain application mode. Comparative analysis of theoretical and experimental research results of the developed laser beam shutting system was performed.

Keywords: vibrations, piezoelectric materials, laser shutter, position control, buckling analysis.

Introduction

In several fields (optics, space, aircraft, fluid control, biomedical, and manufacturing) there is a strong need for compact, robust and efficient positioning mechanisms that also offer high precision, short response times, low power consumption, low electromagnetic interference and multiple degrees of freedom. Piezoelectric actuators are good candidates for development of such mechanisms [1, 6].

Laser technologies are extensively used in modern equipment. Laser shutting or chopping systems are applied in order to control laser beam, which travels without obstruction through laser shutter system, if the shutter is opened. However, in that case if the shutter is completely or partially closed, laser beam is blocked either partially or totally.

In this paper authors investigate a developed novel laser beam shutting system.

Most laser beam choppers or shutters developed to date are based on single resonance frequency. Though recent efforts have been made to broaden the frequency range of laser beam choppers, a robust tunable frequency technique of the chopper is still lacking. 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 required [5, 7].

Scheme and working principle of the investigated laser beam shutter

The investigated piezoelectric laser beam shutter consists of piezoactuator *2* that is housed together in the housing device *1*. Special blade *4* for laser beam *5* shutting is attached to elastic carbon fiber element *3*. Its design is illustrated in *Fig. 1*. Bending deformations of elastic carbon fiber element *3* can be excited by the piezoelectric effect of piezoactuator *2*.

After supply voltage is connected piezoactuator *2* operates in d_{33} mode. It pushes up elastic carbon fiber element *3* and special blade *4* shuts (blocks) laser beam *5*. In order to obtain the required direction of motion of blade *4*, elastic carbon fiber element *3* is bended with primary angle α_{min}. If piezoactuator *2* is affected by supply voltage, elastic carbon fiber element *3* is pushed and bended by angle α_{max}. Displacement of special blade *4* Δd depends on bending angle α_{max} of elastic carbon fiber element *3*.

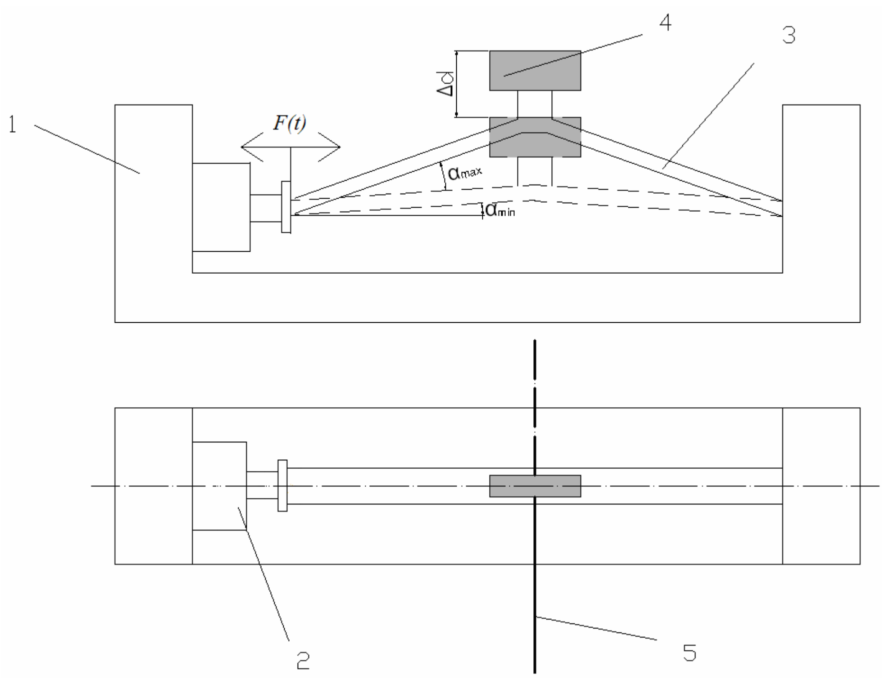

Fig. 1. Scheme of the developed piezoelectric laser shutting system

Carbon fiber and multilayer piezoactuator used in the laser beam shutting system

Carbon fiber plastic is composed from three types of polymer precursors - polyacrylonitrile (PAN) fiber, rayon fiber, and pitch. The tensile stress-strain curve is linear to the point of rupture. Although there are many carbon fibers available on the market, they can be arbitrarily divided into three grades as presented in *Table 1*. They have lower thermal expansion coefficients in comparison to glass and aramid fibers. Carbon fiber is anisotropic material and its transverse modulus is of an order of magnitude less than its longitudinal modulus. The material has a very high fatigue and creep resistance. Since its tensile strength decreases with increasing modulus, its strain at rupture is much lower. Because of the material brittleness at higher modulus, it becomes critical in joint and connection details, which can have high stress concentrations. As a result of this phenomenon, carbon composite laminates are more effective with adhesive bonding that eliminates mechanical fasteners [2, 4]. Mechanical properties of the carbon fiber plastic are presented in Table 1.

Table 1. Properties of the carbon fiber element [2]

Property	Values of carbon fiber	Unit
Density	1.4×10^3	kg/m^{-3}
Young's modulus	73.8×10^9	Pa
Tensile strength	3×10^3	MPa
Shear strength	19	GPa

Employed piezoelectric actuator PSt/150/4/20 VS9 (Piezomechanik GmbH) is used for the laser beam shutter as indicated in Fig. 2 and its technical data is listed in Table 2.

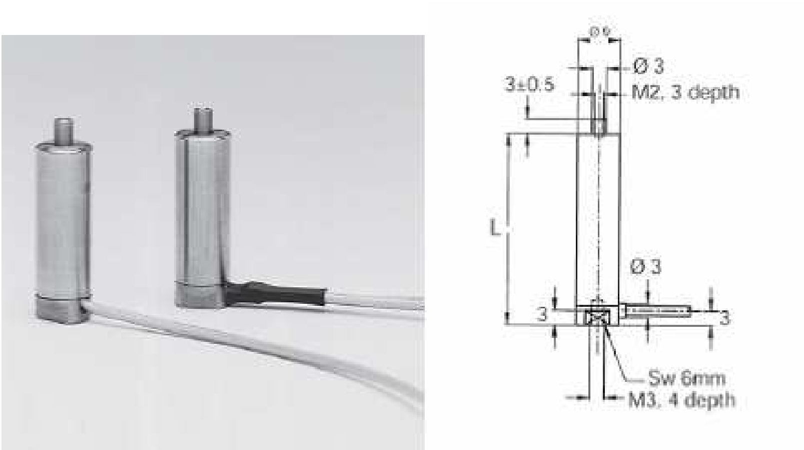

Fig. 2. The scheme of piezoelectric actuator used for laser beam shutter

Table 2. Technical specifications of the piezoactuator [3]

Property of PSt/150/4/20 VS9	Value
Prestress force, tensile force, N	40
Max. load force, N	300
Max force generation, N	300
Max. stroke, µm	27/20
Length, mm	28
El. Capacitance, nF	340
Resonant frequency, kHz	30

Numerical Analysis

For numerical analysis, a finite element (FE) model of the thin carbon fiber elastic plate was developed with subsequent buckling analysis performed in COMSOL software. The types of buckling analysis are: eigen (or linear) buckling analysis and non-linear buckling analysis.

Eigen buckling analysis predicts the theoretical buckling strength of an ideal linear elastic structure. This analysis is used to predict the bifurcation point using linearized model of elastic structure. It is a technique used to determine buckling loads (critical loads) at which the structure becomes unstable and acquires buckled mode shapes (the characteristic shape associated with a buckled response of the structure). COMSOL finite element software package is used to determine the buckling strength of the thin plate through Eigen buckling analysis. In Eigen buckling analysis, nonlinearities cannot be included.

The basic form of the Eigen buckling analysis is given by

$$[K]\{\Phi_i\}=\lambda_i[S]\{\Phi_i\},$$

where [K] - Structural stiffness matrix, $\{\Phi_i\}$ - Eigen vector, λ_i - Eigen value, [S] - Stress Stiffness matrix

Non-linear buckling analysis is a more accurate approach and therefore this finite element analysis has a capability of analyzing actual structures. This approach is highly recommended for design or evaluation of actual structures. This technique employs nonlinear structural analysis with gradually increasing loads to seek the load level at which the structure becomes unstable. Using this nonlinear technique, features such as initial imperfections, plastic behavior etc. can be included in to the model. In this analysis, geometrical nonlinearities are utilized, because the thin plate structure is subjected to large deformations.

We have analyzed buckling of a thin axially-loaded plate. The boundary conditions become free in axial and fixed in other directions in one end of the plate model and fixed in the second end. The actuation model of the piezoelectric laser shutter is presented in Fig. 3, where *F(t)* is an excitation force generated by the piezoelectric actuator, 1 – elastic carbon fiber plate of length l, width a and thickness h, 2 – shutting blade of mass m. Two plates of length 44 mm and 52 mm where investigated. The calculated dependences of buckling deformations of the elastic carbon fiber plates are presented in Fig. 4-5. Fig. 6 presents the dependence of middle point buckling displacements Δd of elastic carbon fiber plate on the piezoelectric actuator displacements Δu.

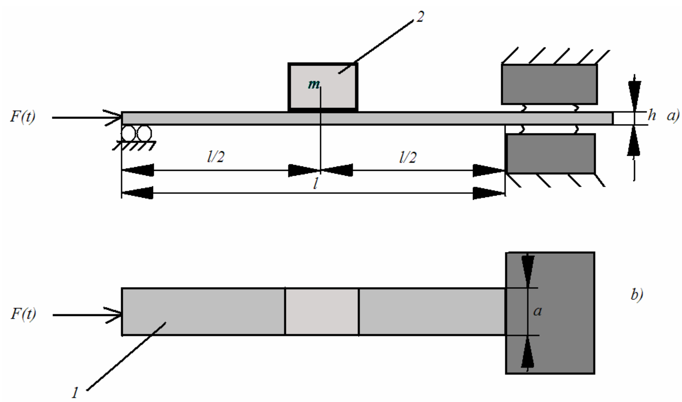

Fig. 3. Actuation model of the piezoelectric laser shutter

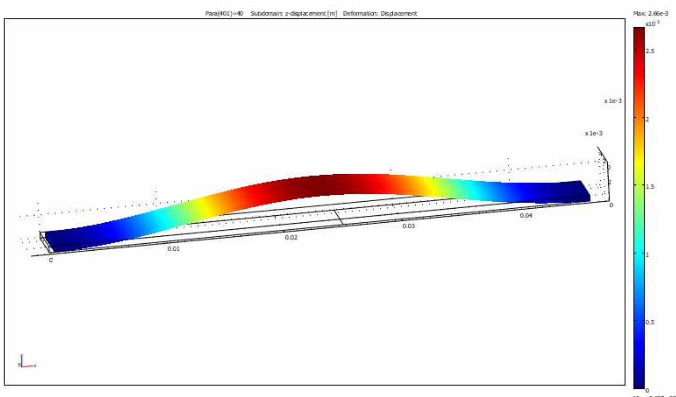

Fig. 4. Buckling deformations of elastic carbon fiber plate

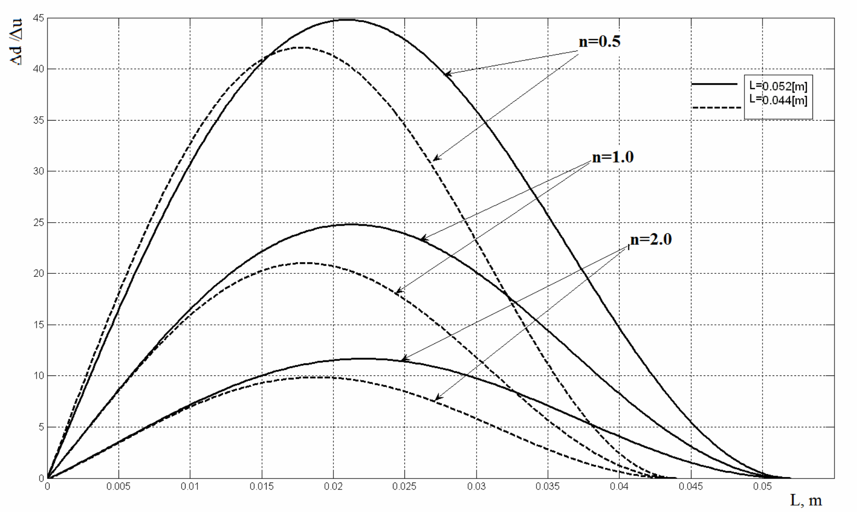

Fig. 5. Relative buckling displacements of elastic carbon fiber plates of length of 44 mm and 52 mm at the pre-strained deformations of 0,5 mm, 1,0 mm and 2,0 mm at middle point of the plate

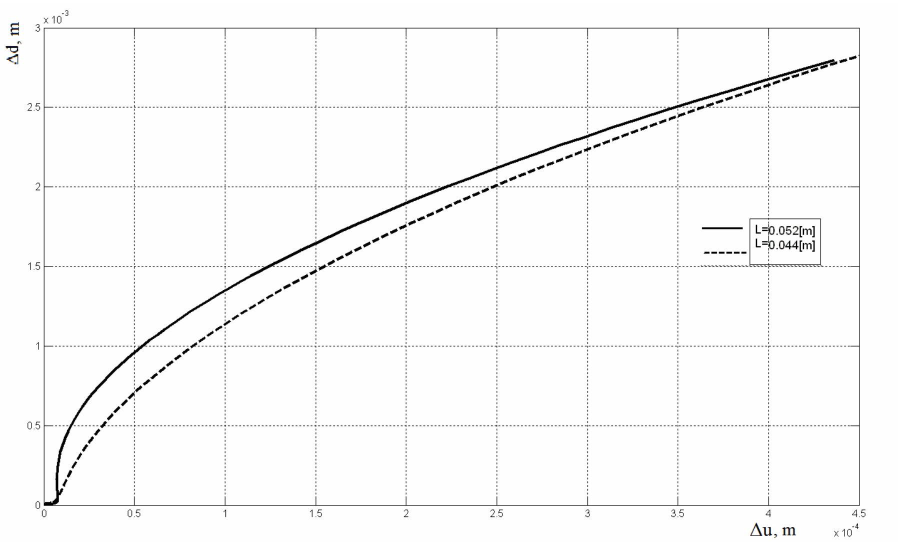

Fig. 6. Dependence of middle point buckling displacements Δd of elastic carbon fiber plate on the piezoelectric actuator displacements Δu for the plates of the length of 44 mm and 52 mm

Experimental investigation

Displacements of piezoelectric laser beam shutter were measured by experimental setup illustrated in Fig. 7. Experimental setup 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 laser beam shutter.

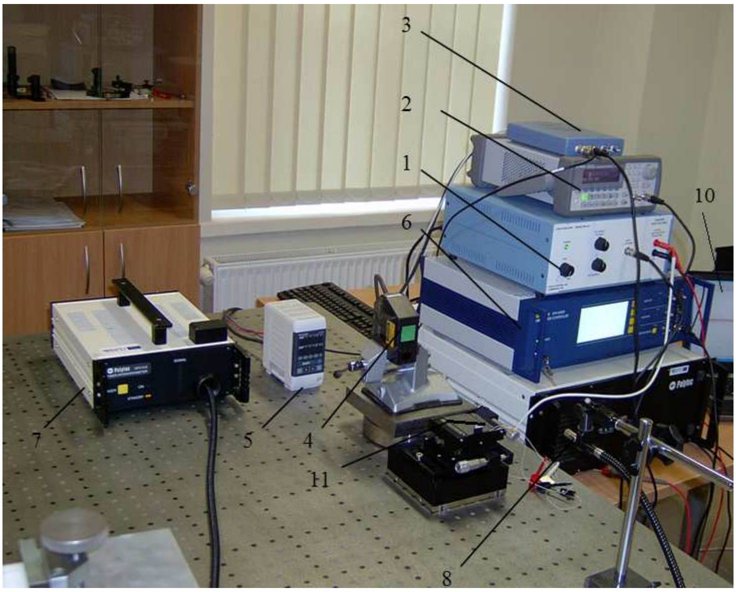

Fig. 7. Experimental setup

The measurements of displacements at vibrational frequency of 120 Hz for the piezoelectric laser beam shutter were performed in three points as it is indicated in Fig. 8. Experimental results provided in Fig. 9 are in agreement with the curves of theoretical calculations (Fig. 5) and indicate the asymmetry of deformations of the elastic plate due to different fixation conditions of the plate ends.

Dependence of middle point displacements Δd of elastic carbon fiber plate on piezoelectric actuator static displacements Δu for the plate lengths 44 mm and 52 mm is presented in Fig. 10

The obtained theoretical results provided in Fig. 6 are close to experimental (Fig. 10) and indicate the highest displacements at small pre-strained deformations of the elastic plate.

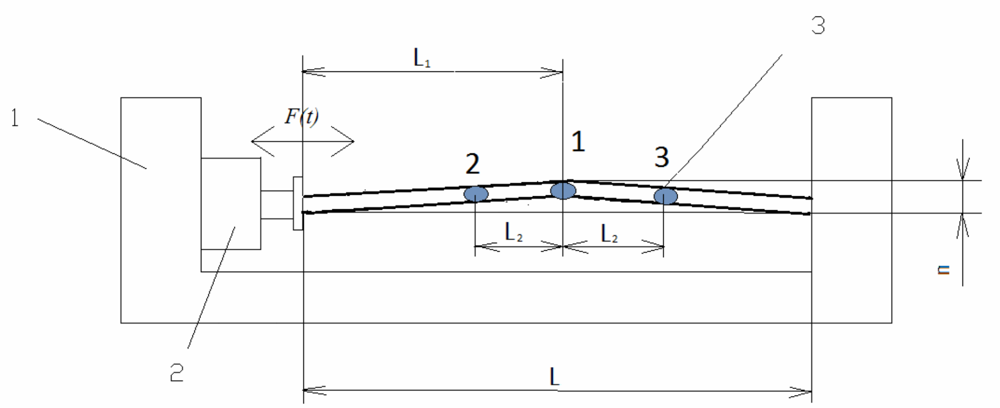

Fig. 8. The scheme of experimental measurements

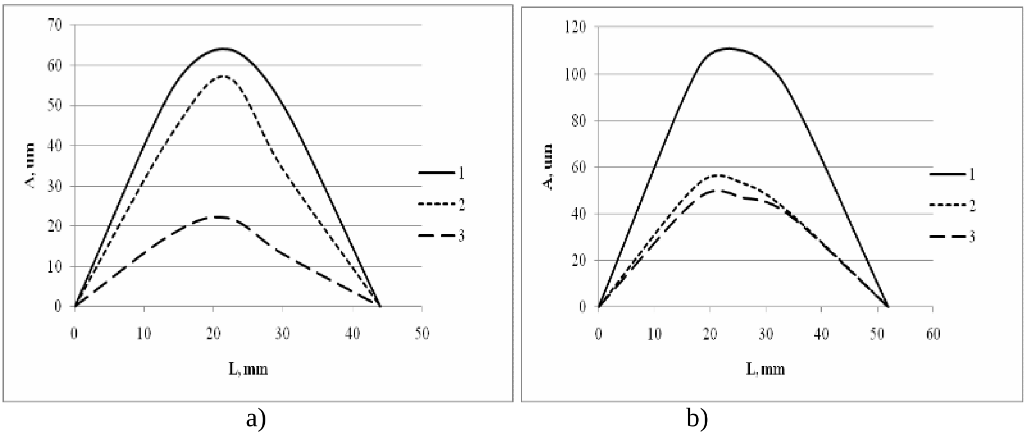

Fig. 9. Displacements of elastic carbon fiber plate: a – plate length L = 44 mm, b – plate length l = 52 mm

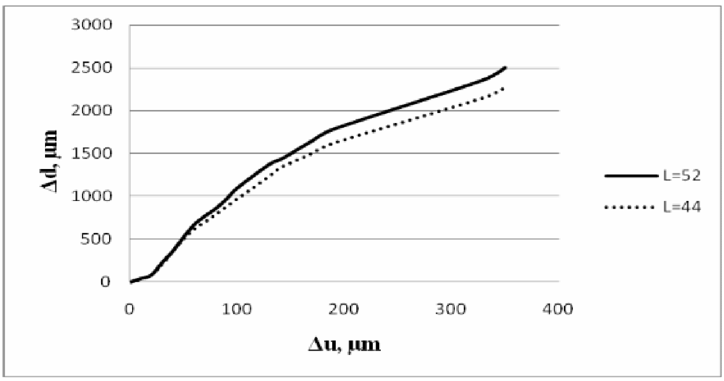

Fig. 10. Dependence of middle point displacements Δd of elastic carbon fiber plate on piezoelectric actuator displacements Δu for the plate lengths of 44 mm and 52 mm

Conclusions

The article presents a theoretical and experimental investigation of the developed laser beam shutter with buckling type displacement amplification member actuated by the piezoelectric actuator. Finite element model of thin plate was built for numerical analysis. The FE model of the laser beam shutting system was developed by means of COMSOL nonlinear buckling analysis of the thin plate. The results of experimental investigation fully confirmed the data obtained during solution of the mathematical model and revealed the possibilities to optimize the design and materials for generating maximum displacements of the laser shutter.

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