274. Modeling and design optimization of butterfly type piezoelectric actuator

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Abstract. A study of a novel design miniature butterfly type piezoelectric actuator is proposed and analyzed in the paper. Actuator consists of butterfly type oscillator and two piezoceramic elements. Operating principle of the actuator is based on exciting electrodes of the piezoceramic elements using input voltage of the same frequency but different phases. Elliptic trajectory of the contact point movement is achieving when phases of the voltage differ by π/2 on different electrodes. Numerical modelling and simulation of the piezoelectric actuator was performed using finite element method. Natural frequencies, modal shapes and actuator response to the different input voltage sets were analyzed. Optimization of actuator boundary conditions was carried out. Experimental prototype of the piezoelectric actuator was built and measurements of driven tip movements were performed. The results of numerical and experimental studies are discussed.

Keywords: piezoelectric actuator, finite element modeling

Introduction

Demand of new displacement transducers that can achieve high resolution and accuracy of the driving object increases significantly. Piezoelectric actuators are advanced in this field of machinery [1, 2, 3]. There are many different design principles of the actuators to transform mechanical vibrations of the piezoceramic elements into linear or rotational movement of the slider [4, 5, 6]. A new idea of elliptic trajectory formation of the actuator for linear piezoelectric motor is introduced in the paper. Elliptic trajectory of the contact point's movement is achieve by using bending oscillations of the actuator that has special shape of "butterfly type". Prototype actuator has been made. Size of the prototype actuator not exceeds 25 mm^3. Numerical modelling of the piezoelectric actuator was carried out using finite element method (FEM). Experimental investigation was made and results were analysed and discussed.

Operating Principle of the Piezoelectric Actuator

Configuration of actuator includes following parts: "butterfly type" oscillator and two rectangular piezoceramic plates that are glued to the oscillator using adhesive (Fig. 1a, 1b). Polarization of piezoceramic is oriented along thickness of the plates and piezoelectric effect d31 is used for the actuation. Contact zone is located on top surface of the actuator (Fig. 1b) and have elliptical trajectory of motion when actuator is in the operating mode. Inertial movement of the slider is achieved when electrodes of piezoelectric plates are excited by sinusoidal voltage and has the same amplitudes but different phases by π/2 on each plate. Equivalent mechanical forces are obtained from piezoceramic plates that excite particular modal shape of the actuator at resonance operating frequency. Actuator modal shape at operating frequency is specific because shape of the oscillator's horizontal plates is closed to the third bending mode of structural plates (Fig. 1a). Oscillations from the plates are transferred to the pair of connecting rods where contact zone is located. "Shaking beam" principle [7, 8] can be applied to the motion of the connecting rods and based on it contact zone produce elliptical motion.

Reverse motion of the slider is achieving when phase of input voltage on different piezoceramic plates is changed to -π/2.

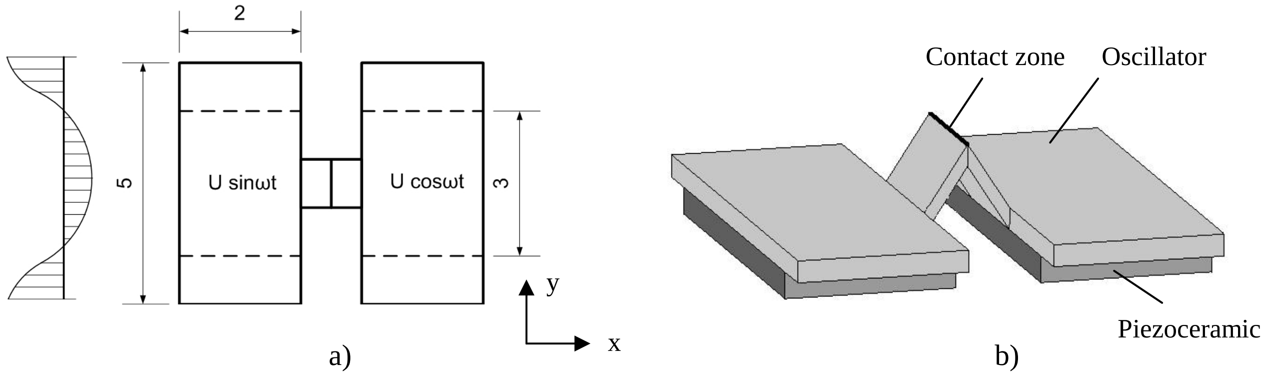


Fig. 1. Schematic scheme of the butterfly type actuator: a) 2D view and amplitude diagram; b) 3D view

FEM Modeling and Optimization of the Actuator

Finite element method was used to perform modal frequency and harmonic response analysis and to calculate trajectories of the driven tips movements. Basic dynamic equation of the piezoelectric actuator are derived from the principle of minimum potential energy by means of variational functionals and for piezoelectric actuator can be written as follows [7, 8]:

$$\left.\begin{aligned}&[M]\{\ddot{u}\}+[C]\{\dot{u}\}+[K]\{u\}+[T_1]\{\phi_1\}+[T_2]\{\phi_2\}=\{F\}\\&[T_1]^T\{u\}-[S_{11}]\{\phi_1\}-[S_{12}]\{\phi_2\}=\{Q_1\}\\&[T_2]^T\{u\}-[S_{12}]^T\{\phi_1\}-[S_{22}]\{\phi_2\}=\{0\}\end{aligned}\right\},\quad(2)$$

where [M], [K], [T], [S], [C] are accordingly matrices of mass, stiffness, electro elasticity, capacity, damping; $\{u\}, \{F\}, \{Q_1\}$ are accordingly vectors of nodes structural displacements, potentials, external mechanical forces and charges coupled on the electrodes, $\{\phi_1\}, \{\phi_2\}$ are accordingly vector of nodal potentials of the nodes associated with electrodes and vector of nodal potentials calculated during numerical simulation. Vector of nodal charges $\{Q_1\}$ can be written as follows [7, 8]:

$$\{Q_1\}=\left([T_1]^T-[S_{12}][S_{22}]^{-1}[T_2]^T\right)\{u\}+ +\left([S_{12}][S_{22}]^{-1}[S_{12}]^T-[S_{12}]^T\right)\{\phi_1\}.$$

Mechanical and electrical boundary conditions are determined for piezoelectric actuator i. e. mechanical displacement of the fixed surfaces of the actuator are equal to zero and electric charge of piezoelements that are not coupled with electrodes are equal to zero too.

Natural frequencies and modal shapes of the actuator are derived from the modal solution of the piezoelectric system [5]:

$$\det\left([K^*]-\omega^2[M]\right)=\{0\},$$

where [K^*] is modified stiffness matrix. Harmonic response analysis of piezoelectric actuator is carried out applying sinusoidal varying voltage with different phase on electrodes of piezoelements. $\{F\}=\{0\}$ because structural mechanical loads are not used in the modeling. Referring to Eq. 2 mechanical forces obtained because of inverse piezoelectric effect can be calculated as follows:

$$\{R\}=\left([T_2][S_{22}]^{-1}[S_{12}]^T-[T_1]\right)\{U\}\sin\omega_k t,$$

where $\{U\}$ is vector of voltage amplitudes, applied on the nodes coupled with electrodes. Results of actuator's structural displacements obtained from harmonic response analysis are used for determining the trajectory of contact point movement.

Trajectory and energy of the contact point motion strongly depends on boundary conditions of the actuator, so optimization of actuator must be performed. Following on technical requirements, constrain must be placed on the edges of actuator's horizontal plates (Fig. 1a). Dominating coefficient [9] of the contact zone oscillation components were chosen as optimization criteria, because they explicitly define characteristics of contact zone motion. Dominating coefficients for the actuator can be written as follows [9, 10]:

$$m_{jk}^n=\frac{S_j^n}{S_k^n},\quad j\neq k$$

here $S_k^n=\sum_{i=1}^{r}\left(A_{ik}^n\right)^2,\quad r=\frac{l}{k}$ (3)

where k – number of degrees of freedom in the node, l – number of nodes (degrees of freedom) in the contact zone, r – size of modal shape vector for k coordinate, n- modal shape number, A_{ik}^n - value of i element of modal shape vector. Optimization problem can be written as follows.

$$\begin{cases}m_{jk}^n\Rightarrow\max\\u(x_i,y_i,z_i)=0\end{cases}\quad(4)$$

where $u(x_i,y_i,z_i)$ is structural displacements function.

Results of Numerical Modeling

Numerical modeling of piezoelectric actuator was used to verify and validate actuator design and operating principle through the modal and harmonic response analysis. Commercial FEM package ANSYS 10.0 was employed in this simulation. Finite element model was meshed using three-dimensional structural solid element SOLID45 and coupled-field solid element SOLID5. Following materials were used for actuator modelling: brass was used for the oscillator and piezoceramic PZT-8 was used for piezoelements.

Modal-frequency analysis was performed to find optimal places for structural constrains when dominating coefficient m_{12} must be maximized. Optimization algorithm contains two steps. Firstly sequence number of modal shape vector in the global matrix of actuator modal shapes must be identified. This step is required because sequence of modal shape vectors depends on geometrical parameters and boundary conditions. Dominating coefficient m_{13} was calculated for piezoceramic and horizontal plates and was used for modal shape identification. The next step is used to calculate coefficient m_{12} of the contact zone. Following this algorithm optimal places for structural constrains were found. Max m_{12} value was achieved when boundary conditions are as shown in Fig. 2a. Modal shape of the actuator when these boundary conditions are applied is shown in Fig. 2b.

Harmonic response analysis was performed with the aims to find out the actuator's response to sinusoidal voltage applied on electrodes of the piezoceramic plates and to calculate trajectories of the contact point's movement. The contact point is located at the middle of the oscillator's contact zone. Excitation scheme was used in simulations as shown in Fig. 1a. A 30V AC signal was applied to electrodes. Optimized scheme of structural boundary conditions was applied. A frequency range from 50 kHz to 80 kHz with a solution at 1 kHz intervals was chosen and adequate response curves of contact point's oscillation amplitudes and phases were calculated. Results of calculations are given in Figs. 3a and 3b where the contact point's amplitude and phase versus frequency are given.

Graphs of contact point's oscillation amplitudes show that the excitation frequency at 71 kHz has local peak and is close to natural frequency No. 6. Also phase differences between graphs u_x, u_y and u_z significantly differ from 0 and π, therefore this frequency was chosen as the input frequency of the piezoelectric actuator for calculations of contact point's trajectories.

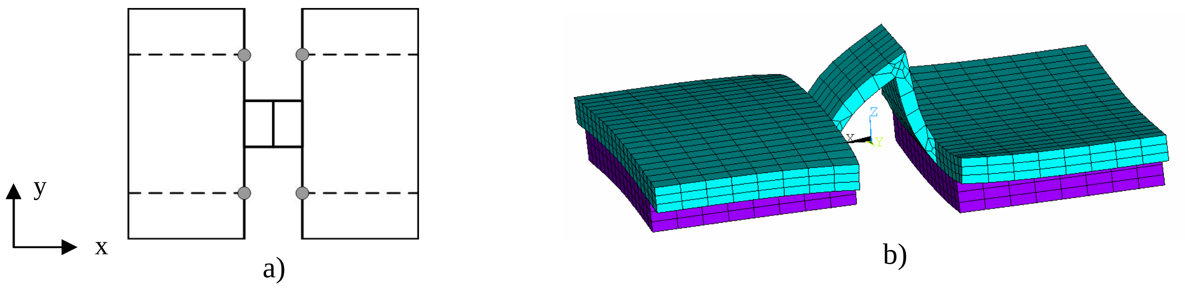


Fig. 2. a) Constrain conditions of the actuator; b) modal shape with given constrains (71.3 kHz)

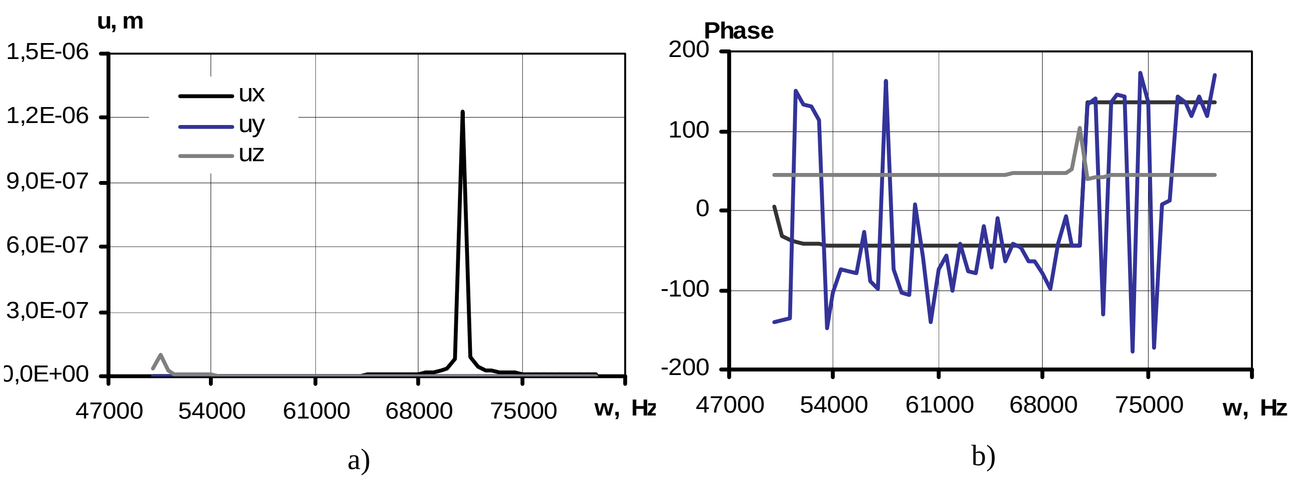


Fig. 3. Results of harmonic response analysis: a) contact point's oscillation amplitude versus frequency; b) contact point's oscillation phase versus frequency

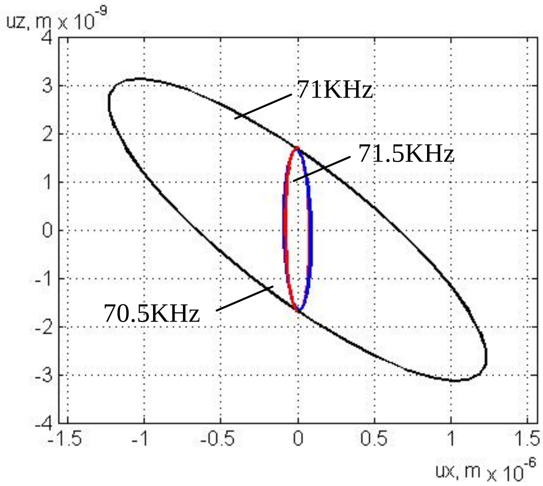


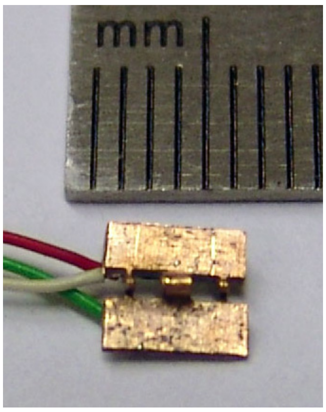
Fig. 4. Trajectories of contact point's movements at different excitation frequencies

Calculations of the contact point's moving trajectories were done applying excitation of the electrodes as shown in Figs. 1a. Three different input voltage frequencies, i.e. 70.5 kHz, 71 kHz, 71.5 kHz were used to simulate the motion of the contact point. Ellipses in Figs. 4 illustrate trajectories of the contact point's movement. It can be seen that trajectories have ellipsoidal shapes and ellipsis at 71 kHz has a much larger length of the major axis then others. It means that the contact point's motion and the strike, respectively, at 71 kHz is much more powerful, therefore, the experimental study was performed analyzing oscillations of the actuator at this excitation frequency. Numerical simulations of the piezoelectric actuator have shown that small changes of the electric input signal frequency significantly influence the contact point's movement characteristics.

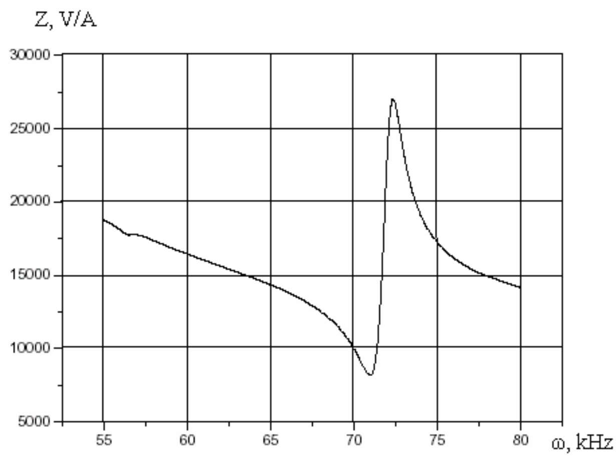
Experimental Investigation

A prototype actuator, made for experimental studies, is shown in Fig. 5. The aims of experiment were to evaluate operating principle of the actuator and to verify results of the numerical modeling. Impedance-frequency characteristics of the actuator were determined with the help of the 4192A LF Impedance Analyzer (Hewlett Packard). Top surface's oscillations were measured using a vibrometer POLYTEC CLV 3D. The resonant frequency at 69.5 kHz was determined by means of electrical impedance study (Fig. 5b). The difference between experimental and numerical resonant frequencies is 2.14%.

Measurements of the actuator's top surface's oscillations were done to verify operating principle of the actuator. Results of measurements are given in Fig. 6.They confirm results of numerical modeling that the elliptical trajectory of the contact point can be achieved using this actuator. The distribution of oscillation amplitudes on the top surface of the actuator is the same as were obtained in numerical simulation. The difference between the contact point's oscillation amplitudes obtained in numerical modeling and measured in experiments is 5-8%.

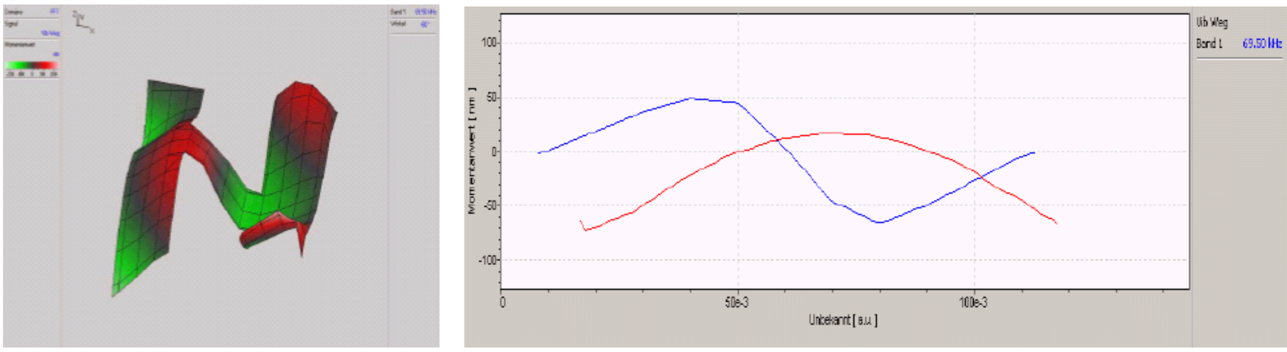


a)



b)

Fig. 5. a) Prototype actuator; b) impedance – frequency characteristic



a) b)

Fig. 6. Distribution of oscillation amplitudes on top surface of the actuator: a) 3D view; b) at the middle line of top surface

Conclusions

A piezoelectric actuator of the novel design was developed for linear motor. Numerical and experimental studies confirm the possibility to achieve elliptical trajectories of driven tips and to move the slider. Values of the resonant frequency and amplitudes from the optimised finite element model are in good agreement with the experimental results.

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