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HOLOGRAPHIC VISUALIZATION OF CYLINDRICAL PIEZOCERAMIC TRANSDUCERS VIBRATIONS

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The piezomaterial used in cylindrical piezoceramic transducers vibrations requiring high precision displacements indicates that accuracy depends on design and technological factors. The analyzed criteria have made possible to choose the piezomaterial for optimal mechatronic system having a maximal displacement. The experimental investigation of precision vibrosystems by means of 3D holographic visualization enables one to obtain appreciably larger amount of information about the vibrating surface in comparison with traditional methods. On the basis of the developed methodology of analyzing the experimental data derived from 3D holographic visualization and by using the experimental holography stand, we have obtained results making it possible to optimize the design of operation of the piezoceramic mechatronic system or its separate elements. (E-mail: r.vasiliauskas@mruni.eu)

Key words: piezomaterial, mechtronics systems, holographic visualization, cylindrical piezoceramic transducers vibrations.

Introduction

Piezoceramics can be more sensitive to electric and mechanical effects scores of times compared to natural crystals and it is mechanically strong, chemically inert and resistant to atmospheric effects. Piezoelectric cells can be made of various sizes and parameters which enable them to be used in any manufactured structure with 90 % efficiency. Theoretical investigation of cylindrical piezoceramic transducers′ vibrations (we suggested the principles for the development of precision piezoelectric motors with several degrees of freedom, thus realizing high precision in space and in plane positioning systems) [1, 2] and dynamic analysis of their components have indicated that an increase in the loading force and initial tension decreases the harmonic components of fluctuations.

This article analyzes the working cylindrical piezoceramics transducers (Figure 1), when a control signal is sent only to one active control cylindrical transducer of the mechatronic system [3–5]. In this case, even deformation of the working part surface in the operation area of the active cylindrical piezoceramics transducers′ vibrations is observed. Slight surface deformation in the operation area of other active piezostack emerges due to conditions of their fixing onto the surface of the working part of the mechatronic system.

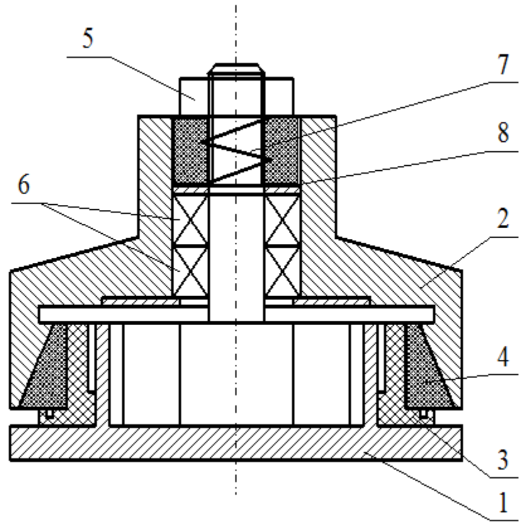


Figure 1 – The main structural elements of construction of transducers vibrations: 1 – holder; 2 – rotor; 3 – sealing material; 4 – cylindrical transducers; 5 – clamping element; 6 – bearings; 7 – spring; 8 – gain control

This study employs the double-exposure and time-average holographic visualization technique for the quality assessment of surface deformation. The essence of this technique is the recording of holograms of two objects state (being in different conditions, initial and deformed, for instance, before and after an increase of voltage) on the same layer of a light-sensitive photographic plate. Upon having illuminated the hologram after two exposures with a copy of the cylindrical piezoceramic transducers vibrations, both transducers reflected by the object surface before and after the deformation, are restored at the same time [6–8].

The results of their interference – the system of interferential fringes is observed against the background of the surface of the object image, which provides information about changes in the object's status having occurred in the period between showings. The 3D holographic visualization of cylindrical piezoceramic transducers′ vibrations method used in the experimental work has strengthened the expressions of differential equations and is used for describing of conclusions of the investigation. The ineffective electrical energy is stored as electrostatic energy in the piezoceramics material and reverts it to the power supply in the final process of an operating cycle. The analyzed criteria have made possible to choose the piezomaterial for an optimal construction having a maximum displacement [9, 10].

The experimental investigation of precision vibrosystems by means of holographic interferometry enables one to obtain appreciably larger amounts of information about the vibrating surface in comparison with traditional methods. The paper deals with the consideration of methods for the determination of the vibrational characteristics of precision mechanical systems from the holographic interferograms of linked analysis of these characteristics by using numerical techniques based on the theories of mechanical system vibration and holographic interferometry [11, 12].

Method of holographic visualization of cylindrical piezoceramic transducers vibrations

When wave properties are defined by a travelling wave, quantitative analysis of interferograms shall be performed in the following method.

Let us consider any point on the piezoceramic cylinder surface (Figure 2) whose spatial vibration vector may be defined by the equation:

$$\overline{R}_i(\varphi,\tau) = U(\varphi,\tau)\hat{i} + V(\varphi,\tau)\hat{j} + W(\varphi,\tau)\hat{k}, \quad (1)$$

where φ is an angular coordinate of the analyzed point on piezoceramic cylinder; τ – time of harmonic fluctuations; *i, j, k* – unit vectors of corresponding coordinate axis *z, t, r*; *W* – normal constituent of spatial vibration at point *i*; *U* and *V* – tangential constituents.

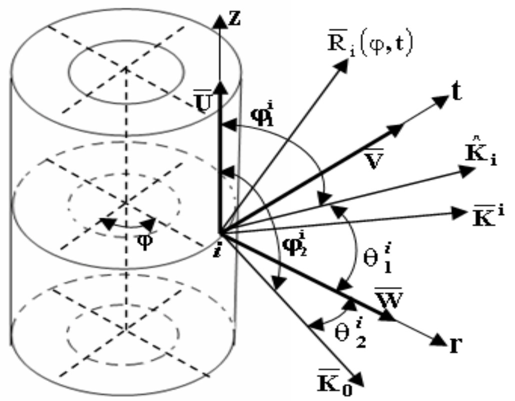


Figure 2 – Interpretation of vibrations of waves in a piezoceramic transducer

If an observation unit vector of point *i* is named K_0, and the vector opposite to an illumination unit vector of point *i* is named K_i, the sensitivity vector of point *i* will be defined by the following equation:

$$\overline{K}^i = K_z^i\hat{i} + K_t^i\hat{j} + K_r^i\hat{k}, \quad (2)$$

where K_z^i, K_t^i, K_r^i shall be calculated from the following system of equations:

$$\begin{aligned} K_z^i &= \cos\varphi_2^i + \cos\varphi_1^i, \\ K_t^i &= \sin\theta_1^i \sin\varphi_1^i - \sin\theta_2^i \sin\varphi_2^i, \\ K_t^i &= \cos\theta_1^i \sin\varphi_1^i + \cos\theta_2^i \sin\varphi_2^i, \end{aligned} \quad (3)$$

where θ_1^i, θ_2^i are angles formed by the observation and illumination vectors of point *i* in relation to coordinate axis *r*; φ_1^i, φ_2^i are correspondent angles formed by the observation and illumination vectors in relation to coordinate axis *z*.

A change of the light wave phase that appears due to surface vibration of the piezoceramic cylinder, when the light travels from the source to the analyzed point *i* located on the surface of the piezoceramic cylinder and then proceeds to the holographic interferogram, is defined as:

$$\Omega_i = 2\pi \overline{R}_i(\varphi,\tau)\frac{\overline{K}^i}{\lambda}, \tag{4}$$

where λ is the wavelength of the laser light used for fixing the interferogram; $R_i(\varphi, t)$ and K^i are defined by equations (1) and (2). Scalar product of spatial vibration and sensitivity vectors are defined as

$$\overline{R}\overline{K}^i = U(\varphi,\tau)K_z^i + V(\varphi,\tau)K_t^i + W(\varphi,\tau)K_r^i. \tag{5}$$

If we insert this equation into the expression of the change of the light wave phase (4), we get

$$\Omega_i = \frac{2\pi}{\lambda}[U(\varphi,\tau)K_z^i + V(\varphi,\tau)K_t^i + W(\varphi,\tau)K_r^i], \tag{6}$$

where tangential constituents U and V of spatial vibration vector $R_i(\varphi, t)$ and normal vibration constituent W at a surface point i are expressed as:

$$\begin{aligned} U(\varphi,\tau) &= U_0^i(\varphi)\cos(\omega\tau+\alpha_i),\\ V(\varphi,\tau) &= V_0^i(\varphi)\cos(\omega\tau+\beta_i),\\ W(\varphi,\tau) &= W_0^i(\varphi)\cos(\omega\tau+\gamma_i), \end{aligned} \tag{7}$$

where $U_0^i(\varphi)$, $V_0^i(\varphi)$, $W_0^i(\varphi)$ are values of amplitude tangential and normal vibration constituents of spatial vibration vector $R_i(\varphi, t)$ that are expressed as:

$$U_0^i(\varphi) = \sum_{j=1}^{n} A_j^u F_{ij}^u,\ V_0^i(\varphi) = \sum_{j=1}^{n} A_j^v F_{ij}^v,\ W_0^i(\varphi) = \sum_{j=1}^{n} A_j^w F_{ij}^w, \tag{8}$$

where i – number of point i located on the surface of the cylinder; j – number of the type of self-excited vibration of the piezoceramic cylinder analyzed; F_{ij} – value of the amplitude of the number of self-excited vibration type j in point i; A_j – coefficient of influence of self-excited vibration type j; n – number self-excited vibrations types.

The characteristic function of the distribution of interference bands on the surface of the piezoceramic cylinder, when holographic interferogram is fixed at time-average and harmonic vibration is present, is defined as [12]:

$$M_x(\Omega_i) = \frac{1}{T}\int_0^\tau \exp(k\Omega_i)dt. \tag{9}$$

Inserting expressions (7) into the equation (6) we get the value of Ω_i that should be inserted into the characteristic function of band distribution (9). We obtain the following

$$M_x(\Omega_i) = \frac{1}{T}\int_0^\tau \exp\left[i\frac{2\pi}{\lambda}(\Omega_1\cos\omega\tau - \Omega_2\sin\omega\tau)\right]dt, \tag{10}$$

where

$$\Omega_1 = U_0^i(\varphi)K_z^i\cos\alpha_i + V_0^i(\varphi)K_t^i\cos\beta_i + W_0^i(\varphi)K_r^i\cos\gamma_i, \tag{11}$$

$$\Omega_2 = U_0^i(\varphi)K_z^i\sin\alpha_i + V_0^i(\varphi)K_t^i\sin\beta_i + W_0^i(\varphi)K_r^i\sin\gamma_i. \tag{12}$$

After the use of equation [4] equation (10) will look like:

$$M_x(\Omega_i) = J_0\left[n_i(\Omega_1^2+\Omega_2^2)^{\frac{1}{2}}\right], \tag{13}$$

where J_0 – Bessel function of the first kind of order zero.

Using (7), (11), (12) and (13) values of point i located on the surface of piezoceramic cylinder, we will obtain the following equation of the distribution of the interference bands on the surface of the vibrating piezoceramic cylinder:

$$\begin{aligned}\frac{\Omega_i\lambda^2}{4\pi} = &\left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i\cos\gamma_i + \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i\cos\beta_i + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i\cos\alpha_i\right]^2 + \\ &+\left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i\sin\gamma_i + \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i\sin\beta_i + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i\sin\alpha_i\right]^2\end{aligned} \tag{14}$$

The equation (14) is commonly used for identification of spatial vibration coordinates, when the object is analyzed in the method of time-average. In the equation, we know the parameter Ω_i, which is obtained for the centre points of dark interference bands of interferograms with the help of the following equation:

$$\Omega_p = (p-0{,}25)\pi + \frac{0.125}{(p-0.25)\pi}, \quad (15)$$

where p is the order number of an interference band (in a holographic interferogram), in the centre of which point i is located; the order number is set calculating from the brightest modular band.

Coefficients K_z^i, K_t^i, K_r^i of the equation (14) are obtained from the equation (3), using optical scheme parameters obtained during the experiment of fixing holographic interferogram; coeficients $F^W{}_{ij}$, $F^V{}_{ij}$, $F^U{}_{ij}$ are calculated using analytical expressions of self-excited vibration types related to the geometrical shapes of transducers and the conditions of their fixing in various structures.

Aiming to calculate coefficients A_j^W, A_j^V, A_j^U and angles α_i, β_i, γ_i we need to minimize the equation formed on a basis of the equation (14) in a method described [12]:

$$F_i = \left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \cos\gamma_i + \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i \cos\beta_i + \right.$$
$$\left. + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i \cos\alpha_i\right]^2 - \left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \sin\gamma_i + \right. \quad .(16)$$
$$\left. + \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i \sin\beta_i + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i \sin\alpha_i\right]^2 - \left[\frac{\Omega_i\lambda^2}{4\pi}\right]^2$$

Function F_i shall be differentiated with respect to each unknown component of vibration. In respect of A_j^W we obtain the following:

$$G_j^{(i)} = \frac{\partial F_i}{\partial A_j^w} = 2\left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \cos\gamma_i + \right.$$
$$+ \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i \cos\beta_i +$$
$$\left.\left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i \cos\alpha_i\right] F_{ij}^w K_r^i \cos\gamma_i - \quad . \quad (17)$$
$$-2\left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \sin\gamma_i + \right.$$
$$+ \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i \sin\beta_i +$$
$$\left. + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i \sin\alpha_i\right] F_{ij}^w K_r^i \sin\gamma_i$$

Analogical expressions will be obtained in respect to other unknown components of vibration, i.e. A_j^V, A_j^U.

In respect of the unknown γ_i:

$$G_{1+3n}^{(i)} = \frac{\partial F_i}{\partial \gamma_i} = 2\left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \cos\gamma_i + \right.$$
$$\left. + \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i \cos\beta_i + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i \cos\alpha_i\right] \times$$
$$\times \left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i(-\sin\gamma_i) + \left[\left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \sin\gamma_i + \right. \quad (18)$$
$$\left. + \left(\sum_1^n A_j^v F_{ij}^v\right)K_t^i \sin\beta_i + \left(\sum_1^n A_j^u F_{ij}^u\right)K_z^i \sin\alpha_i\right] \times$$
$$\times \left(\sum_1^n A_j^w F_{ij}^w\right)K_r^i \cos\gamma_i$$

Analogical expressions will be obtained in respect to other unknowns α_i and β_i.

In such a way q number of points evenly located on a deformed (due to vibration) surface of the piezoceramic cylinder is analyzed. According to the method described above, calculation of coefficients K_z^i, K_t^i, K_r^i and $F^W{}_{ij}$, $F^V{}_{ij}$, $F^U{}_{ij}$ of equation (14) is followed by the formation of the matrix $\left| G^{(i)} \right|$. If q is the number of points analyzed and n is the number of types of self-excited vibration of the piezoceramic cylinder obtained in result of the resolution of vibration at point i on the surface of piezoceramic cylinder in respect to the corresponding coordination axis r, t and z, then matrix $\left| G^{(i)} \right|$ will feature a dimension qx3(2n+3).

Solutions of the non-linear equation (14) will be obtained by the way of iteration. We will have to find out the following vector of unknowns:

$$N_V = \left[A_1^U, A_2^U, ..., A_n^U, A_1^V, A_2^V, ...A_n^V, \right. \\ \left. A_1^W, A_2^W, ...A_n^W, \alpha, \beta, \gamma\right], \quad (19)$$

That will ensure minimal value of correction vector defined from the following expression:

$$\{R\} = [T]^{-1}\{P\}, \quad (20)$$

Where $[T]$ and $\{P\}$ are obtained from

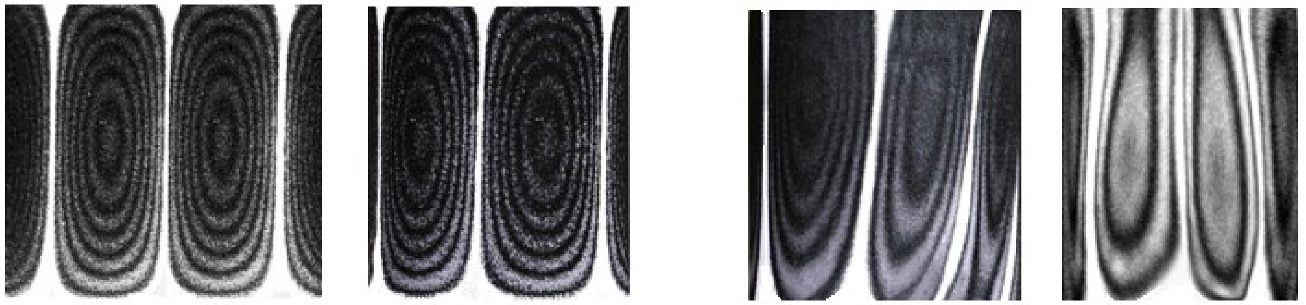
$$T_{1j} = \sum_{i=1}^q G_1^{(i)} G_j^{(i)}, \quad (21)$$

where j = 1, 2,… (3+3n),

$$P_j = -\sum_{i=1}^{q} F_i G_j^{(i)}, \tag{22}$$

where j = 1, 2,…, (3+3n).

Thus, performing the analysis of holographic interferograms in transducers with excited vibrations of a standing wave in the method described, several holographic interferograms from various illumination and observation angles could be obtained (Figure 3).



a b c

Figure 3 – Waves formed on holographic interferogram of a surface of piezoceramic cylinder: a, b – when parameters of excitation and claims are optimal angle of illumination for fixed hologram 80°; b – angle of illumination for fixed hologram 40°; c, d – when parameters of excitation and claims are not optimal: a – angle of illumination for fixed hologram 80°; b – angle of illumination for fixed hologram 40°

We select q number of points evenly located in the centres of interference bands on the surface of transducers. Sensitivity vector projections K_z^i, K_t^i, K_r^i are defined for each point i (i = 1, 2,..., q) selected by the way of an experiment. $F^W{}_{ij}$, $F^V{}_{ij}$, $F^U{}_{ij}$ of each selected point i are calculated using analytical expressions of the first n self-excited vibrations related to geometrical shape and fixing conditions of transducers. Ω_i is defined for each selected point i located in the centre of dark interference bands. These values shall be inserted into equation (14). For calculation of coefficients A_j^W, A_j^V, A_j^U and angles α_i, β_i, γ_i the equation (16) will be transformed to vector $\left| G^{(i)} \right|$ and, using (20) and (21), minimal value correction vector will be formed. Theoretical calculation results are illustrated in Figure 4.

The analyzed criteria have made it possible to choose the piezomaterial for an optimal construction having a maximum displacement. The automatic control has been determined to affect the correction of the hysteresis loop thus allowing a reduction in displacement error up to 0,2 %. Performing the analysis of holographic interferograms in transducers with excited vibrations of a standing wave in the method described, several holographic interferograms from various illumination and observation angles can be obtained. Experimental investigation of cylindrical transducers makes it possible to determine the optimal initial tension force, and the dependence of displacement of the loose cylindrical transducers on some constructional and technological parameters.

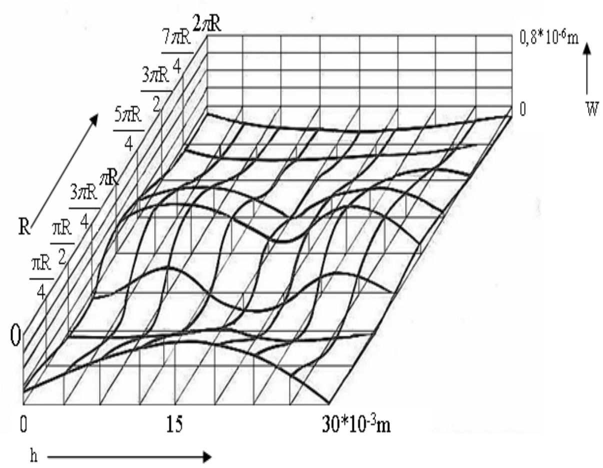


Figure 4 – Theoretical investigation of the radial oscillation amplitude of a surface of piezoceramic cylinder from the presented figure 3 interferogram. h – piezoceramic cylindrical height; R – development of the piezoceramic cylindrical of surface; W – radial oscillation amplitude

The experimental results are easy to access and they are applied to develop a tool for loosening rigid tightening and eliminating corrosion impurity in machining and tool adjustment, medicine equipment, optical systems, and items used in criminology for adjustment various elements.

Conclusion

Dependability of friction and tension force in a kinematic pair has been analyzed and it confirms the fact that reducing the friction force magnitude of the wave processes become recurring processes in the ring drive. The expressions of linear and rotational speeds allow us to calculate and apply the deformations to the optimal extent in piezoactuators. The distribution of tangential and radial deformations in piezoactuators with a ring drive plays an important role in designing of piezodrives and it has been employed when developing new structures. The experimental results are easy to access and they are applied to develop a tool for loosening rigid tightening and eliminating corrosion impurity in machining and tool adjustment, medicine equipment, optical systems, and items used in criminology for adjustment various elements.

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Василяускас Р., Рагульскис К., Паташене Л., Федаравичус А.

Голографическая визуализация вибраций пьезокерамических цилиндрических преобразователей

Исследования пьезоматериалов, используемых для возбуждения вибраций в цилиндрических преобразователях для высокоточных перемещений, показали, что их точность зависит от дизайна и технологических факторов. Анализ критериев позволил выбрать пьезоматериал оптимальных мехатронных систем с максимальными перемещениями. В сравнении с традиционными методами, экспериментальные исследования точности вибросистем средствами голографической визуализации 3D позволяют получить намного больше информации о вибрирующих поверхностях. На базе разработанной методологии анализа экспериментальных данных, полученных благодаря использованию метода голографической визуализации 3D и экспериментального голографического стенда, получены результаты, позволяющие оптимизировать общий дизайн мехатронной системы или ее отдельных элементов. (E-mail: r.vasiliauskas@mruni.eu)

Ключевые слова: пьезоматериал, мехатронная система, голографическая визуализация, цилиндрический пьезокерамический преобразователь вибрации.

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