Development and Experimental Analysis of Piezoelectric Optical Scanner Based on FEM and Laser Holography

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D	electric induction in the piezoceramic exciter
E	tension of the electric field
ε	dielectric constant
e	piezoelectric coefficient
S	transverse deformation
σ	elastic stress
c_0	velocity of acoustic deformation waves in the piezoceramics
j	imaginary unit
ω	resonant frequency
U_o	displacement of particles in the piezoceramics in the direction of axis x
t	time
U_1	displacement in the waveguide
c_1	velocity of acoustic deformation waves in the waveguide
V_0	amplitudes of harmonic vibrations of the piezoelectric exciter
V_1	amplitudes of harmonic vibrations of the waveguide
a	height of the piezoelectric exciter
l	height of the waveguide
ρ_0	material density of the piezoelectric exciter
ρ_1	material density of the waveguide
Q	contact area between the piezo exciter and the waveguide

ABSTRACT

Piezoelectric optical scanner is developed for multi-coordinate control of optical laser beam. Such type of opto-micro-mechanical systems can be used for accurate angular or linear deflection of optical elements in various optomechanical and optoelectronic systems. The operating principle of these devices is based on piezoelectric effect and on conversion of high-frequency multi-dimensional mechanical oscillations of piezoelectric vibration transducers into directional multi-coordinate motion of the optical elements in the measurement chain. The main distinctive feature of such optical piezoelectric scanners is the combination of high micrometer range resolution with a wide range of angular deflections of the scanning elements. The device consists of piezoelectric cylinder and a scanning element with three degrees of freedom. The control model of this device was derived using mixed finite element techniques. Special procedures were developed to obtain optimal configuration of discrete electrodes on the surface of piezoelectric cylinder. Dynamic model comprising matrix differential equation of the scanning element and FEM model of the piezoelectric actuator was used to derive adaptive control scheme.

Experimental time averaging laser holography was used to validate the numerical model and to test the functionality of piezoelectric optical scanner.

INTRODUCTION

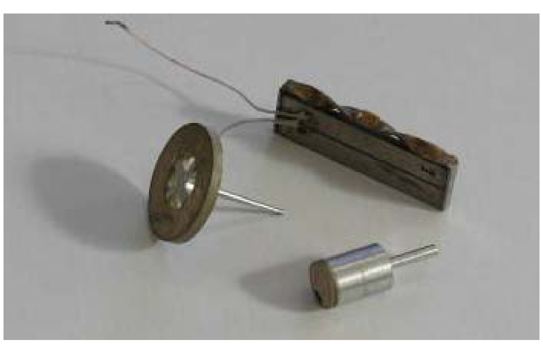
Optical scanning equipment is exploited in numerous areas of engineering and science – applications ranging from defense to communications [1, 2, 3]. The object of this paper is to investigate possibilities for development of fast operating two-coordinate enhanced angular range scanner of optical laser beam.

The initial predetermined data for the optical scanner under consideration were the following. The mirror diameter had to be 5 mm; thickness 0.3 mm. The mirror must perform harmonic oscillations in respect of mutually perpendicular axes in the plane of the mirror. Oscillation frequency must be 20.5 kHz and 25 Hz. Amplitudes of oscillations must be at least 2° in both directions thus enabling to cover angular scanning field 4° x 4°. Essential requirement is the coincidence of the centre of the mirror with the point of intersection of the coordinate axes. The oscillations at 25 Hz can be of the saw type – in that case the linearity of the angle dependence from time must be not worse than 0.5 %.

Possible strategies for the design of optical scanner are discussed in this section. The most difficulties occur when the oscillations must be excited at frequency 25.6 kHz (ultrasonic frequency range) at the predefined amplitudes. As the frequency of excitation is constant in time, it is purposeful to exploit piezoelectric resonance type mechanical systems. Absence of mechanical transmission links is possible only when rotational oscillations are excited with the axis of symmetry coinciding with one of the bending axis. Such type of scanner design technology has been exploited in different application including low and high scanning frequency range. A tuning fork type scanners with mirror dimension 40 x 40 mm, scan angle 20° (± 10°) at frequency 30 Hz and mirror dimension 5 x 5 mm, scan angle 3° (± 1,5°) at frequency 1500 Hz are described in [4]. Electromagnetic two-arm tuning fork waveguide type exciters are exploited in those scanners. More advanced one-coordinate scanners based on rotational oscillations and magnetosrtiction transformers are described in [5]. Such systems posses good stability and are well operating at one pre-designed frequency. A mirror diameter 4 mm is atomized onto a surface at the end of concentrator of angular oscillations. The frequency of oscillation is 28,35 kHz at amplitude 7°.

The tendency of development of high frequency one-coordinate scanners based on angular oscillations at fixed pre-designed frequencies is described in [6]. That confirms also our experience accumulated at Kaunas University of Technology in the area of design of precision scanning mechanisms [7]. Angular oscillation systems with piezoelectric vibration concentrators seem to be optimal solution for high frequency scanning at predefined frequencies constant in time.

Different types of optical scanners developed at Kaunas University of Technology are presented in Figure 1. We will concentrate on investigation of development and experimental analysis of one of the simplest types of scanners comprising a piezoelectric exciter, waveguide, vibration concentrator and a mirror attached to the end of the concentrator (Figure 2).



a)

b)

Figure 1. Piezoelectric optical scanners: a- general view of different types of piezoelectric optical scanners developed at Kaunas University of Technology; b- optical scanner with piezoceramic cylinder.

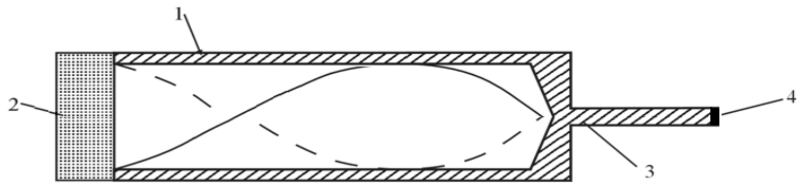


Figure 2. Construction of optical scanner: 1 – waveguide; 2 – piezoelectric exciter; 3 – vibration concentrator; 4 – mirror.

INVESTIGATION OF THE DYNAMICAL EXCITATION OF THE MIRROR

The equations of direct and inverse piezoeffects in the piezoceramic exciter 2 (Figure 2) take the form:

$$\begin{aligned} D &= E\varepsilon + eS \\ \sigma &= -eE + c_0 S \end{aligned} \tag{1}$$

where D denotes electric induction in the piezoceramic exciter; E – the tension of the electric field; ε – dielectric constant; e – piezoelectric coefficient; S – transverse deformation; σ – elastic stress; c_0 – the velocity of acoustic deformation waves in the piezoceramics.

If the piezoceramic exciter operates at the resonant frequency, Eq.(1) is transformed to

$$\begin{aligned} D\exp(-j\omega t) &= E\varepsilon + e\frac{\partial U_0}{\partial x} \\ \sigma &= -eE + \frac{\lambda_0\omega}{2\pi}\cdot\frac{\partial U_0}{\partial x} \end{aligned} \tag{2}$$

where j denotes imaginary unit; ω – the resonant frequency; U_o – the displacement of particles in the piezoceramics in the direction of axis x; t – time; $\lambda_0 = 2\pi c_0/\omega$.

Then the elastic stress in the piezoceramics can be expressed like:

$$\sigma = \frac{\lambda\omega}{2\pi}\cdot\frac{\partial U_0}{\partial x} - \frac{e}{\varepsilon}\left(D\exp(-j\omega t) - e\frac{\partial U_0}{\partial x}\right) \tag{3}$$

The oscillatory motion in the mechanical waveguide 1 (Fig. 1) is described by the following system of equations [8]:

$$\begin{aligned} \frac{\partial^2 U_0}{\partial t^2} &= c_0^2\frac{\partial^2 U_0}{\partial x^2} \\ \frac{\partial^2 U_1}{\partial t^2} &= c_1^2\frac{\partial^2 U_1}{\partial x^2} \end{aligned} \tag{4}$$

with the following boundary conditions:

$$\begin{aligned} &U_0 = U_1 \\ &\frac{\lambda_1\omega}{2\pi}\cdot\frac{\partial U_1}{\partial x} = \frac{\lambda_0\omega}{2\pi}\cdot\frac{\partial U_0}{\partial x} - \frac{e}{\varepsilon}D\exp(-j\omega t) + \frac{e^2}{\varepsilon}\cdot\frac{\partial U_0}{\partial x} \end{aligned} \tag{5}$$

where U_1 denotes the displacement in the waveguide; c_1 – the velocity of acoustic deformation waves in the waveguide; $\lambda_1 = 2\pi c_1/\omega$.

When the piezoceramic exciter performs the harmonic oscillations, the solution of Eq.(4) with conditions Eq.(5) can be approximated by the following relationships:

$$\begin{aligned} & -V_1 \sin\frac{\omega l}{c_1} = V_0 \sin\frac{\omega a}{c_0} \\ & \rho_1 c_1 \omega V_1 \cos\frac{\omega l}{c_1} = V_0 \omega \cos\frac{\omega a}{c_0}\left(\rho_0 c_0 + \frac{e^2}{\varepsilon c_0}\right) - \frac{e}{\varepsilon} D \end{aligned} \qquad (6)$$

where V_0 and V_1 – the amplitudes of harmonic vibrations of the piezoelectric exciter and the waveguide; a – height of the piezoelectric exciter; l – height of the waveguide; ρ_0 and ρ_1 – material density of the piezoelectric exciter and the waveguide; a – height of the piezoelectric exciter.

The force transferred to the mechanical wavequide can be calculated from the following relationship:

$$F_1 = Q\frac{\lambda_1 \omega}{2\pi} \cdot \frac{\partial U_1}{\partial x}. \qquad (7)$$

where Q denotes the contact area between the piezo exciter and the waveguide. Finally, the expression of contacting force takes the form:

$$F_1 = \frac{-\rho_1 c_1 \frac{e}{\varepsilon} DQ \exp(-j\omega t)}{\rho_1 c_1 \cos\frac{\omega l}{c_1} + \sin\frac{\omega l}{c_1} \operatorname{ctg}\frac{\omega \mathrm{a}}{\mathrm{c}_0}\left(\rho_0 c_0 + \frac{e^2}{\varepsilon c_0}\right)} \qquad (8)$$

Now, the optimal length of the waveguide can be selected from the condition of maximization of the transferred force:

$$l = \frac{c_1}{\omega} \operatorname{arctg}\left(\frac{\rho_0 c_0 + \frac{e^2}{\varepsilon c_0}}{\rho_1 c_1} \operatorname{ctg}\frac{\omega \mathrm{a}}{\mathrm{c}_0}\right) \qquad (9)$$

Eq.(9) shows that the maximum force of pressing is approximately achieved when the length of the waveguide is integer number and one quarter of the acoustic deformation wave length in the waveguide. This is important conclusion which can be applied for the practical design of waveguides for scanning equipment.

HYBRID NUMERICAL-EXPERIMENTAL METHODOLOGY

A number of experimental studies are needed in order to ensure high dynamic accuracy of operation of the optical scanners. In most cases the exciting frequencies are quite high, and the amplitudes corresponding to them are measured in micrometers. Therefore the holographic method can be effectively applied for the visual representation of wave processes taking place in the waveguide of the optical scanner. The most effective method for studying the standing wave processes is the method of holographic interferometry with time averaging. It should be noted that the most clearly expressed bands in the holographic interferograms are those recorded at the positions of minimum amplitudes.

The amplitudes of vibration of the structure are determined using the methodology presented in papers [10-16]. Figure 3 presents the structural diagram of a setup for experimental analysis of the tabular vibratory valve and the piezo-mechanical exciter. The stand contains the optical piezoelectric scanner 1 which piezo-mechanical exciter is harmonically excited by the high-frequency signal generator 2 and the amplifier 3. The signal frequency is monitored by the frequency meter 4, the voltage amplitude of the power supply is monitored by the voltmeter 5. The optical circuit of the stand includes a holographic installation with a helium-neon laser which serves as a source of coherent radiation. The beam from the laser 6 splits into two mutually coherent beams passing through the beam splitter 7. The object beam, reflected from the mirror 8, is split by the lens 10 and illuminates the surface of the tubular working tube 1 and, after reflecting from it, impinges on the photographic plate 12. The reference beam, reflected by the mirror 9, and expanded by the lens 11, illuminates the holographic plate 12 where the interference structure is recorded.

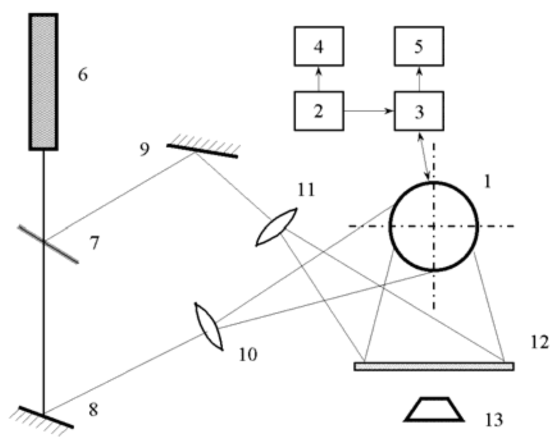


Figure 3. The schematic drawing of the laser holographic interferometry system.

The characteristic function defining the complex amplitude of the laser beam M_T in the plane of the hologram formed by the time averaging holography techniques takes the form [11]:

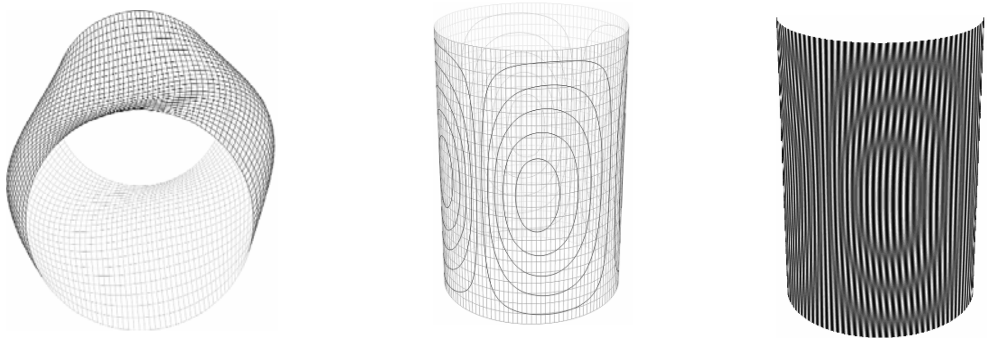
$$M_T = \lim_{T\to\infty} \frac{1}{T}\int_0^T \exp\left(i\left(\frac{4\pi}{\lambda}\right) Z(x)\sin\omega t\right) dt = J_0\left(\left(\frac{4\pi}{\lambda}\right) Z(x)\right) \qquad (10)$$

where T – the exposure time of the hologram, ($T >> 1/\omega$); ω – the frequency of structural vibrations, λ – the laser wavelength; J_0 – zero order Bessel function of the first type. Then, the resulting intensity I of the point (x,y) on the hologram is:

$$I(x,y) = a^2(x,y)\left|M_T\right|^2 , \qquad (11)$$

where a(x,y) – the distribution of the amplitude of the incident laser beam. It can be noted that the centers of dark interference bands in the holographic interferogram coincide with such values of $Z(x)$ which turn the Bessel function to zero. The structure of the distribution of the interference bands does not depend from the static deformations of the structure, nor from the distance between the structure and the hologram.

Hybrid numerical – experimental techniques can be effectively exploited for interpretation of experimental results. Finite element model of the waveguide is constructed and its high frequency harmonic oscillations around the state of equilibrium are visualized in virtual computational environment mimicking the fringe formation in optical experiments.

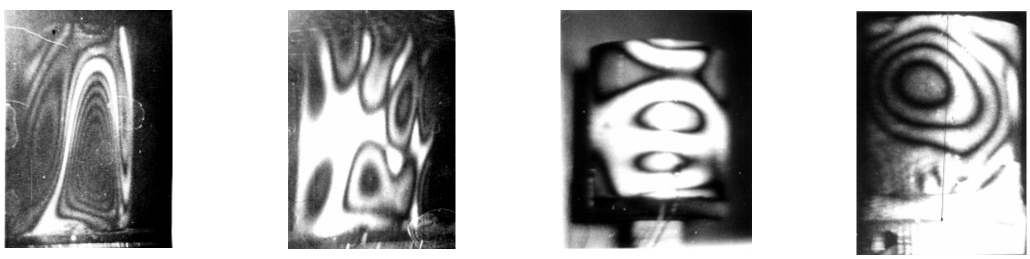


(a) (b) (c)

Figure 4. Finite element model of the waveguide: a – deflections of the waveguide according to its first eigenshape; b – isolas describing magnitudes of dynamic deflections; c – numerically mimicked interference fringes.

EXPERIMENTAL INVESTIGATIONS

Experimental investigations were based on time average laser holography concentrating on the dynamics of the waveguide. Four different laser holograms are presented in Figure 5.

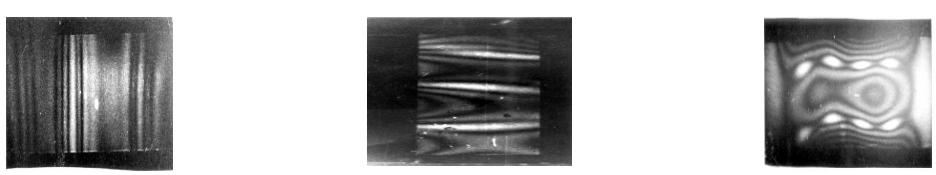


(a) (b) (c) (d)

Figure 5. Time average holograms of the waveguide.

Figure 5a shows a pattern of holographic interference fringes on the surface of the waveguide when the piezoelectric exciter performs resonance vibrations at 20.5 kHz. A well developed mode of bending vibrations can be noted. Figure 5b presents time average hologram of the waveguide at the frequency of excitation of 25 kHz. As this frequency is out of resonance, one can note large white areas in the hologram which correspond to very small field of dynamic amplitudes. The reactions of the waveguide to piezoelectric excitation are poor and the functionality of the scanner is unacceptable.

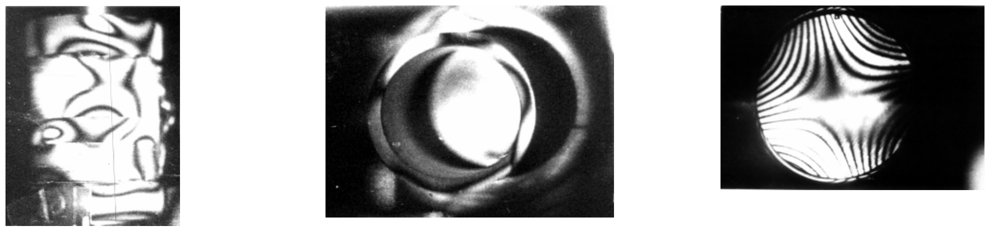
Figure 5c and Figure 5d present time average holograms of a waveguide which height *l* is 1.2 times smaller compared to the wave guide analysed in Figure 5a and Figure 5b. Again, Figure 5c corresponds to excitation frequency 20.5 kHz and Figure 5d – to 25 kHz. Well developed pattern of fringes in Figure 5d confirms that the waveguide is operating at resonance mode what ensures good operation of the optical scanner. Large white areas in Figure 5c correspond to poor out of resonance functionality. The conclusion is that the optical scanners of this type cannot be operated at different frequencies of excitation – every pre-determined scan frequency must be evaluated in the design stage of the instrument.



(a) (b) (c)

Figure 6. Time average holograms of the vibration concentrator.

Figure 6 presents time average holographic interferograms of the vibration concentrator at different modes of operation. Figure 6a shows the concentrator at the operation frequency 20.5 kHz (the first type of the waveguide). Almost parallel interference lines show that the concentrator is deflecting along the *x*-axis in a well defined manner. This is an excellent mode of operation and such scanner dynamic reaction is well suited for optical scanning applications. Figure 6b shows the interferogram of the concentrator at 25 kHz (the second type of the waveguide). Again, the concentrator dynamics is satisfactory, it performs a well defined mode of vibration along the y-axes. Figure 6c shows the dynamics of the concentrator at 20.5 kHz with the second type of the waveguide. The well developed pattern of fringes now shows that the concentrator does not deflect in a simple way; complex standing waves are occurring in the concentrator's plane. Such mode of operation is unacceptable for optical scanning and confirms the conclusion of the preceding section.



(a) (b) (c)

Figure 7. Time average holograms of the piezoelectric exciter and the mirror.

Figure 7. shows time average laser holographic interferograms of the piezoelectric exiter. The side view of the exciter (Figure 7a) reveals a complex structure of interference pattern confirming complex interactions between the piezoelectric material and the waveguide. Figure 7b presents a bottom view which reveals nice fringe contours around the contact surface between the piezoelectric exciter and the waveguide. Figure 7c presents a pattern of interference fringes of the mirror. A well defined pattern of fringes confirms the applicability of the presented scanning techniques for optical scanning applications.

CONCLUSIONS

New type of piezoelectric optical scanner is designed and analyzed. The methodology of identification of vibration peaks enabled experimental optimization of the working regimes of the system. Such type of analysis could be successfully applied in the design stage of different precise vibratory systems. Numerical modeling based on development of FEM system model and is coupled with optical fringe formation and analysis algorithms providing the basis for hybrid numerical-experimental techniques which can be applied for a rather broad class of mechanism, applicable for optical scanning.

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