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Design of Shaking Beam for Piezoelectric Linear Ultrasonic Motor

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ABSTRACT

Design of a piezoelectric actuator for the ultrasonic motor must ensure that contact point has elliptic trajectory of movement. The new idea of an elliptic trajectory formation of the piezoelectric actuator is investigated in the paper. Shaking beam for the piezoelectric linear ultrasonic motor was introduced to realize this new idea. The principle is based on the excitation of longitudinal and flexural vibrations of the actuator by using two sources of longitudinal mechanical vibrations shifted by $\pi/2$. Mode-frequency and harmonic response analyses of the actuator based on FEM have been carried out. The moving trajectory of the contact point has been defined. Finally, The experimental research of shaking beam has been confirmed an opportunity of the elliptic trajectory reception with the help of one stable mode of the vibrations.

Key words : Piezoelectric actuator, Linear motor, Shaking beam, FEM, Longitudinal and flexural vibrations

1. Introduction

High speed and high accuracy positioning systems are essential elements in advanced manufacturing systems such as the semiconductor industry. Demands of a new type of displacement transducers, which can adjust exact position or drive objects with high accuracy have increased significantly.

An ultrasonic motor using powerful ultrasonic mechanical vibrations produced in a piezoelectric vibrator is attractive device in its development and applications. It is entirely different from the present motors which utilize interactions of electric and magnetic fields. It is generally said that ultrasonic motors have the following specific characteristics: (1) stable operation with low velocity and high torque, which is suited for direct drive; (2) quick response and excellent controllability of starting, stopping and reversing; (3) small and light weight structures; (4) no electronic disturbances.

There are many distinct constructions of the actuators that are used to transform mechanical vibrations of the piezoelectric vibrators into linear or rotational movement of the slider.[1-4] The new idea of elliptical trajectory formation of the actuator for the piezoelectric linear ultrasonic motors is introduced in the paper. Based on the elliptical trajectory formation, the new construction of the actuator called "Shaking Beam" was developed. Elliptic trajectory of the contact point is achieved by using superposition of two resonance vibration modes of the actuator i.e. longitudinal and flexural vibrations.

2. Principle of "Shaking Beam" Actuator

Design of actuator as a main part of ultrasonic motor is very complex scientific and engineering problem. In our point of view, three ways for formation of elliptical trajectory are considered; (1) rectangular piezoelectric and plate using the split electrodes by Bansevichyus,[5] (2) ring with the packet actuator by Claeyssen[6] and (3) excitation of standing wave in a flat rod and arrangement of rods near to central zones of displacement.[1] Besides the above three ways, we would like to give attentions to new way of moving slider. One of the purposes of developing a new actuator was to achieve traction force of the motor as large as possible. Traction force or rotational moment of the ultrasonic motor is proportional to the actuator held-down force to the moving element of the motor.[1,2] But an increase of the traction force results in the loss of the balance of interaction vibration modes used for elliptic trajectory achievement of the contact point.

We realized a totally new closed trajectory formation principal of the actuator. This principle is based on the exciting the ends of the Shaking Beam indicated by ab in Fig. 1 by two sources of the harmonic vibrations that have identical frequency, but phases are different by $\pi/2$ (see Fig. 1).[7]

Let's make analysis of this type of Shaking Beam, in which free ends vibrates harmonically with the phase difference $\pi/2$. The vibrations of a and b ends of the beam can be written as:

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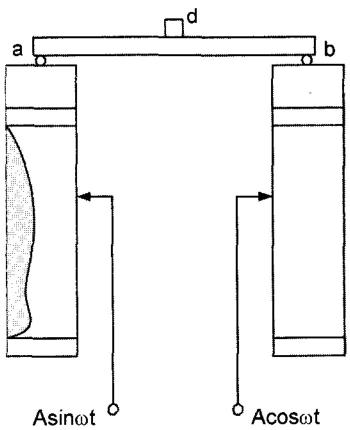

Fig. 1. Mechanical system of the Shaking Beam.

$$y_a = A \sin\omega t \tag{1}$$

$$y_b = A \cos\omega t \tag{2}$$

where A is amplitude of the oscillations, ω is circular frequency of the oscillations, and t is time.

Fig. 2 shows the position of the beam through every quarter of vibration period. From movement diagrams we can see that middle point d of the beam has movement of closed trajectory and movement of the beam looks like beam shaking (Fig. 2).

3. FEM Modeling of "Shaking Beam" Actuator

Modeling of the actuator was done using FEM analysis, because it is one of the most effective numerical methods for engineering problems solving. The aim of numerical modeling was to find out natural frequencies and modal shapes of the actuator and to perform harmonic response analysis. Basic equation of motion of the actuator can be written as follows.[8,9]

$$[\boldsymbol{M}]\frac{\partial^2\{\boldsymbol{u}\}}{\partial t^2}+[\boldsymbol{C}]\frac{\partial\{\boldsymbol{u}\}}{\partial t}+[\boldsymbol{K}]\{\boldsymbol{u}\}=\{\boldsymbol{F}\} \tag{3}$$

where $[\boldsymbol{M}]$, $[\boldsymbol{C}]$, $[\boldsymbol{K}]$, are matrices of mass, damping, and stiffness, respectively, $\{\boldsymbol{u}\}$ is vector of structural displacements, and $\{\boldsymbol{F}\}$ is vector of mechanical forces.

Eq. (3) can be solved applying finite element method, and then matrices have the following expressions:

$$[\boldsymbol{k}] = \int_V [\boldsymbol{B}]^T[\boldsymbol{D}][\boldsymbol{B}]dV \tag{4}$$

$$[\boldsymbol{M}] = \rho\int_V [\boldsymbol{N}]^T[\boldsymbol{N}]dV \tag{5}$$

$$[\boldsymbol{C}] = \alpha[\boldsymbol{M}]+\beta[\boldsymbol{K}] \tag{6}$$

where $[\boldsymbol{B}]$ is matrix of shape functions derivatives, $[\boldsymbol{D}]$ is matrix of elastic coefficient, ρ is mass density, $[\boldsymbol{N}]$ is matrix of shape function used for evaluation of structural displacements, $\boldsymbol{V}$ is volume of the structure and $\boldsymbol{\alpha}$, $\boldsymbol{\beta}$ are constants.

Damping matrix C is derived using mass and stiffness matrices by assigning constants α and β. Modal shapes and natural frequencies of the actuator are obtained by reducing Eq. (3) into standard eigenvalue form. The eigenvalues (natural frequencies) and eigenvectors (normalized structural displacements) are derived from following equation:

$$\det([\boldsymbol{K}] - \omega^2[\boldsymbol{M}]) = 0 \tag{7}$$

Harmonic response analysis was applied to determine the steady state response of the actuator to the harmonic loads. Harmonic response analysis of the actuator was done analyzing FEM model of linear ultrasonic motor Fig. 3(a). Sinusoidal varying external forces were achieved using stack of the piezoelectric ceramic elements when voltage was applied to the electrodes.

$$\{\boldsymbol{F}\} = -\sum_e [\boldsymbol{T}]^e\{\varphi\}^e \tag{8}$$

where $\{\boldsymbol{F}\}$ is vectors of mechanical forces, $[\boldsymbol{T}]$ is matrix of electro-elasticity, and $\{\boldsymbol{\varphi}\}$ is vector of nodal electric potentials.

Vector of nodal potentials of the element has the following expression:

$$\{\varphi\}^e = \{\boldsymbol{U}\}^e \sin\omega_k t \tag{9}$$

Using Eq. (9) vector of external mechanical forces can be rewritten as follow:

$$\{\boldsymbol{F}\} = -\sum_e [\boldsymbol{T}]^e\{\boldsymbol{U}\}^e\sin\omega_k t \tag{10}$$

Results of structural displacements of the actuator obtained from harmonic response analysis are used for determining trajectory of movement of middle point of Shaking Beam.

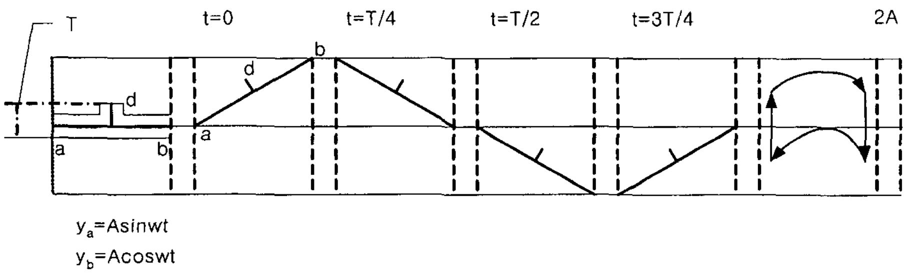

Fig. 2. The position of the beam through every quarter of the vibrations period.

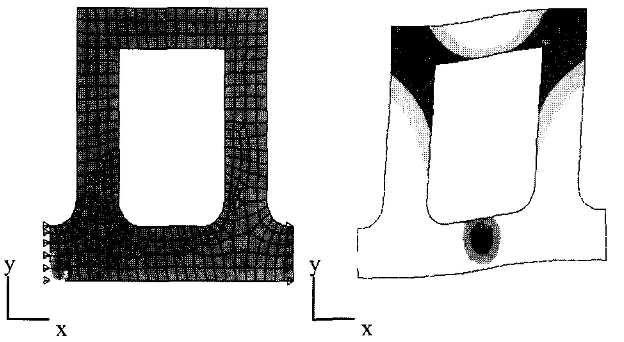

Fig. 3. Two dimensional "Shaking Beam" actuator: (a) FE model and (b) 3rd modal shape (21.15 KHz).

4. Results and Discussion

4.1. Modeling Process and Results

FEM modeling was carried out employing FEM software ANSYS 5.7 that was used to create solid FE model and to make dynamic analysis of the actuator and was analyzed as two-dimensional system. Modal frequency analysis was done using Power dynamic mode extraction method that internally uses the subspace iterations. Needful modal shapes and natural frequencies were calculated. It was the 3rd modal shape of two dimensional actuator (21.15 KHz).

As we can see from Fig. 3(b), modal shapes of the actuators correspond to the principle of Shaking Beam and can be used for elliptic trajectory achievement of the middle point movement.

A full harmonic response analysis was performed by using Incomplete Cholesky Conjugate Gradient solver with tolerance 10^{-6}. Actuator was analyzed as part of the linear piezoelectric ultrasonic motor, so additionally FE model of two dimensional motors was build. Stack of the piezoelectric elements for piezoelectric motor was excited using AC signals applied on the executing electrodes. The phases of the applied voltage were shifted on 90° for the each piezoelectric element. Shapes of the motor displacements after quarter of oscillations period are shown in Fig. 4.

Results of the middle point movement of the shaking beam were used to build trajectory of movement. As we can see from Fig. 5, trajectories are very closed to the elliptic with main axes rotated on particular angle. The angle of rotation is −36.1° for two dimensional actuator (see Fig. 5). Using the elliptical displacement motion shown in Fig. 5, an ultrasonic motor can be constructed, where the direction of movement can easily be changed by altering the phase angle.

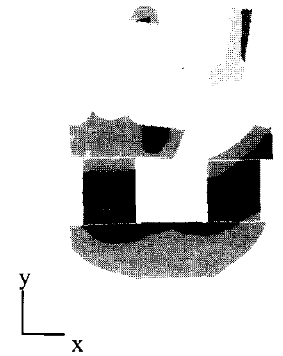

Fig. 4. Harmonic response analysis of two dimensional motor (56.05 KHz).

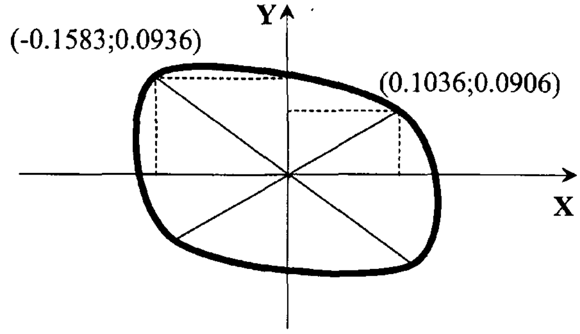

Fig. 5. Two dimensional (10^{-5} m) trajectory of movement of middle points of the Shaking Beam.

4.2. Measurement Results of Shaking Beam Actuator

The purpose of the experiments was confirmation of the theoretical model of a principle moving mobile element motor with the help Shaking Beam, and the measurement system is shown as Fig. 6.

The measuring point of the actuator is indicated in Fig. 7

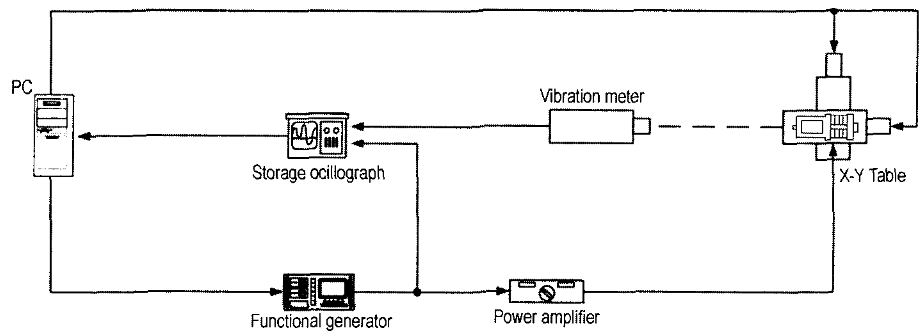

Fig. 6. Measurement system of the displacement of the actuator.

as the numbers (1-9).

The each displacement in the specified points was measured the laser vibration meter. The measurement of the oscillatory speed results in the following points actuator are shown in Fig. 8, where are: 7-longitudinal vibrations of the right shoulder of actuator, 8-normal components contacting with a mobile element of the actuator, 2- tangential components, contacting to the mobile element of the motor. From dependences is visible precisely concurrence of the maximum oscillatory speeds on working frequency of one shoulders actuator (7) and contacting elements (8). The absence of the maximum admittance in measuring point (2) on working frequency shows absence of resonant flexural vibrations at the actuators.

The characteristics of Fig. 8(b) are shown evidently that changing the driving bar height, the tangential component of its oscillatory speed and the motor speed can be changed. It is necessary to pay attention that the change of points 2 and 3 in the field of the work motor is identical, and that also specifies absence influence resonant properties driving bar on the work actuator.

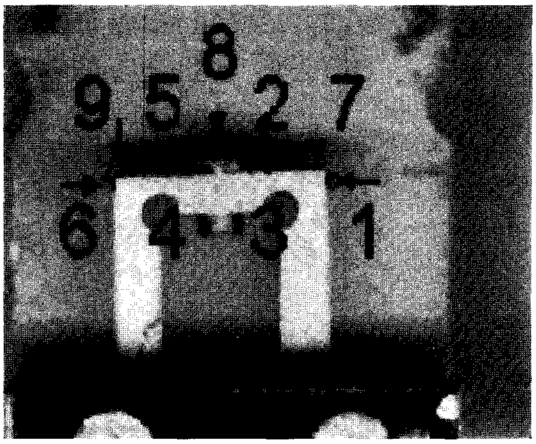

Fig. 7. Measuring point of the actuator.

The laser measurements of both shoulders (point 7 and 9)

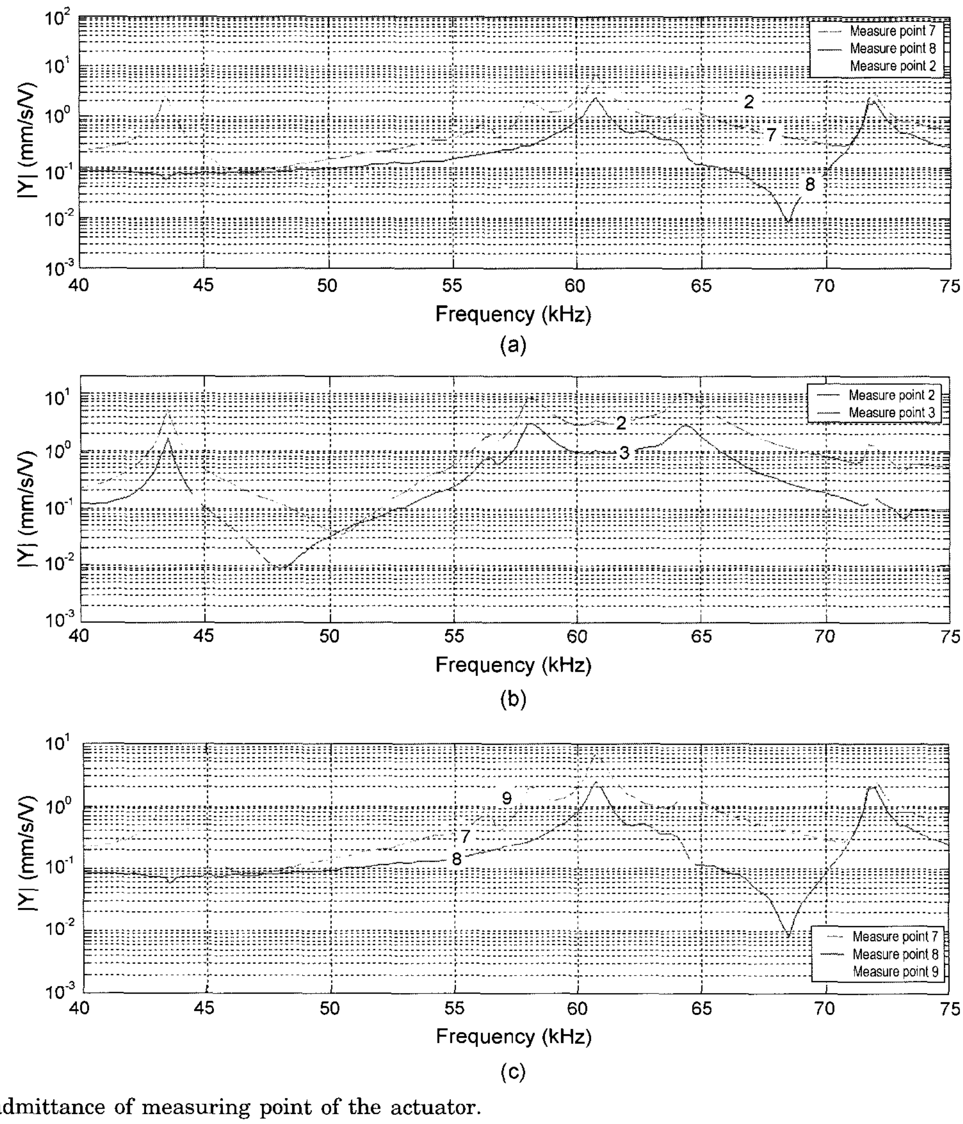

Fig. 8. Entrance admittance of measuring point of the actuator.

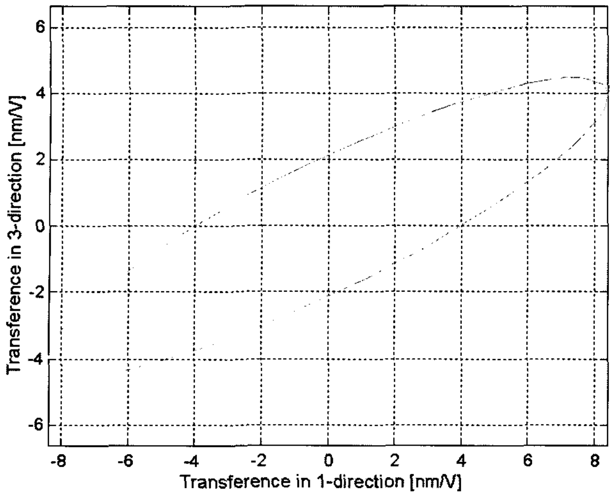

Fig. 9. Elliptical trajectory of the point 2 in the Shaking Beam.

are shown in Fig. 8(c).

The elliptical trajectory driving actuator bar, which is received by summation of the measured oscillatory speed in the point 2 is shown on Fig. 9.

5. Conclusions

New principle of closed trajectory formation for the actuator has been developed using the Shaking Beam actuator. Numerical analysis of the actuator using FEM has been performed. Elliptic trajectory of contact point has been achieved when harmonic response was carried out. The experimental investigation of the actuator has been confirmed an opportunity to achieve elliptical trajectory with the help of the stable mode vibration. The results of numerical research and experimental investigation will be used in future optimization of the actuator and realization of the ultrasonic motor.

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