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Hybrid numerical-experimental investigation of two-degree-of-freedom piezoelectric positioning actuator

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1. Introduction

According to report from Innovative Research and Products (iRAP) entitled “Piezoelectric Operated Actuators and Motors – A Global Industry and Market Analysis (ETP-102)”, the global market for piezoelectric operated actuators and motors will double from \$5.3 billion in 2006 to \$10.7 billion by the year 2011”. New applications are emerging for piezoelectric operated actuators and motors in the applications including aircraft, automobile hydraulics and drug delivery. The report also found that the life science and medical technology fields also constitute a high-growth segment of piezoelectric-operated actuators and motors. This market is expected to grow at 18.7% annually and could record an even higher growth rate if there is a wider acceptance by end users. The global market of these devices has reached \$10.6 billion and is expected to hit \$19.5 billion by 2012, according to iRAP.

The process of gradual replacement of classical motion generating devices and motors is especially noticeable in the design of high accuracy multidegree of freedom (DOF) positioning systems, both in 3D space and on the plane. This paper is devoted to the research and development of one of such systems – nanoresolution positioning devices on the plane (2 DOFs).

Piezoelectricity is the combined effect of the electrical and mechanical behavior of the material. The electrical behavior of an unstressed medium under the influence of an electric field is defined by relationship (1) of the field strength E and the dielectric displacement D (there ε – the permittivity of medium). The mechanical behavior of the same medium at zero electric field strength is defined by relationship (2) of the stress applied T and the strain S (there s – the compliance of medium). The interaction between the ele ctrical and mechanical behavior can be described by linear relations of corresponding variables (3), (4). Eq. (3) presents the relation in strain-charge interaction case and Eq. (4) presents the stress-charge interaction.

$$D = \varepsilon E \tag{1}$$

$$S = sT \tag{2}$$

$$\left.\begin{aligned} \{S\} &= \left[s^E\right]\{T\} + [d]^T\{E\} \\ \{D\} &= [d]\{T\} + \left[\varepsilon^T\right]\{E\} \end{aligned}\right\} \tag{3}$$

$$\left.\begin{aligned} \{T\} &= \left[c^E\right]\{S\} - [d]\{E\} \\ \{D\} &= [d]^T\{S\} + \left[\varepsilon^S\right]\{E\} \end{aligned}\right\} \tag{4}$$

where $\{T\}$ is stress, N/m^2; $\{S\}$ is strain, m; $\{E\}$ is electric field strength, V/m; $\{D\}$ is dielectric displacement, C/m^2 vectors. Vectors are interrelated by matrices: $[s^E]$ is elastic compliance, m^2/N; $[c^E]$ is stiffness, Pa; $[d]$, $[d]^T$ are direct and transposed piezoelectric charge, C/m^2, N/Vm (in other literature it is indexed with $[e]$); $[\varepsilon^T]$, $[\varepsilon^S]$ are permittivity, F/m constants [1-3].

The oscillation forms of piezoelectric transducer depend on geometrical shape, dimensions, excitation and type of its material. Piezoceramic transducer can have natural and piezoactive vibration forms and accordingly, there are complex shapes of vibrations. Piezoactive vibration forms can be excited by harmonic electric field, applied to electrodes. The complex vibration form is superimposition of natural ones. The main causes of this effect are shape geometrical proportions [2, 4].

The aim of experimental investigation of hemisphere piezoelectric transducers is to obtain the full picture of distribution of oscillations, nodes and deformations in case when there is asymmetrical excitation. There are numbers of advanced measurement technologies, such as Laser Displacement Sensor, Laser Doppler Vibrometry system and PHASE III PRISM System that perform non-contact measurement of deformations and oscillations. The latter also identifies vibration pattern [5-7]. Experimental results were verified using numerical calculations based on finite element method (FEM) [8, 9].

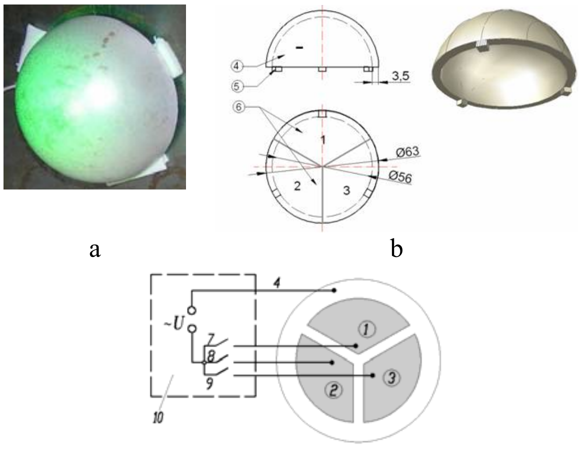
This paper presents the hybrid experimental-numerical investigation of operating regimes of three piezoceramic actuators. The schematics of hemisphere piezoelectric transducers were developed in the Mechatronics Centre for Research, Studies and Information of Kaunas University of Technology. The hybrid numerical-experimental investigation included the following tasks: (*a*) to investigate the vibrating piezoelectric transducer using time-average holographic interferometry; (*b*) to compose the numeric model of piezoelectric transducer and (*c*) – to investigate it by using eigenfrequency analysis.

2. Experimental setup

The objects of experimental and numerical investigation were three hemisphere piezoelectric transducers (positioning on the plane, 2 DOFs). Piezoelectric transducers were designed to perform positioning operation by translational motion. The object of interest is oscillations occurring in working regime. The excitation regimes were selected experimentally.

Three types of 2 DOFs positioning actuators, having the same operational principle, (Figs. 1-3) were designed to perform translational motion. Geometry and electric schemes are presented in Figs. 1-3. Transducers perform translational motion in three directions on the plain. By switching particular electrodes, different translational motion directions are obtained. The operating parameters of transducers: actuator No 1 (Fig. 1) is functioning at 58.3 kHz, actuator No 2 (Fig. 2) – at 81.3 kHz and actuator No 3 (Fig. 3) – at 33.2 kHz. The parameters were identified experimentally.

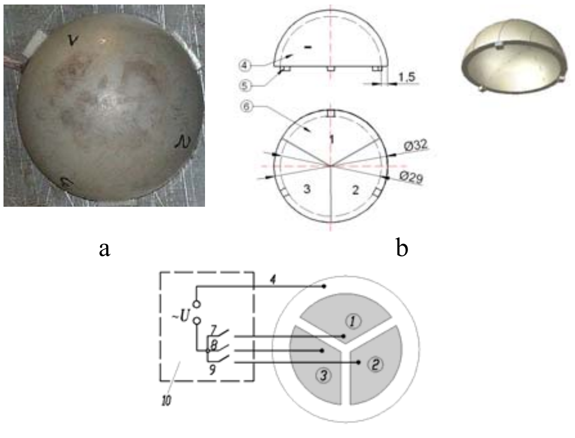
Experimental investigation was performed using the PHASE III PRISM system (measurement resolution - 20 nm, measurement range - 100 μm, largest part size - 1000 mm, working distance > 1.3 m, data acquisition rate - 30 Hz, laser power - 20 mW, laser wavelength - 532 nm), produced by Hytec Company [10]. The PRISM working principle is based on a time-average and real-time holographic interferometry techniques [11]. Experiments were done in the Mechatronics Centre for Research, Studies and Information of Kaunas University of Technology. Results were confirmed using commercial software COMSOL Multiphysics, based on FEM [12]. It was used to determine the natural vibration modes.



a b

c

Fig. 1 2 DOFs positioning actuator No 1 (a), its drawing (b) and scheme of electric circuit (c)



a b

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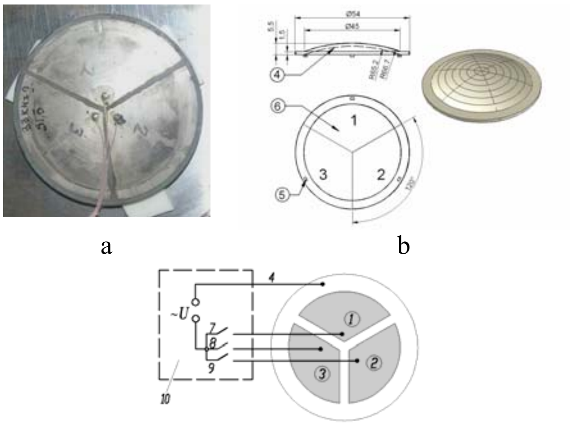
Fig. 2 2 DOFs positioning actuator No 2 (a), its drawing (b) and scheme of electric circuit (c)



a b

c

Fig. 3 2 DOFs positioning actuator No 3 (a), its drawing (b) and scheme of electric circuit (c)

3. Results

Hybrid numerical - experimental investigation is composed of holographic technique investigation and FEM eigenfrequency analysis.

Positioning devices on the plane.

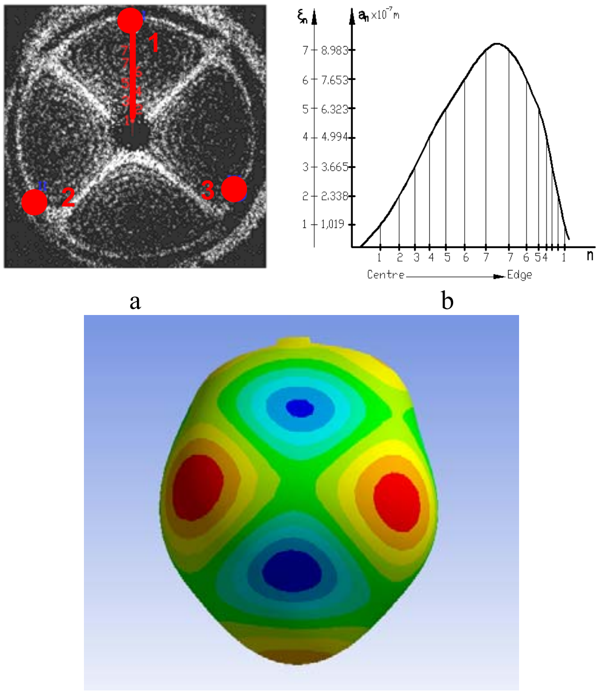
The experimental investigation of three positioning actuators (Figs. 1-3) was made in their typical operation mode; results are presented in Figs. 4 - 10, a-b. Contact pins positions are marked and numbered. The numbering of contacting pins and segmented electrodes corresponds.

The experimental investigation showed that oscillation pattern has clearly expressed the form for No 1 and No 3 positioning actuators (Figs. 4, a - 6, a; 8, a - 10, a). There are four oscillating regions separated with node lines, which appear as brightest lines in holographic image. Oscillation patterns of all the actuators are rotated by 120° degrees for each of three electrodes. The active electrode and particular contacting pin, situated in the area of that electrode, are related as particular pin appears in front of the highest oscillation amplitude region, while remaining pins are situated near nodal regions. The No 2 positioning actuator has complex vibration form, but show the interrelation of active electrode and locating pin (Figs. 7, a-c).

Analysis of holographic images resulted in composition of deformation amplitude graph. There x-axis represents the distribution of fringes n and y-axis – the deformation amplitude a_n and zeroes ξ_n of Bessel function (Figs. 4, c - 10, c). It showed that oscillation amplitudes differ when excited by different electrodes. When 1st electrode of actuators No 1 is connected to signal generator, the oscillation amplitude (Fig. 4, b) is 0.9 μm. When 3rd electrode is connected to signal generator – the amplitude is 0.5 μm (Fig. 6, b). This can be caused by electrode layer and piezoceramic material promiscuity. Consequently, the variation of oscillation amplitude for different excitation combinations causes variations of transversal speed. The transversal speed could be changed by controlling voltage of excitation signal.

For numerical investigation analogous geometry models were composed and set to eigenfrequency analysis. Numerically obtained oscillation patterns coincided with experimental ones for positioning actuators No 1 and No 3 (Figs. 4, c and 9, c). The numerical investigation of actuator No 2 failed, numerical investigation outputted natural oscillation forms while experimental oscillation form is complex. It is superposition of several natural vibration modes. The obtained spatially oscillating bodies were used to explain translational motion principle.

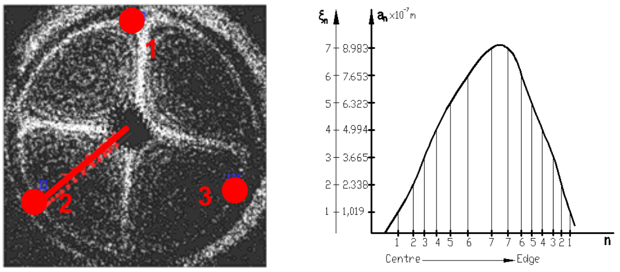
Spherical body oscillates in all three directions. It can be assumed that radial oscillation of spherical body has close amplitude as normal oscillations. The numerical investigation illustrated spatial vibration and explained shaded and uneven edge of actuator No 1 and No 3 in holographic image. The numeric model of actuator No 1 and No 3 sustains edge oscillations, which in holographic image appear as shaded region due to concentrated deformation and highly concentrated fringe pattern. There are more than four oscillating regions.



a b

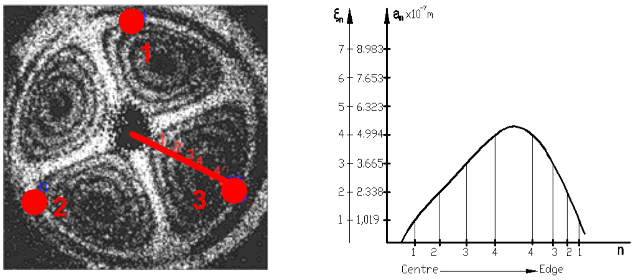
c

Fig. 4 Actuators No 1 hologram (a), oscillation form (b) (max. amplitude 0.9 µm, U = 19.9 V, F = 58.3 kHz, electrode 1) and its normal oscillation view of corresponding eigenmode (c) (mode 4, F = 15.5 kHz)



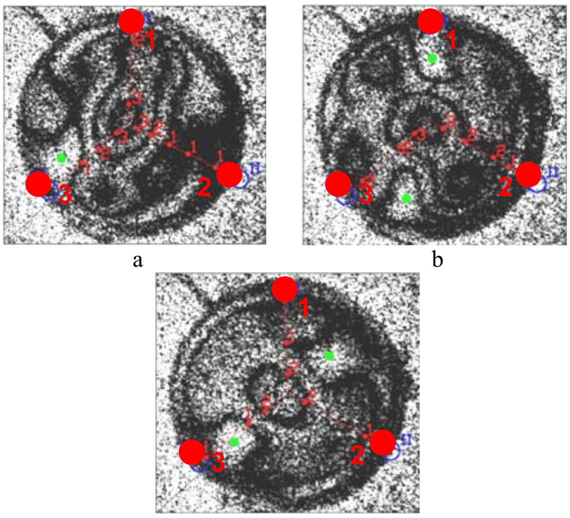
a b

Fig. 5 Actuators No 1 hologram (a) and oscillation form (b) (max. amplitude 0.9 µm, U = 19.9 V, F = 58.3 kHz, electrode 2)



a b

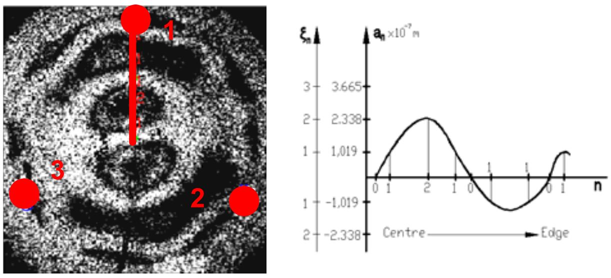
Fig. 6 Actuators No 1 hologram (a) and oscillation form (b) (max. amplitude 0.5 µm, U = 19.9 V, F = 58.3 kHz, electrode 3)



a b

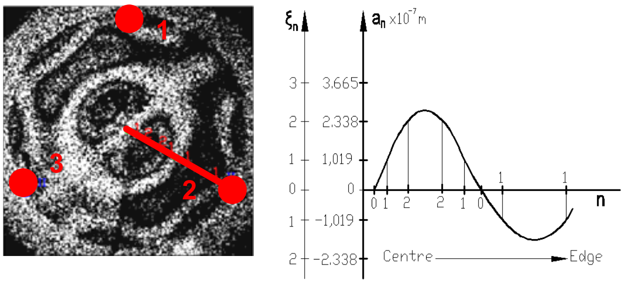
c

Fig. 7 Holograms of actuator No 2 (U = 40.3 V, F = 81.3 kHz): a) active electrode 1 (max. amplitude 0.366 µm), b) active electrode 2 (max. amplitude 0.366 µm), c) active electrode 3 (max. amplitude 0.234 µm)



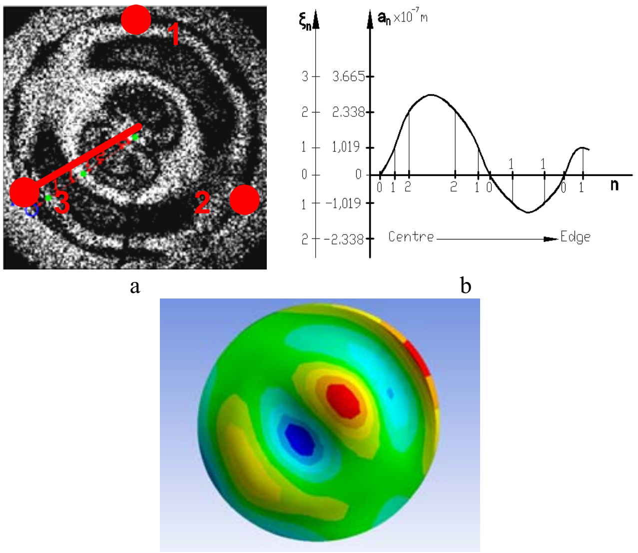
a b

Fig. 8 Actuators No 3 hologram (a) and oscillation form (b) (max. amplitude 0.24 µm, U = 20 V, F = 33.2 kHz, electrode 1)



a b

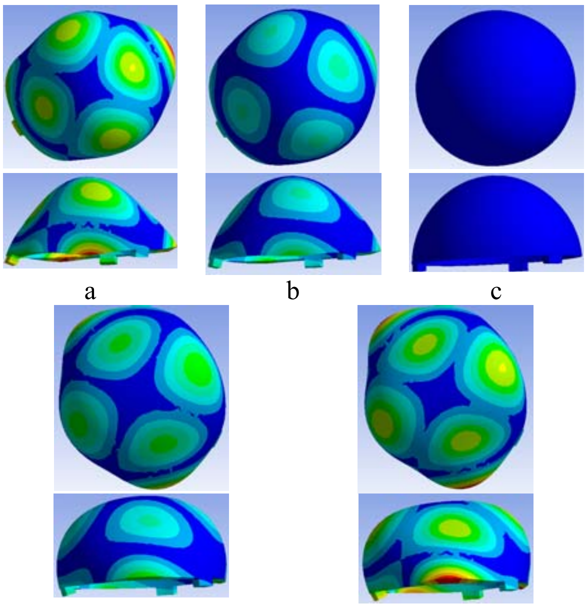
Fig. 9 Actuators No 3 hologram (a) and oscillation form (b) (max. amplitude 0.28 µm, U = 20 V, F = 33.2 kHz, electrode 2)



a b

c

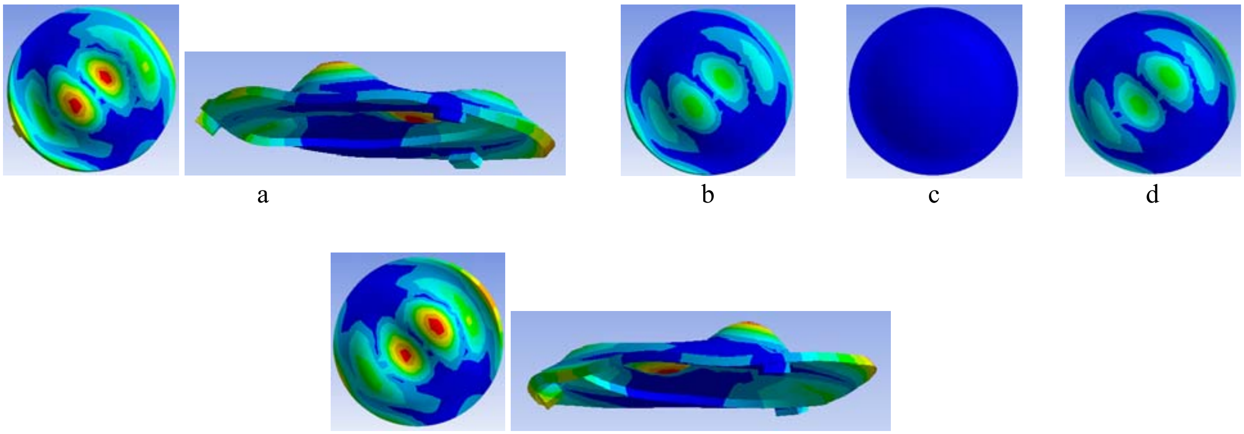
Fig. 10 Actuators No 3 hologram (a) and oscillation form (b) (max. amplitude 0.28 µm, $U = 20$ V, $F = 33.2$ kHz, electrode 3) and its normal oscillation view of corresponding eigenmode (mode 10, $F = 18.51$ kHz) (c)



a b c

d e

Fig. 11 The total deformation images of half oscillation of positioning actuator No 1: a) $t_0 – T/4$; b) $t_0 – T/8$; c) t_0; d) $t_0 + T/8$; e) $t_0 + T/4$



a b c d

e

Fig. 12 The total deformation images of half oscillation of positioning actuator No 3: a) $t_0 – T/4$; b) $t_0 – T/8$; c) t_0; d) $t_0 + T/8$; e) $t_0 + T/4$

The numerical analysis showed that motion is based on total body deformation and pins position changes to the same direction, while one locating pin sustains higher position changes than other. One half oscillation of actuators No 1 and No 3 are presented in Figs. 11 and 12. For each electrode the oscillation patterns, as well as pins position, are rotated by 120°. Motion to particular direction is related to particular contacting pin that sustains highest amplitude vibrations and position changes.

4. Conclusions

Combination of experimental and numerical investigation mutually expands and verifies information of experiment. The investigation of positioning actuators located on three positing pins showed that translational motion is based on unidirectional pins position changes. Typical pins position changes were analogues to very different geometry actuators (actuator No 1 and No 3), while the actuators sustained very different total body deformations.

Electrodes distribution determines the rotation of oscillation pattern. The active electrode and particular locating pin situated in the area of that electrode are related as particular pin appears in front of the highest amplitude vibration region, when that electrode is excited. The particular pin sustains highest position changes and determines the translational motion direction.

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DVIEJŲ LAISVĖS LAIPSNIŲ PJEZOELEKTRINIŲ POZICIONAVIMO SISTEMŲ SKAITMENINIS-EKSPERIMENTINIS TYRIMAS

Reziumė

Straipsnyje nagrinėjamos naujo tipo pjezoelektrinės pozicionavimo sistemos, pagamintos iš pusrutulio formos pjezokeramikos, leidžiančios pozicionuoti plokštumoje (du laisvės laipsniai) dideliu tikslumu. Pusrutulio formos pjezokeramikos elektrodai suskaidyti į tris simetriškas dalis. Tai leidžia generuoti atitinkamų formų virpesius ir išgauti pozicionavimo sistemos kontroliuojamą judėjimą plokštumoje.

Straipsnyje aprašomas pjezoelektrinių pozicionavimo sistemų skaitmeninis-eksperimentinis tyrimas. Jį sudaro eksperimentinių ir skaitmeninių rezultatų lyginimas ir analizė, siekiant paaiškinti pozicionavimo sistemų veikimo principą. Tikslui įgyvendinti naudojama nekontaktinė holografinės interferometrijos sistema PRISM ir baigtinių elementų pagrindu veikianti programinė įranga „COMSOL Multiphysics“.

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HYBRID NUMERICAL-EXPERIMENTAL INVESTIGATION OF TWO-DEGREE-OF-FREEDOM PIEZOELECTRIC POSITIONING ACTUATOR

Summary

New types of piezoelectric elements, made in the form of hemisphere piezoceramic transducers and aimed at the application in nanoresolution positioning devices on the plane (2 DOFs), are presented. Hemisphere piezoceramic transducers with specific excitation zones, realized by sectioning electrodes into symmetric parts, enable the generation of several vibration forms with controllable amplitudes and orientation.

Hybrid numerical-experimental investigation of hemisphere piezoceramic actuators is presented. It includes combination, comparison and analyzes of experimental and numerical results for the explanation of transducer translational motion. Non-contact measurement PRISM system and COMSOL Multiphysics software were applied for the investigation.

Р. Бансявичюс, С. Телксните, Г. Янушас, А. Палявичюс

ЦИФРОВОЕ - ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ПЬЕЗОЭЛЕКТРИЧЕСКОЙ СИСТЕМЫ ПОЗИЦИОНИРОВАНИЯ С ДВУМЯ СТЕПЕНЯМИ СВОБОДЫ

Резюме

В статье рассматривается пьезоэлектрическая система позиционирования нового типа, позволяющая достичь высокой точности позиционирования на плоскости (две степени свободы). Электроды полусферических пъезокерамик разделены на три симметричные части, что позволяет генерировать соответствующие формы колебаний и произвести управляемое движение системы в плоскости.

В статье представлены цифровые - экспериментальные исследования пьезоэлектрической системы позиционирования. Исследование состоит из анализа и сравнения экспериментальных и численных результатов с целью объяснить принцип работы системы. Для осуществления цели использована система голографической интерферометрии PRISM и компьютерная программа COMSOL Multiphysics, действующая на основе конечных элементов.

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