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The Optimisation of Electrodes Configuration for Multicomponent Ultrasonic Actuators

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Abstract: The multicomponent ultrasonic actuators operate in resonance mode and in order to achieve the desired modal shape, it's necessary to obtain exact dislocation of excitation zones. This paper presents a study of optimisation of the electrodes dislocation of ultrasonic actuator. The following conditions of optimisation problem are considered: to unify excitation voltage forms, to achieve reverse motion and maximum coefficient of efficiency. Realisation of this requirement means that current source has to generate voltage of constant frequency, amplitude and phase, reverse motion must be achieved only through changing the polarity of the current source and that the surface of the ultrasonic actuator is fully covered with electrodes. FEM modelling is performed in calculating process. The results of calculations for the ultrasonic actuator are shown for two options of fixing conditions.

Key-Words: ultrasonic actuator, electrodes configuration, multicomponent oscillations.

1 Introduction

Recent advances in development, theory and applications of new smart materials, structures and devices, including materials with extremely high piezoelectric properties extended the area of the researches of new systems with high levels of integration and multifunctionality. Particular interest is concentrated in development piezoelectric drives as high precision and sensitiveness system, that enables the creation of a time constant positioning drives, micro manipulators, micro pumps, transducers for materials physical properties measurement, transmission of motion into vacuum chambers without power losses, converters, vibration concentrators, scanners, etc.

The performance of such devices strongly depends on the features of the actuator, the main part of the piezoelectric system. Many different constructions of the actuators (such as beam, plate, cylinder, disc and etc.) are used in order to achieve particular law of movement of actuator and final link of kinematics pair[1,2]. The shape and optimal location of the electrodes on the surface of actuator have the great importance to vibration mode of the actuator. Using different configurations of electrodes, vibration of main and higher resonance modes of ultrasonic actuator could be achieved [7]. In case of optimal electrodes configuration, needless harmonics of actuator could be eliminated and also the concentration of mechanical stresses could be reduced. These facts are very important in case of multicomponent oscillations of actuator that is analysed in this paper.

2 Construction of Ultrasonic Actuators

Synthesis of needful fields of the oscillations must be obtained by using the particular shape and dimensions of the actuator and also certain geometry of excitation zones locations. Various constructions of the actuators are used in order to achieve particular law of movement of the actuator and the final link of kinematics pair [8, 9](Fig.1). There are some basic shapes of the ultrasonic actuator such as beam, plate, cylinder, disc, ring and etc., but also more complex constructions are used in the ultrasonic motors: cross shaped, various multilayer actuators with or without attached masses.

Characteristics and types of the excited multicomponent oscillations of ultrasonic actuator depend on geometrical parameters, boundary conditions and direction of the polarisation vector. Topology of electrodes and geometrical parameters of the actuator define the direction of the excited oscillations. In order to achieve suitable characteristics of the oscillations, particular geometrical parameters of the actuator must be calculated. Especially important is to select the suitable correlation between these parameters [5, 7].

The beam and plate shape actuators are mostly used in the ultrasonic motors.

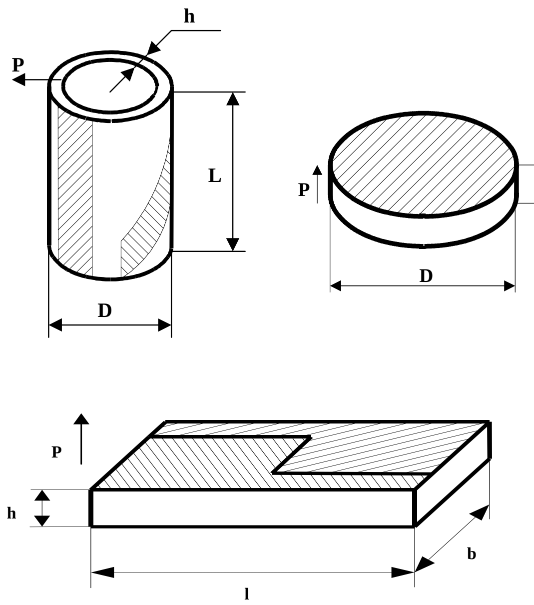


Figure 1. Constructions of the ultrasonic actuators [4].

Many different types of multicomponent oscillations can be excited using these actuators: longitudinal-flexural, longitudinal - torsional and etc. Using variable vector of polarisation, three and four components oscillations of the beam shaped actuator can be achieved [1].

The maximum of oscillation amplitudes (till 10 μm) can be exciting in bimorfical plates. Usually these multicomponent oscillations have longitudinal and flexural components. Some constructions of piezo actuators with different electrodes configurations are presented in Fig.1.

Also many other constructions of the actuators are designed and used in ultrasonic motors, but the applications, described above clearly indicates complexity of multicomponent oscillations and in order to achieve optimum of actuator design, the analysis of complex piezomechanical problem must be done.

3. Mathematical modelling of ultrasonic actuator

In most cases ultrasonic actuator are resonance systems that operate in the first or higher resonance frequency. The synthesis of the needful field of oscillations must be obtained by using a particular shape and dimensions of actuator and also certain geometry of the locations of excitation zones. Equations (1) fully define the piezoeffect [3, 5]:

$$\begin{cases}\{\sigma\} = \left[c^E\right]\{\varepsilon\} - [e]^T\{E\} \\ \{D\} = [e]\{\varepsilon\} + \left[\ni^S\right]\{E\}\end{cases} \qquad (1)$$

where $[c^E]$, [e], $[\ni^s]$ – the matrix of stiffness for a constant electric field; the matrix of the piezoelectric constant; the matrix of dielectric constant evaluated at the constant strain, respectively; $\{\sigma\}$,$\{\varepsilon\}$,{D}, {E} – the vectors of stress, strain, electric induction and electric field, respectively.

Various kinds of resonance oscillations of actuators - longitudinal, flexural, rotational, shear and so on - could be obtained using a different geometry of electrodes [1]. In order to achieve required resonance oscillations of the actuator, particular electrodes must be excited.

Analysis of the piezoelectric actuator must be carried out appreciating the electric occurrence in the system. Based on FEM, every node of the element has one additional DOF used for electric potentials in FEM modeling. The solution applied for the equations of motion, suitable for the actuator, can be derived from the principle of minimum potential energy by means of variation functional [3]. The basic dynamic FEM equation of motion for piezoelectric transducers that are fully covered with electrodes can be expressed as[8]:

$$\begin{aligned}&[M]\{\ddot{\delta}\} + [C]\{\dot{\delta}\} + [K]\{\delta\} - [T]\{\varphi\} = \{R(\omega_k t)\} \\ &[T]^T\{\delta\} + [S]\{\varphi\} = \{Q\}\end{aligned} \qquad (2)$$

where [M], [K], [T], [S], [C] - the matrices of mass, stiffness, electro elasticity, capacity and damping, respectively; $\{\delta\}, \{\varphi\}, \{R\}$ - the vectors of nodes displacements, potentials and external mechanical forces, respectively.

Here:

$$[K] = \int_V [B]^T \left[c^E\right] [B]\, dV \qquad (3)$$

$$[T] = \int_V [B]^T [e]\, [B_E]\, dV \qquad (4)$$

$$[S] = \int_V [B_E]^T \left[\ni^s\right] [B_E]\, dV \qquad (5)$$

$$[M] = \rho \int_V [N]^T [N]\, dV \qquad (6)$$

$$[C] = \alpha [M] + \beta [K] \qquad (7)$$

where [B], $[B_E]$ – the matrices of geometry used for evaluation of displacements and potential, respectively; [N] – the function of the shape used for evaluation of the mass matrix. The damping matrix [C] is derived using mass and stiffness matrices by assigning constants α and β.

Usually only the first equation from system (2) is used in the modeling process, because it is considering that the current source is powerful enough and ensures defined values of the electric potentials.

4.Optimization analysis

In order to obtain optimal electrodes configuration of the actuator, the following conditions to the piezoelectric system were accepted: to unify excitation voltage forms, to achieve reverse motion and maximum coefficient of efficiency. Realisation of the first requirement means that current source has to generate voltage of stable frequency, amplitude and phase, in order to simplify construction of the machine, second - that reverse motion must be achieve by changing the polarity of the electric flux and third - that the actuator must be fully covered with the electrodes[6, 8]. When all aforementioned conditions are achieved, any mode shape of ultrasonic actuator could be obtained by changing polarity of the voltage, supplied to the particular electrode. In order to find the sign of the polarity, corresponding to the certain modal shape, the comparison between directions of the vector of amplitude of the equivalent mechanical force and particular eigenvector of the actuator must be done. If the direction of displacement eigenvector of the piezoelectric actuator and the vector of amplitudes of the equivalent mechanical force is the same or similar i. e. the angle is within the limits [-π/2; +π/2], then the polarity of the voltage, supplied to particular electrode have initial sign. In other case the sign of polarity must be changed. So depends on the angle of aforementioned vectors, the polarity of voltage is defined.

Active frequency of the ultrasonic actuator is closed to the resonance, so the electric flux must have the same excitation voltage frequency [6]. Modal shapes and natural frequencies are obtained by reducing equations (4), into standard eigenvalue form.

$$[M]\{\ddot{\delta}\}+[K]\{\delta\}-[T]\{\varphi\}=\{0\}$$
$$[T]^T\{\delta\}+[S]\{\varphi\}=\{0\} \qquad (8)$$

The natural frequency and normalised displacement eigenvectors are derived from the modal solution of the piezoelectric system [4] and used in further optimisation analysis process.

Due to the first condition of optimisation to unify excitation voltage, the potential of electrodes of all piezoelements must be equal as shown in equation (11) [7]:

$$\{\varphi\}^e=\{U\}^e sg_e \sin\omega_k t$$
$$sg_e=\begin{cases}+1\\-1\end{cases} \qquad (9)$$

where $\{U\}^e$, ω_k - accordingly vector of element excitation voltage amplitude and *k* resonance frequency. When the vector of the external mechanical forces {R} is setting to zero in equation (8), we obtain the following equations :

$$[M]\{\ddot{\delta}\}+[C]\{\dot{\delta}\}+[K]\{\delta\}=\{-F\} \qquad (10)$$

Here:

$$\{F\}=\sum_e [L]^e[T]^e\{U\}^e sg_e \sin\omega_k t = \sum_e \{F\}^e \sin\omega_k t \qquad (11)$$

where $\{F\}$- vector external equivalent mechanical forces; $\{F\}^e$- vector of amplitude of external equivalent mechanical force at the nodes of finite element in global coordinate system; $\{T\}^e$- matrix of electroelasticity of finite element; $\{L\}^e$- matrix of transformation between local and global element coordinates.

Here:

$$\{F\}^e=[L]^e[T]^e\{U\}^e sg^e \qquad (12)$$

The solution of the basic dynamic FEM equation of motion for piezoelectric actuator could be written in following form:

$$\{\delta\}=[\Delta_0]\{z(t)\} \qquad (13)$$

where $[\Delta_0]$- normalised eigenvectors; z(t) - coefficient of proportional.

Here:

$$[\Delta_0]=[\{\delta_0\}_1,\{\delta_0\}_2,\ \dots,\ \{\delta_0\}_n] \qquad (14)$$

Coefficient of proportional could be obtained from equation (15):

$$\ddot{z}_i+2\omega_i h_i\dot{z}_i+\omega_i^2 z_i=-\{\delta_0\}_i^T\{F\}$$
$$i=1,2\dots n \qquad (15)$$

Solving equation (15) we could calculate coefficient $z_k(t)$, that corresponds to *k* natural frequency of actuator.

Now let's make the analysis of effective job of the external forces when electrodes of the actuator are excited. Referring to the third condition of optimisation problem to obtain the maximum of the coefficient of efficiency, the effective job of actuator A_k^{ef} must be maximised. The average of effective job, corresponding to the k natural frequency could be obtained as follow:

$$\max A_k^{ef} = \frac{\omega_k}{2\pi} \int_0^{\frac{2\pi}{\omega_k}} \{\delta_0\}_k^T \{F\} z_k(t)\, dt \qquad (16)$$

If we put equation (11) into (16), the following expression of the effective job could be obtained:

$$\max A_k^{ef} = \frac{\omega_k}{2\pi} \int_0^{\frac{2\pi}{\omega_k}} \sum_e \{\delta_0\}_k^T \{F\}^e \sin\omega_k t \; z_k(t)\, dt \quad (17)$$

The equation (17) could be rewritten in the form:

$$\max A_k^{ef} = \sum_e \{\delta_0\}_k^T \{F\}^e P_k = \sum_e |\delta_0|_k |F^e| \cos\gamma_k^e P_k \qquad (18)$$

Here:

$$P_k = \frac{\omega_k}{2\pi} \int_0^{\frac{2\pi}{\omega_k}} \sin(\omega_k t)\, z_k(t) dt \qquad (19)$$

Based on equation (19) we can see that P_k is a time independent and referring to the particular conditions $\{\delta_0\}_k$ is constant also, so only the multiplication of the vector of the amplitude of the equivalent mechanical force and eigenvector of ultrasonic actuator must be maximised. In order to achieve maximum value, directions of the vectors must be same or similar i.e. $\cos\gamma_k^e$ - the cosine of the angle of aforementioned vectors must be maximised.

$$\cos\gamma_k^e = \frac{\{\delta_0\}_k^T \{F\}^e}{|\delta_0|_k |F^e|} \qquad (20)$$

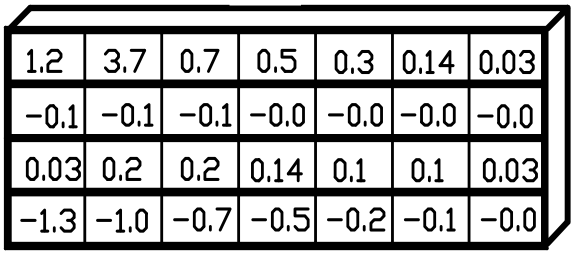
As we can see from the equation (20), the sign of $\cos\gamma_i^e$ depends only on the direction of the vector of the equivalent mechanical forces in finite element. Referring to the equation (12), the direction of the vector could be changed by changing the polarity of the voltage. Based on equation (9), the polarity of the voltage supplied to the element depends on the sg_j The maximum of oscillation of the amplitude, accordingly to the certain modal shape of the piezodrive, is achieved when directions of the eigenvector and vector of amplitudes of equivalent mechanical force are similar i.e. when value of sg_i must be identical to the sign of $\cos\gamma_k^e$

4. Processing and Results

Calculations were carried out with plate shaped actuator on the basis of the equation (20). Two different conditions of fixing of the actuator were selected: the centre nodes were constrained, and the nodes of the left side were constrained. The results of calculations $\cos\gamma_k^e$ are given in the centres of gravity of the element.

The Actuators shown in Figure 2 case (a) has constrained centre nodes and performs in first resonance frequency (case a) and actuator case (b) has constrained nodes of the left side.

a)



b)

Figure 2. Values (*10^{-2}) of $\cos\gamma_k^e$ and configuration of electrodes in ultrasonic actuator under two options of fixing conditions: a) constrained the centre nodes, first modal shape; b) constrained nodes of the left side, second modal shape. Vector of polarisation is perpendicular to paper plane.

Based on the sign of $\cos\gamma_k^e$, two zones of electrodes location are obtained. Zones with different polarity are separated with bold line. For comparison in Figure 2 we can see configuration of electrodes for the same type of actuators created by the intuition of the engineer. This kind of actuators is being used in ultrasonic motors with rotational and linear motion. As we can see in Figure 2 configuration of electrodes strongly depends on constraining conditions.

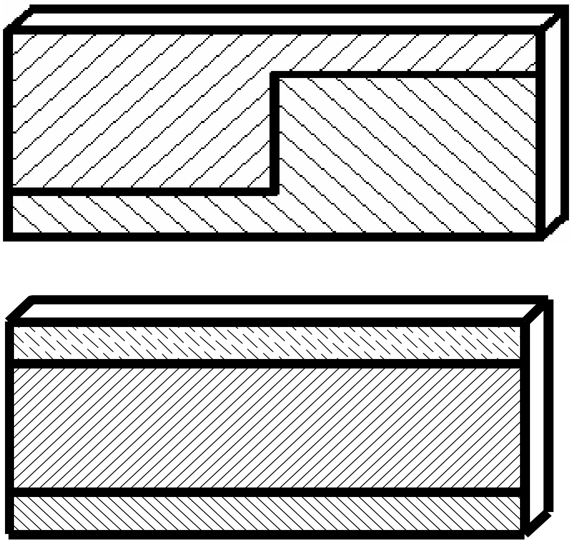


Figure 3. Configuration of electrodes of the ultrasonic actuator according engineer's intuition created for the same type of actuators as shown in figure 2 accordingly. Vector of polarisation is perpendicular to paper plane.

6 Conclusions

The calculation algorithm of optimal electrodes configuration of the piezoelectric actuator provided in this paper is especially important for the multicomponent oscillation. This method is based on FEM and allows achieving precision of calculations according to the limits of the area of finite element.

The calculations of two-dimensional piezodrives were carried out. It was determined that electrodes configuration on the surface of the piezodrive strongly depend on the constrain conditions. The algorithm is important in the design of piezoelectric actuators with some degrees of freedom.

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