

286. Development and experimental analysis of piezoelectric optical scanner with implemented periodical microstructure

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Abstract. Piezoelectric optical scanner is developed for multi-coordinate control of optical laser beam by excitation of microstructures. The manufactured microstructure is the periodical structure which was implemented in piezoelectric optical scanner design. 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 manufacturing process and visualization of the microstructure were presented. The device consists of piezoelectric cylinder and a scanning element with three degrees of freedom. The control model of this device was derived using simulation results of optical scanner by COMSOL Multiphysics software. ESPI digital holographic PRISMA system was used to validate the result of simulation of piezoelectric optical scanner and to test the functionality of piezoelectric optical scanner with implemented microstructures.

Keywords: Piezoelectric optical scanner, holography, periodical microstructure.

Introduction

Optical scanning equipment is exploited in numerous areas of engineering and science – applications ranging from defense to communications [1-3]. 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 tendency of development of high frequency one-coordinate scanners based on angular oscillations at fixed pre-designed frequencies is described in [4]. That confirms also our experience accumulated at Kaunas University of Technology in the area of design of precision scanning

mechanisms [5-8]. 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 [5] are presented in Fig. 1. We will concentrate on investigation of development and experimental analysis of one of the working regimes of piezoelectric optical scanner comprising a piezoelectric exciter, waveguide, vibration concentrator and a microstructure, as periodical structure which is used for laser beam control. The periodical structure is attached to the end of the concentrator.

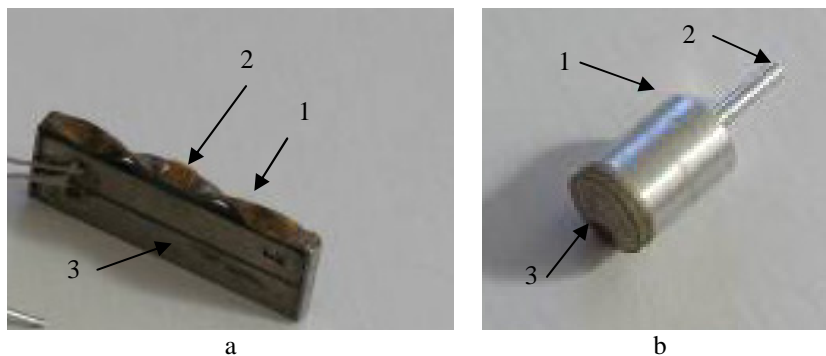


Fig. 1. Different types of piezoelectric optical scanners developed at Kaunas University of Technology: a – twisted plate (1), with implemented diffraction element (2); b – concentrator of vibrations (1), with implemented diffraction element (2) at the end

Manufacturing and analysis of periodical structure

The diffractive optical element produced in the main technological steps such as origination (based on microlithography and dry etching), replication either by UV hardening or by embossing of Ni replica in polymer.

Periodic trapezoidal profile structures were produced in crystalline silicon using standard contact-optical lithography processes and reactive ion etching (RIE). 2D structures in Si substrate were formed by RIE in the SF₆/N₂ gas mixture plasma, using plasma-etching equipment PK-2420RIE [9]. Replicas of these periodical structures were formed by UV light hardening replication using commercial photopolymer (acrylic trimethylolpropane ethoxylate) (layer thickness 2μm, area 3cm²), PET substrate and home made technological device (T=20°C, irradiation distance 10cm, UV light source DRT-230: λ=360nm, I=10000lx) [10]. Then photopolymer replica was metallized with nickel or Al film (thickness of 20 nm). Then nickel stamp was fabricated by using the electroplating process (electroplating based on nickel sulfamate (Ni(SO₃NH₂)) electrolyte and additives) following conditions: pH – 3.5-4.5, temperature 50°C, current density 4 mA/cm². During the process of

replication surface relief of a patterned master - the nickel stamp was transferred to the thin polymer film coated onto a hard substrate using heat and pressure [11, 12]. Embossing experiments were performed using a roll thermal pressure device of original construction controlling pressure force, temperature and duration of exposure (p=0.1÷0.3 MPa, T=100÷130°C, t=1÷5s) [13, 14].

Analysis methods. The following analytical methods were used to analyze geometrical and optical parameters of the master matrix and different replicas: a laser diffractometer (He-Ne, λ=632.8nm, the reflection diffraction spectra were registered by a photodiode), and atomic force microscope NANOTOP-206 (AFM) operating in a contact mode (cantilever force constant 0.35 N/m).

Diffraction efficiencies could be measured by a photodiode of diffracted light in all maxima (0, ±1, ±2, and etc.) for different angles of incidence light with respect to the normal. This method could be used for nondestructive analysis of optical parameters (Fig. 2a) of the sensor shown in AFM photograph (Fig. 2b). The same method could be used for evaluation of geometrical parameters nondestructively and directly in the system.

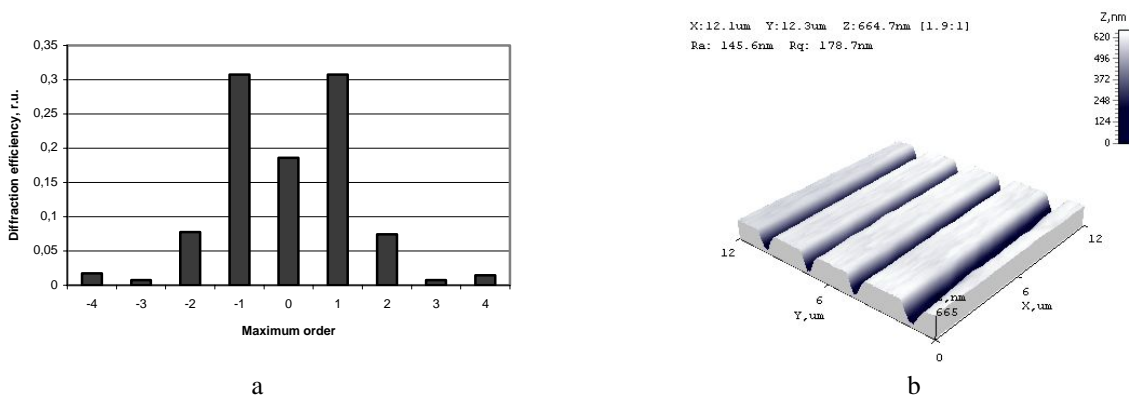
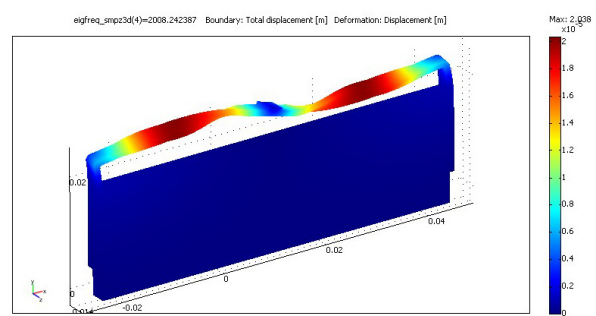
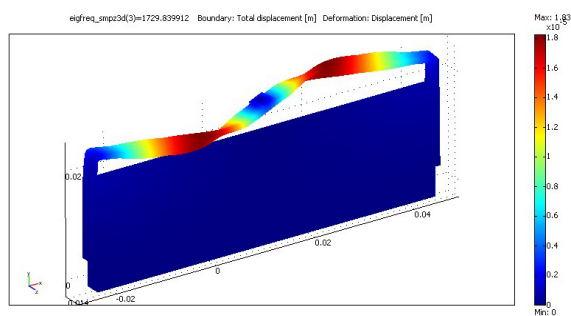


Fig. 2. Relative diffraction efficiencies (a) and AFM photograph (b) of the metallized photopolymer diffraction grating (trapezoidal profile, period $d=3\mu\text{m}$)

Simulation of the dynamical excitation

In order to determine working regimes two types of piezoelectric optical scanners (Fig. 1) were analyzed numerically using finite element method (FEM) by

COMSOL Multiphysics. There are presented surface plots for both scanners: the displacement, and deformed shape plots corresponding to the six different eigenfrequencies are presented in Fig. 3-4.



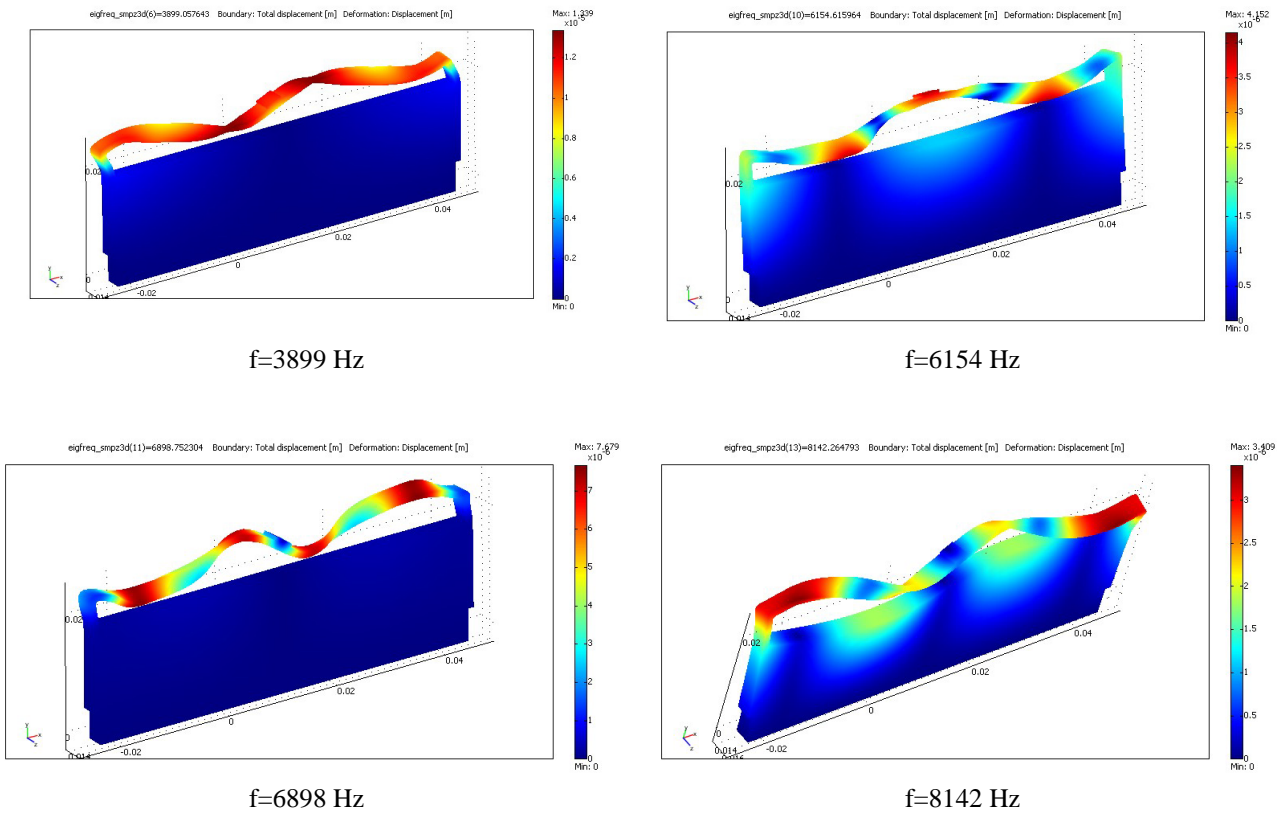
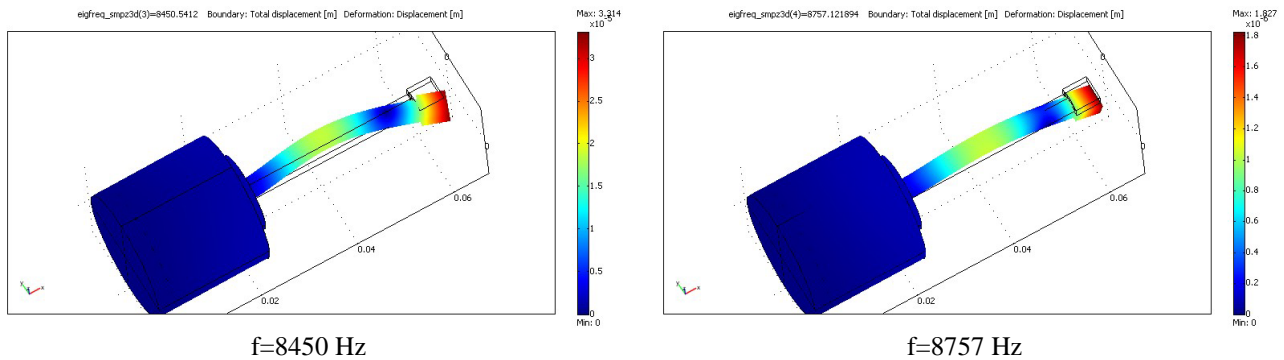


Fig. 3. Surface plot of displacement, and deformed shape plot corresponding to the six different eigenfrequencies

Experimental investigation

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 digital holographic interferometry.

The tests used the PRISMA system [9] layout shown in Fig 5. The PRISMA system shown in Fig. 5 is a two beam speckle pattern interferometer. The laser beam directed at the object is the object beam, the other beam, which goes directly to the camera, is the reference beam. Laser light is scattered from the object and collected by the camera lens, which also images the object onto the CCD camera sensors. The reference beam goes directly to the camera, usually in an optical fiber, where it overlaps the image of the object. Shape changes that occur between a reference and a stressed state of the object produce fringes on top of the image of the object, which is displayed on the TV monitor.



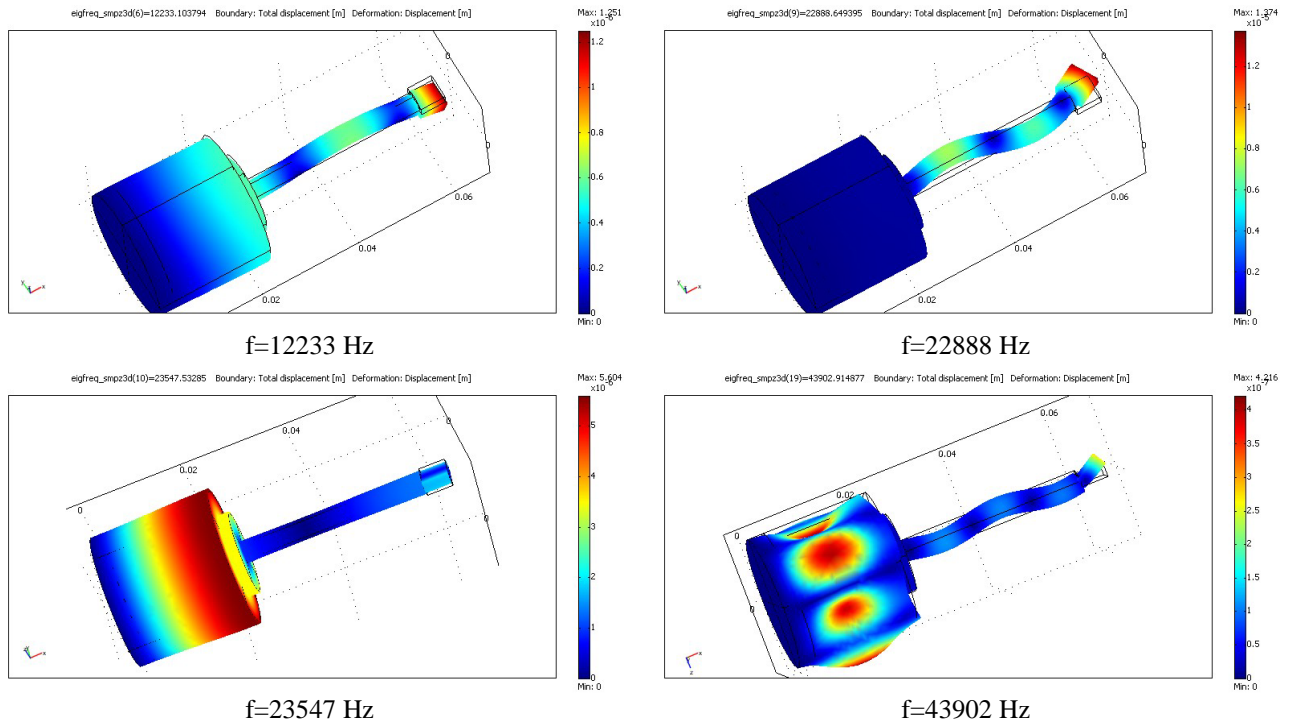


Fig. 4. Surface plot of displacement, and deformed shape plot corresponding to the six different eigenfrequencies

Phase shifting is required for TV holography. Phase shifting is usually accomplished by applying a voltage to a piezoelectric (PZT) crystal behind one of the mirrors in the reference beam. This changes the optical path length of the reference beam by a quarter wave length of light between each frame. A common test procedure is to collect eight TV frames of phase shifted data. The first four frames are collected and stored in computer memory as the reference state of the object. The object is then stressed for the test, and another four frames of data are collected and stored. The eight frames of data, four frames from the object reference state and four frames from the object stressed state, are then processed in the PC. The result is displayed as fringes on top of the image of the object on the TV monitor. The fringes show a contour map of the shape change between the object reference and the stressed state.

Because the TVH system is an optical interferometer, a fraction of a wave length of light path length change between the reference beam and the object beam shifts the fringe pattern, and random path length changes caused by

unwanted vibration completely wipe out the fringes and destroy the data. TVH also imposes special conditions on the laser light source. If the laser has many longitudinal modes, then the reference and the object beam path lengths must be carefully matched. This is of course possible on a large optical table, but inconvenient for building a small TVH system. Single frequency lasers are convenient for TVH. They have a long enough coherence length that object and reference beam path lengths do not need to be the same; consequently, with single frequency lasers it is possible to configure a convenient TVH interferometer package. The disadvantage, of course, is that high power, single frequency lasers are expensive.

PRISMA combines all the necessary equipment for deformation and vibration measurement of most materials in a small lightweight system. A standard system includes holography and computer systems integrated with proprietary state of the art software. The main parts of the PRISMA system setup are presented in Fig. 5.

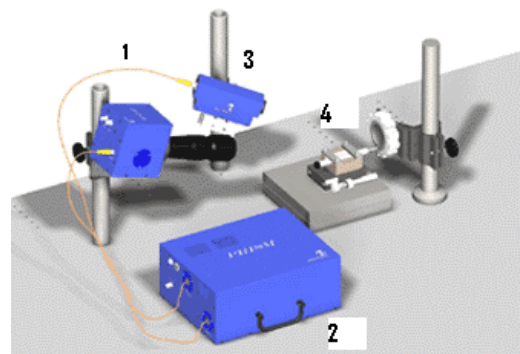
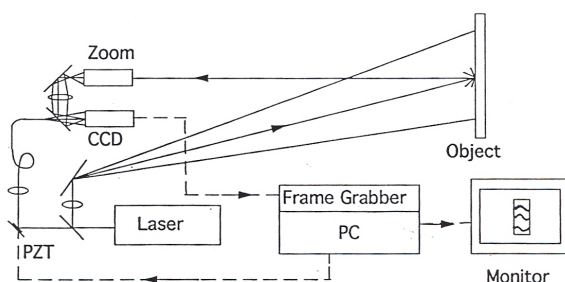
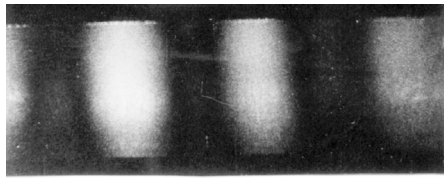
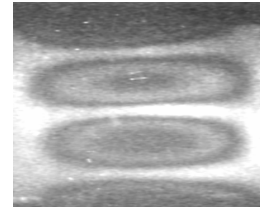


Fig. 5. PRISMA system: a – optical setup; b – PRISMA system setup: 1 – videohead; 2 – control block; 3 – illumination head of the object; 4 – circular piezoceramic plate

Fig. 6a 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. Fig. 6b presents time average hologram of the waveguide at the frequency of excitation of 25 kHz. As



a



b

Fig. 6. Time average laser holographic interferograms of the piezoelectric rectangular plate (a) and cylinder (b) exciters

Fig. 6 shows time average laser holographic interferograms of the piezoelectric cylinder exciter. It is seen that pattern of fringes in holographic interferograms (Fig. 6) confirms the simulation results of working regimes presented Figure 3 and Figure 4.

Concluding Remarks

New type of piezoelectric optical scanner with periodical microstructure is designed and analyzed. The methodology of identification of vibration modes enabled experimental optimization and numerical simulation of the working regimes of the system. Such type of analysis could be successfully applied in the design stage of different precise vibratory systems.

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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.

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