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3DOF High Resolution Inertial Piezoelectric Motor

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Abstract— **Development of multi degree-of-freedom (DOF) high-resolution motors is becoming of increased importance for nanotechnology, micro-robotics, and laser technology. A novel design of 3DOF rotary type piezoelectric motor is proposed. It includes three novel 2DOF inertial piezoelectric actuators, housing, and hemispherical rotor. 2DOF actuator consists of a piezoelectric bimorph disc with the quadrilateral shaped waveguides in the inner circumference of the disc and carbon fiber rod. Such configuration of the bimorph disc is used to transform radial vibrations of the disc into rotational oscillations of the rod. The piezoelectric actuator operates in two vibration modes, i.e., the first out-of-plane bending mode of the disc at 20.5 kHz and the first radial mode of the disc at 138.2 kHz. The bending mode is used to rotate the rotor about x and y axes, while the radial mode is used to obtain rotation about the z-axis. Each piezoelectric actuator is supplied with sawtooth or square waveform voltage, therefore the rotor is driven based on friction – inertia principle. Numerical and experimental investigation of the piezoelectric motor was performed, and results are discussed.**

Keywords—piezoelectric motor, dual-frequency, bimorph disc, inertial actuator

I. INTRODUCTION

Piezoelectric motors are widely used in different high precision devices such as scanning probe microscopes, optical focusing systems, micromanipulators [1, 2]. Piezoelectric motors are capable of reaching a nanometric resolution and possess such features as short response time, self-braking, no electromagnetic interference, etc. [2, 3]. Piezoelectric motors can operate at resonant or non-resonant modes therefore, many design principles of piezoelectric actuators are proposed and used. Piezoelectric inertial type actuators are distinguished by high resolution and large motion range. Simple design and unsophisticated excitation principle allow miniaturizing inertial actuators. However, most of the piezoelectric motors are single DOF devices while there are many applications where multi DOF positioning or manipulation systems are required. Multi DOF systems can be constructed using several separate actuators. However, it is difficult to eliminate assembly errors in combining single DOF actuators, and constant maintenance for eliminating secular error is necessary [2]. Moreover, the mechanical system itself gets more complicated. Also, such an approach of multi-DOF actuation is not suitable for applications where the small weight, size, and high resolution become an issue. On the other hand, large scale multi-DOF systems cannot be constructed using a single multi DOF actuator because of the limited dimensions of piezoceramic elements and requirements of the high accuracy. In this case, the motor must be designed in such a way that the number of actuators is kept to a minimum.

A 3DOF piezoelectric motor system constructed with two sets of piezoelectric actuators mutually perpendicular around a hemispherical surface was proposed by Ting et al. [4]. Each set of curved piezoelectric actuators is designed to provide motion with a single DOF. Applying input voltage signals with a phase difference to the odd and even ceramic actuators, traveling wave is generated in each set. Numerical simulation of the proposed motor showed that the angular speed of 0.262 rad/s could be achieved. The maximum thrust force of 16.82 N was calculated, while torque of 0.51 Nm was obtained. Dong et al. proposed the design of a precision compliant parallel-structure positioner, which is dually driven by six piezoelectric motors and six piezoelectric ceramics [5]. This compliant system has a high load capacity of more than 2 kg. The end platform has the stroke of 10 mm in three linear motion directions and of 6 arc-degrees in three angle motion directions, respectively. The positioning resolution and repeatability of the end platform is a nanometer scale. A new pyramidal-shaped 3-DOF piezo-driven positioning stage was proposed and investigated by Hassani et al. [6]. The mechanism was made from aluminum alloy and equipped with three piezoelectric elements that are separated by 120° angle. This mechanism is designed to deliver elliptical motion in 3-D planes. The dynamic modeling of the mechanism was carried out to show that the designated structure is able to provide different types of motions at different sets of phase differences applied to the three piezoelectric elements. 3DOF piezoelectric ultrasonic motors capable of generating a rotation of a spherical rotor about three axes were proposed and analyzed in several papers [2, 7-9]. Actuators compose of a cylindrical stator and spherical rotor. The operation principle is based on employing superposition of bending and longitudinal vibration modes of the bar-shaped or cylinder-shaped stator.

This paper proposes a 3DOF piezoelectric motor, which uses three novel 2DOF inertial type piezoelectric actuators to generate controllable rotation of the rotor. Implementation of 2DOF actuators allows achieving the simpler design and high resolution of the 3DOF motor. This new design of the motor combines the merits of the inertial type actuator and principles

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of multi-DOF systems. Numerical simulation and experimental measurements have been performed to verify the operating principle and output characteristics of the actuator. The results of numerical and experimental investigations are discussed.

II. Operating Principle of the Motor

The design of the 3DOF rotary type piezoelectric motor is shown in Fig.1. The motor includes three 2DOF inertial piezoelectric actuators, housing, and hemispherical rotor. All three actuators are identical and consist of a piezoelectric bimorph disc (D = 15 mm, h = 0.8 mm) and carbon fiber rod (D = 1.2 mm) that is glued in the center of the disc using epoxy (Fig. 2). Two piezoceramic discs have opposite polarization direction. There are twelve cutouts in the central part of the disk which form quadrilateral shaped waveguides. The orientation of the waveguides is aligned to the tangential direction of the rod cross-section.

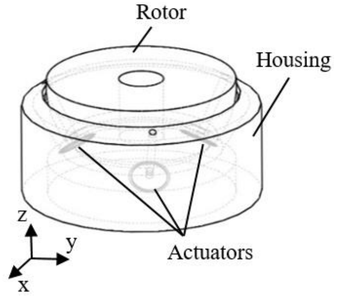
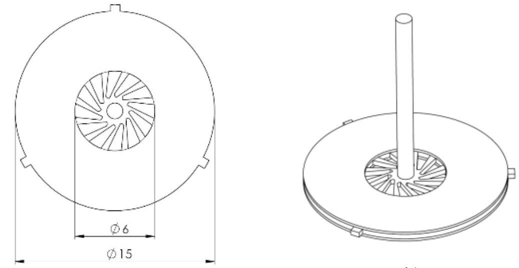


Fig. 1. Structure of 3DOF piezoelectric motor

Actuator employs two different vibration modes of the disc i.e., the first radial mode and the first out-of-plane bending mode of the disc. Radial mode of the disc is used to obtain rotational vibrations of the rod. Quadrilateral shaped waveguides allow transforming radial vibrations of the disc into rotational oscillations of the rod. The bending mode of the disc is used to generate longitudinal vibrations of the rod. All three piezoelectric actuators are fixed in the housing by 120° angle. The hemispherical rotor is positioned at the center of the housing and rests on the carbon rods at three points. Rotor starts rotating about x and y axes when longitudinal vibrations of the rod are excited. Bending vibrations of the bimorph are employed for that. Rotation about z axis is obtained when rotational motion of rod is excited using radial vibrations of the disc. Resonant frequencies of the radial and bending modes do not match therefore, motor operates at two different frequencies. Piezoelectric 2DOF actuators are supplied with sawtooth or square waveform voltage. Therefore the rotor is driven based on friction – inertia principle. Multiple voltage cycles are superimposed, thus the motor can generate large rotation angles about all three axes. Two different excitation schemes of the actuators are used. The radial mode is excited using a single signal when piezoceramic discs are connected in the parallel circuit. Bending mode is obtained when two signals with phase difference by π are used and applied to the top and bottom electrodes of the piezoceramic discs, respectively. Bending mode can be excited by applying voltage just to the single piezoceramic disc, however vibration amplitudes will be smaller. Reverse motion of the rotor is obtained by changing signal phase by π.

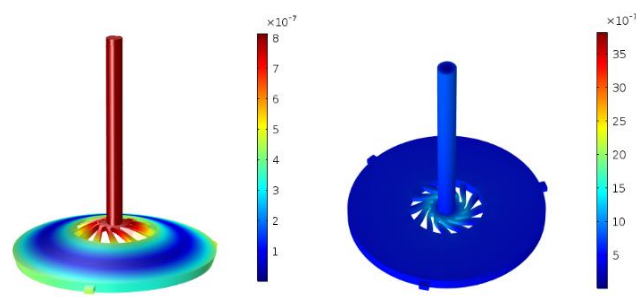


a) b)

Fig. 2. Sketch of the bimorph disc (a), 2DOF piezoelectric actuator (b)

III. Numerical Simulation

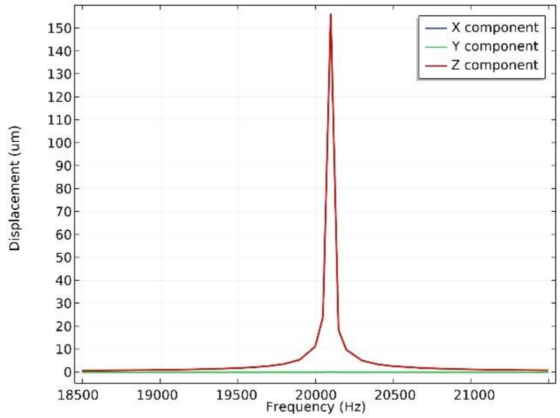
The numerical modeling of the piezoelectric motor was carried out to show that the designated 2DOF actuator is able to provide different types of motions at different excitation frequencies. Modal-frequency, harmonic response and transient dynamic analysis was performed to calculate displacement and velocity of the contact point. Finite element model of the actuator was built and boundary conditions were defined. The following materials were used for modelling: carbon fiber reinforced plastic was used for the rod, PZT-8 piezoceramic and structural steel were used for the bimorph piezoceramic disc. Electrodes of the piezoelectric bimorph disc fully cover top and bottom surface areas of the piezoceramic elements. Modal analysis was performed to ensure that the relevant mode shapes of the actuator are obtained. Figure 3 shows modal shapes of the actuator where color map represents relative total displacements. It can be seen that the modal shape at the frequency of 20.5 kHz has dominant the first out-of-plane bending mode of disc. Meanwhile the first radial mode of the disc was obtained at 138.2 kHz. Bending vibration mode will be used to analyze rod displacements when harmonic and sawtooth signal will be applied.



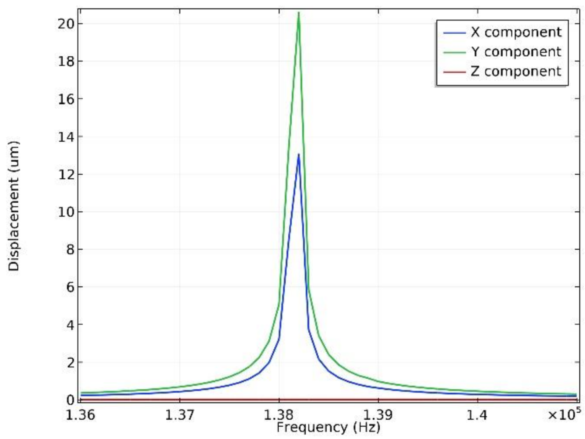
a) b)

Fig. 3. Modal shapes of the actuator: the first out-of-plane bending mode at 20.5 kHz (a), the first radial mode at 138.2 kHz (b)

Harmonic response analysis was performed to find out vibration amplitudes and velocities of the contact point. Investigated contact point was located on the top surface of the rod. Two excitation schemes were simulated as it was described in the previous section. Voltage amplitude of 10V was used. A frequency range from 18.5 kHz until 21.5 kHz with a solution at 50 Hz intervals was chosen for the bending mode analysis and frequency range from 136.0 kHz until 141.0 kHz was used to analyze radial mode. The results are given in Fig. 4 where the contact point vibration amplitudes versus frequency are shown. All graphs show corresponding projections in x, y and z axes.



a)

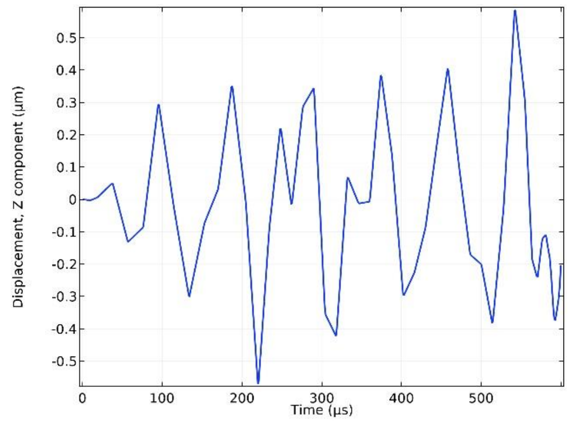


b)

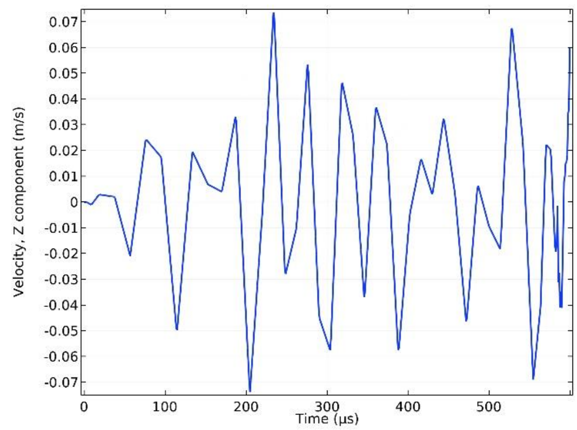
Fig. 4. Amplitude – frequency characteristic of the contact points in frequency range 18.5 -21.5 kHz (a) and 136 -141 kHz (b)

Analyzing results of simulation it can be noted that contact point has dominating vibration in z direction at the frequency of 20.1 kHz, while vibrations in x and y directions dominates at the frequency of 138.2 kHz. Contact point vibration amplitude and velocity in z direction is 156.5 µm and 14.35 m/s at the excitation frequency of 20.1 kHz, respectively. Amplitude value of 13.09 µm and velocity of 11.36 m/s in x direction and 20.62 µm, 17.91 m/s in y direction were obtained at the excitation frequency of 138.2 kHz. Analyzing obtained values it can be seen that vibration amplitude is much higher when actuator operates at the first bending mode however, the difference between velocities does not exceed 21%. Therefore, rotation speed of the rotor will be similar in all directions when the voltage with the value will be used for motor driving.

The transient dynamic analysis was performed to investigate the transient motion of the contact point (Fig.5). The time dependent load was generated by sawtooth waveform voltage. This type of waveform is used to generate asymmetric displacements that are obligatory for inertial actuators. The amplitude of the voltage was set to 10V while the frequency was 20.0 kHz. Excitation frequency was 0.1 kHz lower than the calculated resonant frequency of the actuator because it operates at off-resonant frequency. The analysis of transient displacement and velocity in z direction was performed when the actuator operated at the first bending mode. Time interval from 0 µs till 600 µs was analyzed. Analyzing results of the simulation, it can be noted that non-symmetric sawtooth like displacement curve is achieved and becomes biased to the left side. Analyzing the velocity curve, it can be seen that it has trapezoid shape showing that velocity fluctuation and acceleration value are small on the crest of the curve.



a)



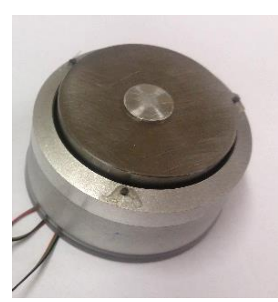
b)

Fig. 5. Transient displacement (a) and velocity (b) of the contact point motion

IV. EXPERIMENTAL STUDY

A prototype 3DOF motor was made for the experimental study (Fig. 6). Mechanical and electrical characteristics of the 2DOF actuators were measured. The aim of the measurements were to validate operating principle of the actuator.

a)

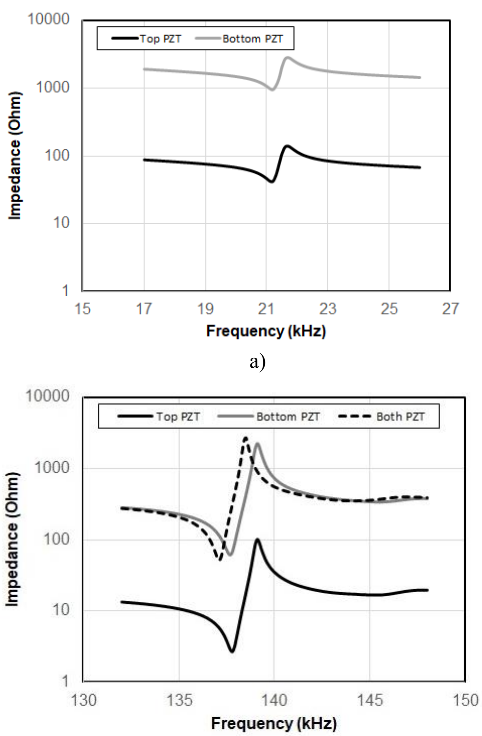


b)

Fig. 6. Prototype of 3DOF motor: actuators and housing (a), assembled motor (b)

Impedance-frequency characteristics of the actuator were measured with the help of the impedance analyzer Agilent 4294A. Results of the measurements are given in Fig. 7 where impedance – frequency characteristics of non - assembled 2DOF actuator is presented. Positions of curve valleys indicate that the resonant frequencies of the first bending mode and the first radial mode of the bimorph disc are obtained at 21.2 kHz (Fig. 7a) and 137.8 kHz (Fig. 7b). However the impedance values of the different piezoceramic discs have big difference. This can be explained because of the poor gluing quality of the bottom piezoceramic disc. In addition, it must be mentioned that impedance values are lower at resonant frequency of 137.8 kHz, therefore radial vibration mode has lower total losses. There are small difference between calculated and measured resonant frequencies. The difference does not exceed 5.2%. The errors mainly come from the FEM simulation, such as the inaccuracy of the material properties and neglecting glue layers of the piezoceramic discs.

Measurements of the rod top point vibrations along the length of the rod were measured when the bending mode of the bimorph disc was excited. Just the upper piezoceramic disc was excited by the harmonic signal. Measurements were made using vibrometer POLYTEC CLV. The results are shown in Fig. 8. It can be seen that amplitude of the top point vibrations is 0.302 µm at the resonant frequency of 21.047 kHz.



a)

b)

Fig. 7. Measured impedance of the actuator versus frequency in frequency ranges 17-26 kHz (a) and 131-148 kHz (b)

Resolution of the rotation angle of the 3DOF motor was measured using vibrometer. Piezoelectric actuator was driven using burst type electric signal consisted of 20 cycles at the frequency of 21.2 kHz. The minimal angular resolution of 25 µrad was obtained.

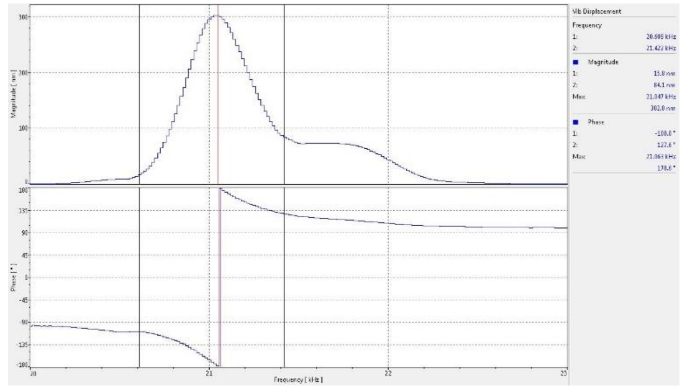


Fig. 8. Results of the actuator rod vibration measurement in z direction

V. Conclusions

A novel design of a 3DOF piezoelectric motor was proposed. The operation of the motor is based on the inertial – friction principle. Numerical analysis of 2DOFpiezoelectric actuators has shown the possibilities of achieving similar vibration velocities of the rod top surface when bending mode or radial mode of vibrations is used for motor driving. Prototype actuator and the motor was made and measurements were performed. Impedance measurement showed good agreement of the resonant frequencies obtained during the numerical simulation and experimental measurement.

Acknowledgment

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