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The square bar-shaped multi-DOF ultrasonic motor

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Abstract In this paper a multi-degree-of-freedom (multi-DOF) ultrasonic motor consisting of a square bar-shaped stator and a spherical or plate type rotor was developed. It can generate multi-DOF rotation of the rotor using "shaking beam" principle of linear motion formation based on previous researches. The multi-DOF rotation generated by four contacting points of a square bar-shaped actuator using four d_{31} piezoelectric plates. The computer simulation by finite element analysis of proposed system is given. The authors used precision laser equipment for testing and measuring both contacting points and surfaces of square bar-shaped actuator.

Keywords Ultrasonic motor · Multi-DOF · Shaking beam · FEM

1 Introduction

The electromagnetic motors have been use in order to construct a multi-DOF motion unit. However, the number of the motors in such units must be equal or larger than the number of DOFs of the motion, because general electromagnetic motors generate only single-DOF rotation. Moreover, gearbox or any reduction mechanisms must be connected to electromagnetic motors in order to obtain large torque and low speed. In this case, the total weight and volume of the multi-DOF motion unit are increases. Hence, several actuators capable of generating multi-DOF motion have been developed in recent years. Roth and Lee [1] proposed a three-DOF variable reluctance spherical wrist motor for example. On the other hand, if multi-DOF system is used, the total weight and volume of the motion unit become smaller. The recent trends in robotics and mechatronic field to necessitate for creating, modelling and developing small size and weight multi-DOF motion system and one of feasible solution of this problem is use the ultrasonic actuators.

Certainly, the number of different ultrasonic actuators for multi-DOF motion has been developed in last ten years. Toyama et al. [2] proposed a multi-DOF actuator, which can generate multi-DOF motions of rotors with the small output torque. Bansevicius [3] developed a piezoelectric multi-DOF actuator with a cylindrical stator and a spherical rotor. Amano et al. [4] developed a multi-DOF ultrasonic actuator where a spherical rotor rotates around three perpendicular axes. Takemura and Maeno [5] developed the multi-DOF ultrasonic motor generates multi-DOF rotation of a spherical rotor using the three natural vibration modes of a bar-shaped stator. The authors have developed a new type of ultrasonic motor capable of generating three-DOF motion [6]. The three-DOF ultrasonic motor generates three-DOF rotation of a spherical rotor using the four "shaking beam" actuators with common basic part.

In present paper, authors proposed new type actuators for multi-DOF ultrasonic motor based on "shaking beam" actuator principle [7]. The square-bar shaped ultrasonic motor can generate the multi-DOF motion of spherical or plate type rotor.

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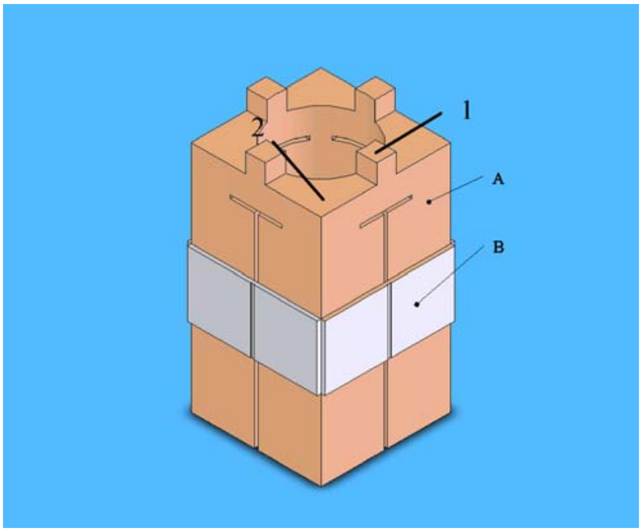

Fig. 1 CAD-model of the stator

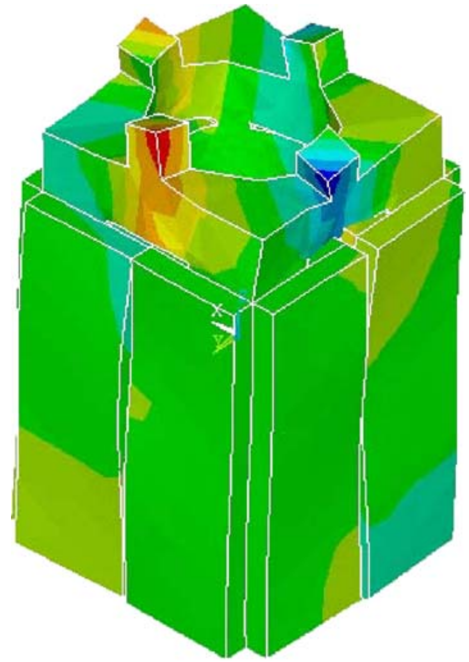

Fig. 2 The eigenmode of the stator on 86 kHz

2 FEM modelling and analysis

The square-bar shaped stator of supposed multi-DOF ultrasonic motor modelled using the finite-element method in order to confirm theoretical operation principle. The aim of simulation was to calculate natural frequencies and modal shapes of the stator and to perform harmonic response analysis, which has been applied to determine the steady-state response of the stator to the harmonic loads. For presented simulation authors used the Finite Elements Codes *ANSYS 6.1*. Finite element models of the ultrasonic motor starting with a three-dimensional CAD model shown on Fig. 1. The ultrasonic motor consists of square-bar shaped stator (A) and four d_{31} piezo-elements around (B).

Current stator used the PZT-8 ceramic with thickness 0.3 mm. The electrode modeled using multi-point constraints so that all nodes at the electrodes have the same electrical potential. From several calculations of eigenmode of the stator with FEM we find the one solution when contacting points has maximum amplitude as it is required for good motor performance. To find the corresponding eigenfrequency of the stator the frequency range from 60 to 100 kHz taken into account. Modal-frequency analysis was done using Power dynamic mode extraction method that internally uses the subspace iterations. For FEM modeling authors used the SOLID 95 type of elements for the stator and SOLID 98 for piezo-ceramics. Needful modal shapes and natural frequencies were calculated. Harmonic response analysis of the stator is shown on Fig. 2, and eigenfrequency 86 kHz. For electrical excitation of the stator, the electrodes are set to varying potentials with phase combination sin, cos, −sin and −cos depend on motion direction of the spherical or plate type rotor. The CAD model and model for FEM analysis has a small difference between, namely ceramics displacement on the stator, which we change during design and optimization. For modelling and measurements, we are use the contacting point ***1*** and point ***2*** as shown on Fig. 1. The point ***1*** is the one of contacting point stator with the rotor. Displacement results on the middle point ***1*** of the "shaking beam" used to build an elliptic trajectory of movement. The point ***2*** is the common part of the two-joined "shaking beam". Displacement results in this point show how is matched two-joined "shaking beam" parts and accordingly performance of the system. The simulation results in point ***1*** had shown on Fig. 3 and in point ***2*** on Fig. 4. The elliptical trajectory of contacting point ***1*** on resonance frequency 86 kHz and

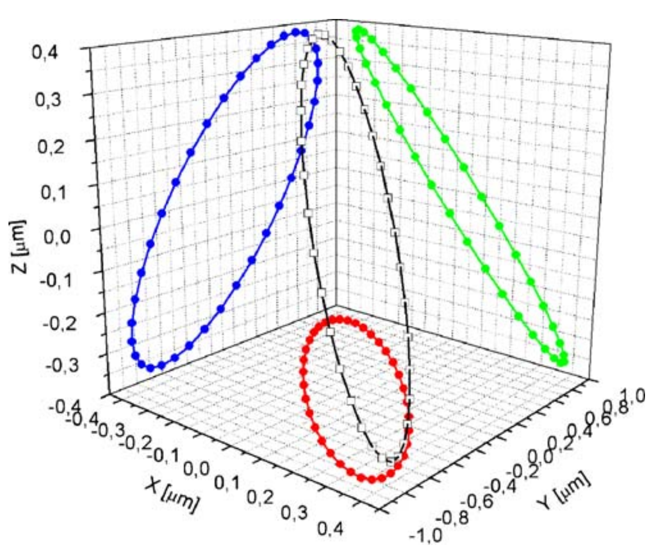

Fig. 3 The elliptical trajectory in point ***1***

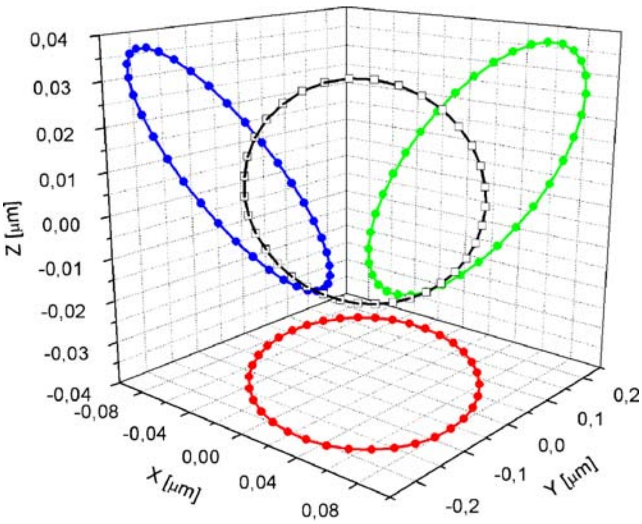

Fig. 4 The elliptical trajectory in point ***2***

FEM analysing results in this case represented the good form of elliptical trajectory. The amplitude value of point ***2*** on Fig. 4 comparing with amplitude of contacting point ***1*** represented the good quality performance of proposed multi-DOF stator. Figures 3 and 4 represented only one direction of test points, because symmetrical system modelling of elliptical trajectory of these points has only phase difference when direction is changed and in this case not to be interesting for us. Below, in experimental part we described both direction motion of proposed system in details, because this is very important things from practical point of view for design of reverse type ultrasonic motor.

The elliptical trajectory of multi-DOF stator contacting points should be controllable by voltages for adjust the speed and direction of ultrasonic motor. The elliptical trajectories of contacting point ***1*** for 10, 50 and 100 V respectively shown on Fig. 5. Several simulations with different potentials on electrodes have shown satisfactory results of elliptical trajectory formation by voltage amplitude control. Moreover, motion direction or speed control of the spherical or plate type rotor of proposed multi-DOF ultrasonic motor possible by voltage amplitude control separately in every channel.

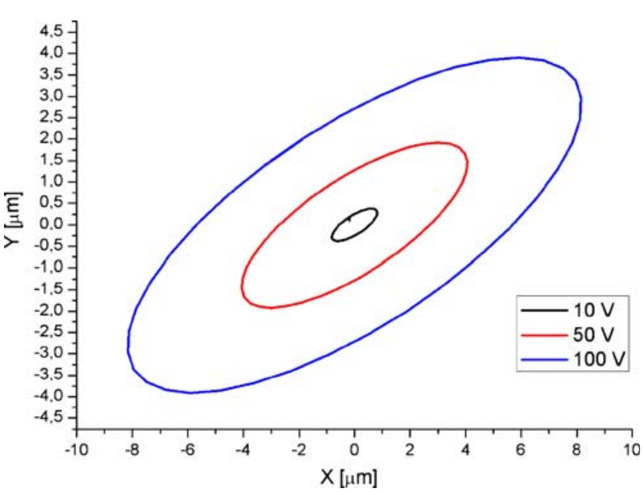

Fig. 5 The trajectories dependences on apply voltages

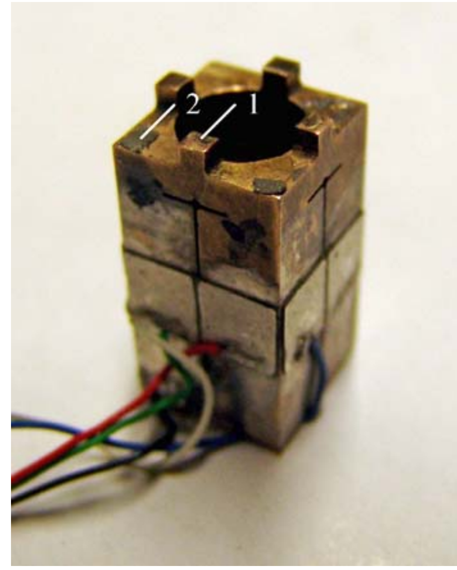

Fig. 6 Multi-DOF square-bar shaped stator

3 Experimental results

The experimental research carried out in order to find distribution of oscillations amplitudes on the stator surfaces and trajectories of contacting points. Furthermore, the experimental investigations should verify by measurement with FEM modelling and analysis of the stator.

Amplitude-frequency characteristics were determined with the help of impedance analyzer 4192A LF Impedance Analyzer (Hewlett Packard). Surface oscillations of contacting points ***1*** and ***2*** controlled using Doppler-laser interferometer (POLYTEC CLV 3D). This unique instrument can resolve to the register oscillations of any stator point simultaneously in three directions (X, Y, Z). Therefore, as

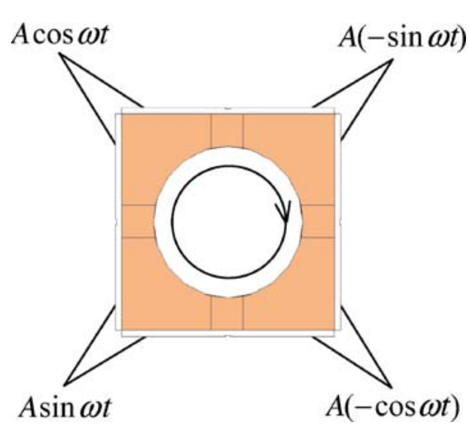

Fig. 7 Connection for rotary motion

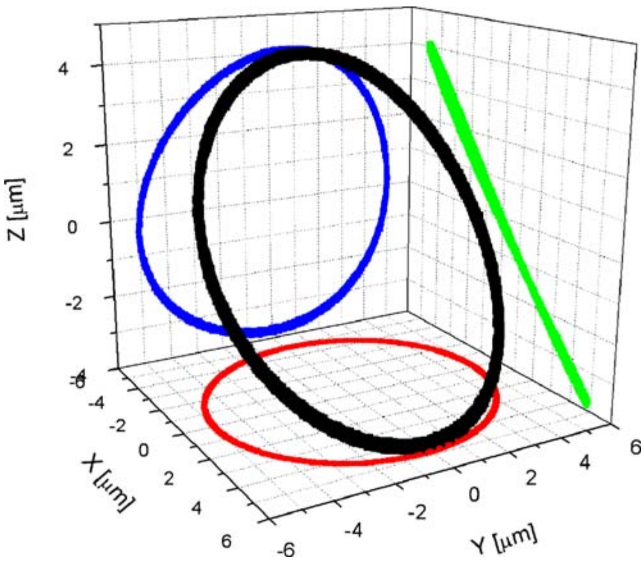

Fig. 8 The elliptical trajectories of point ***1*** on 89.5 kHz on the first direction

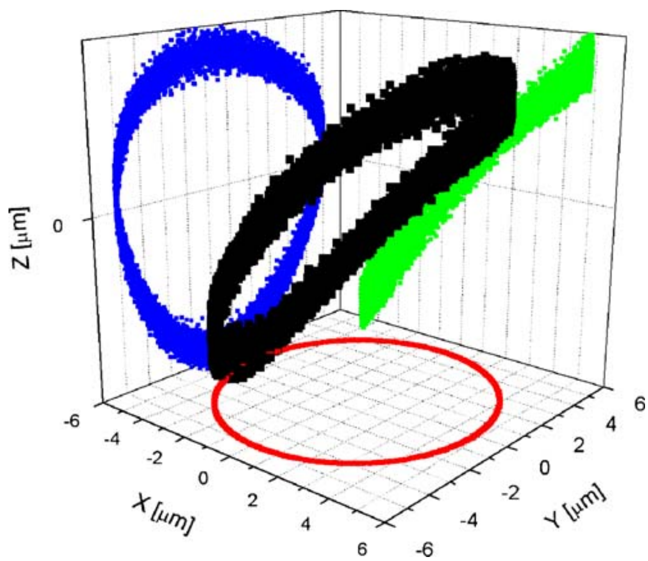

Fig. 10 The elliptical trajectories of point ***2*** on 89.5 kHz on the first direction

a result complete trajectory of movement of different stator points could be received. The proposed square-bar shaped multi-DOF ultrasonic motor based on "shaking beam" principles shown on Fig. 6, where *1* and *2* are measurement test points. The square-bar stator has a dimension: 10× 10 mm and height 18 mm. From the practical point of view rotor dimension does not mutter and depend on defined application of this multi-DOF ultrasonic motor.

Four "shaking beam" actuators joined to common part. One d_{31} piezoelectric plate with separated electrodes connected to every side. Authors proposed multi-DOF ultrasonic motor use the four electrical channels for direction and speed control. The connection scheme for rotary motion shown on Fig. 7. In this case, the travelling wave running to clockwise direction and rotor has opposite rotation direction. The direction of motion or speed of spherical or plate type rotor preloaded to proposed multi-DOF ultrasonic stator can be control by amplitude or phase variation. Depend on the value of electrical amplitude and phase we can control the type of motion mode. Of cause, speed variations and torque depend on preloaded force and defined by application field of the present square bar-shaped multi-DOF ultrasonic motor.

Contacting point's oscillations amplitude measured by laser interferometer. Measured amplitude distributions in three axial coordinates of the contacting point ***1*** of a "shaking beam" (point ***1*** in Fig. 6.) on resonance frequency 89.5 kHz in linear mode on the first direction is shown on Fig. 8 and on opposite direction on Fig. 9.

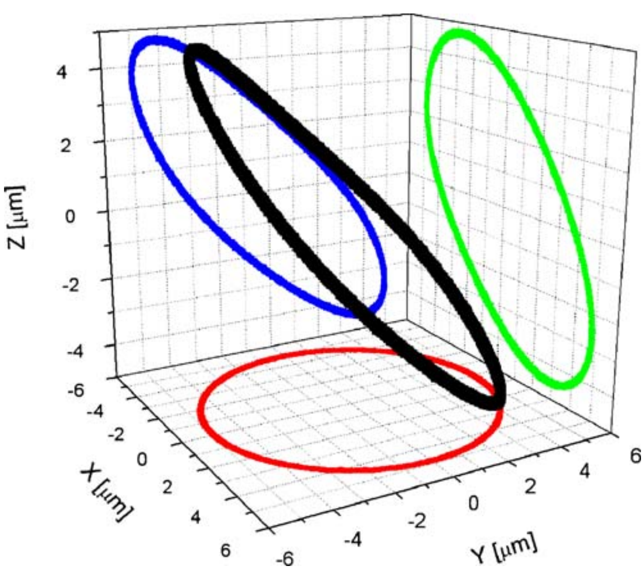

Fig. 9 The elliptical trajectories of point ***1*** on 89.5 kHz on the opposite direction

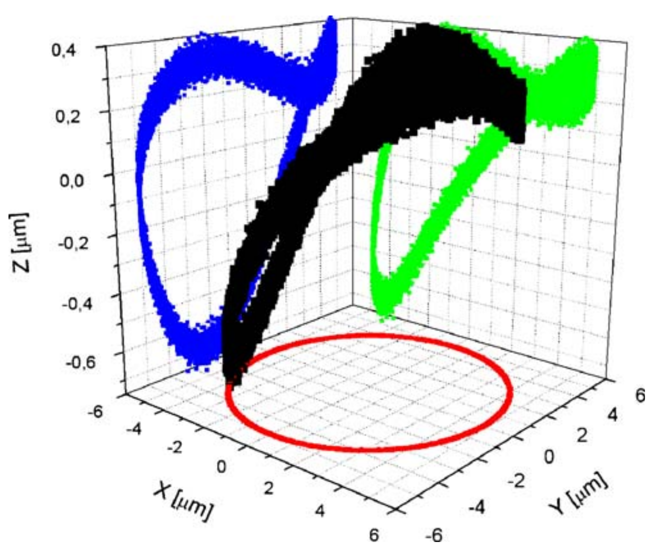

Fig. 11 The elliptical trajectories of point ***2*** on 89.5 kHz on the opposite direction

Measurement results of movement trajectories shows, that oscillation trajectories of the contacting point of the stator has closed curves similar to ellipse and its major axis directed to the side of movement of the preloaded rotor. In spite of the fact that, some asymmetric exist on characteristics in reverse mode, one may assume, that we get the satisfactory results. The elliptical trajectories of the point 2 on resonance frequency 89.5 kHz in both directions shown on Figs. 10 and 11, respectively. From the last figures, we can conclude then despite the parallel connection of neighboring piezo-element (Fig. 7), the point 2 generates some distortion, but absolute value of this distortion much less, than in point 1. It is necessary to note than difference between numerical FEM analysis of eigenfrequency and experimental results less than 4 kHz and to make it clear good theoretical and experimental results correlation. Authors make different experiments both with a spherical and plate type rotor. The control of the proposed square-bar shaped multi-DOF ultrasonic motor in open-loop system with both rotors obtained the satisfactory results. Experimental investigation of the proposed square bar-shaped stator has confirmed in the main results of the numerical analysis and the opportunity to achieve spherical or plate type rotor for multi-DOF ultrasonic motor.

4 Conclusion

New design of the square bar-shaped stator for multi-DOF ultrasonic motor based on “shaking beam” principles was developed. Numerical analysis by FEM of the stator has shown the possibilities to achieve elliptic trajectory of contacting point movement when shoulders of the stator are excited using harmonical forces with the phase shifted by $\pi/2$. Experimental investigation of the stator has confirmed in the main results of numerical analysis and the opportunity to achieve multi-DOF motion using this type of square bar-shaped stator with preloaded spherical (3D-motion) or plate type (2D-motion) rotor.

The author has proposed design of multi-DOF ultrasonic motor using d_{31} piezo-ceramic and design philosophy to enable to give an opportunity for creating 2D and 3D ultrasonic multi-DOF motion units with smaller overall dimensions comparing with ultrasonic units using d_{33} piezo-ceramic.

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