Disc Type Piezoelectric Actuator for Optical Lens Positioning

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Abstract

The paper presents a novel inertial piezoelectric actuator developed for optical lens positioning and autofocusing function with high resolution. The actuator comprises a bimorph piezoelectric hollowed disc and carbon fiber tube with three fixing points used to glue the tube on the top surface of the bimorph disc. A ring-shaped slider is mounted on the tube and moves the optical lens along the axial direction of the tube. Electrodes of the disc are divided into six sections and grouped into two groups. Two sawtooth or square waveform electric signals with the phase difference of π are used to drive the actuator. The operation principle of the piezoelectric actuator is based on the excitation of B_{03} out-of-plane vibration mode of the bimorph disc. Asymmetrical vibrations of the bimorph disc are transferred into vibrations of the carbon fiber tube in the axial direction and inertial displacement of the slider, respectively. The numerical investigation of the actuator was performed to validate the operation principle of the actuator and to indicate the mechanical and electrical characteristics of the actuator. The prototype of the piezoelectric actuator was made and experimental measurements were performed. The maximum linear speed of 20.61 mm/s and thrust force of 0.18 N was obtained when the voltage of 60 $V_{p\text{-}p}$ was applied.

1 Introduction

The intensive development of active optical systems for precise machining, image capturing and auto-focusing devices increase the demand for high-precision actuators. Different types of actuators for instance electromagnetic, electrostatic, or piezoelectric are used to generate precise motion of optical lens [1]. However, piezoelectric actuators have the advantages in terms of high resolution, short response time, scalable design, good controllability, etc. [2]. Several piezoelectric actuators were proposed for optical lens positioning and autofocusing [3-5] however new actuators with a simple and scalable design as well as advanced dynamic characteristics have high demand.

The piezoelectric actuators used for optical lens positioning can have hollowed structures used for lens and the optical beam focusing or they can include additional mechanical components used to hold a lens. The hollowed structure allows reducing the size of the whole system including the size of the active part of the actuator. However dynamic output characteristics of the actuator decrease in this case. On the other hand, additional mechanical components or links mounted on the actuator gives more flexibility during the design process but the overall size of the actuator is increased.

A smooth impact drive mechanism with a dual-slider and single piezoelectric element was proposed for a zoom lens system [3]. The mechanism can move two lenses independently, however, such functionality is rarely used. The rectangular-shaped multilayered piezoelectric actuator was developed for autofocusing system [4, 5]. The actuator operates based on the multimode principle, has low power consumption, and achieves a resolution of 110 µm. A small size piezoelectric ultrasonic motor with a thin and hollow design was proposed for focus systems as well [6]. Experimental measurements showed that a thrust force of 12.9 mN and linear velocity of 92.8 mm/s were obtained. A piezoelectric actuator comprising six unimorph piezoelectric beams was developed to move symmetrically a micro-lens holding platform [7]. However, such a design has the main drawback that it is difficult to achieve resonant frequency matching of all six piezoelectric beams. Therefore vibration amplitudes and thrust forces generated by piezoelectric beams have minor differences.

This paper presents the results of numerical and experimental investigation of a novel piezoelectric actuator. The paper is organized as follows: the design and operating principle of a new actuator are shown in Section 2. Results of numerical investigation including modal shapes, and transient vibrations analysis of the actuator when sawtooth and square waveform signal is applied are presented in Section 3. The results of the experimental measurements are presented in Section 4. Finally, the conclusions of the work are given in Section 5.

2 Design and operation principle of the actuator

The proposed actuator has a simple design and consists of a bimorph piezoelectric hollowed disc (D_{out} = 12 mm, d_{in} = 6 mm, h = 0.6 mm) and carbon fiber tube (D_{out} = 9 mm, d_{in} = 8 mm, h = 3 mm) with three fixing points used to glue tube on the top surface of the bimorph disc (**Figure 1**). The polarization of both piezo ceramic discs is aligned along with the thickness and has the same direction.

Electrodes of the piezo ceramic discs are divided into six sections and grouped into two groups (**Figure 2**). Configuration of the electrodes is defined based on the position of nodal lines of the bending vibration mode of the bimorph disc. The dividing lines of the electrodes coincide with the nodal lines. The actuator has six clamping points used to mount it on PCB or other devices. A ring-shaped slider is mounted on the tube and moves the optical lens along the axial direction of the tube via the stick-slip principle. The slider can be placed inside the tube as well. It depends on the requirements of the specific application.

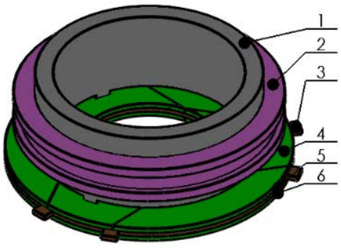


Figure 1 Design of the actuator: 1 – carbon fiber tube; 2 – slider; 3 – clamping point; 4 – electrode; 5 – piezo ceramic disc; 6 – bronze disc

The operation of the piezoelectric actuator is based on the excitation of B_{03} out-of-plane vibration mode of the bimorph disc. Two sawtooth or square waveform electric signals with the phase difference of π are applied to the corresponding group of the electrodes (**Figure 2**) and asymmetrical vibrations of the bimorph disc and carbon fiber tube are induced, respectively. The asymmetric axial motion of the tube generates the stick-slip motion of the slider and moves it along the tube. The reverse motion of the slider is obtained by changing the phase of the saw-tooth electrical signals by π or by changing the duty ratio of the square waveform signals.

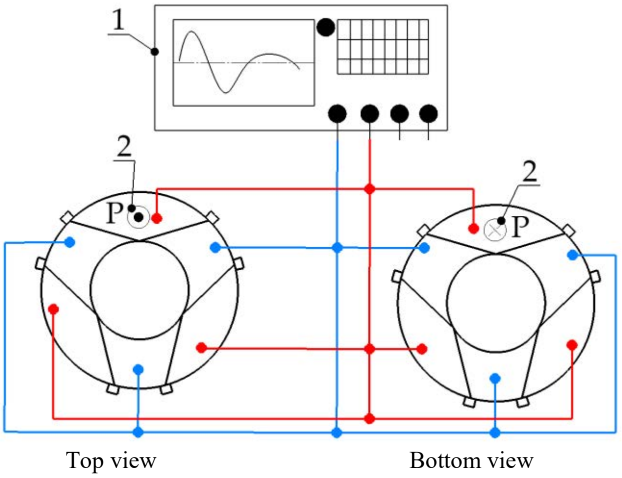


Figure 2 Configuration of the electrodes and excitation scheme of the actuator: 1 – signal generator; 2 – polarization direction of the piezoceramic disc

3 Numerical modeling

A numerical investigation of the actuator was performed to validate the operation principle as well as analyze mechanical and electrical characteristics. A finite element model was built using Comsol Multiphysics 5.4. Firstly, the modal-frequency analysis was performed to analyze vibration modes and natural frequencies. A closed-circuit electric boundary condition was applied. The model was not clamped. A suitable vibration mode was found at a frequency of 23.45 kHz which corresponds to the B_{03} out-of-plane vibration mode of the bimorph disc (**Figure 3**). It can be seen that the dividing lines of the electrodes coincide with the nodal lines while the position of the three gluing points of the tube coincides with the anti-nodes of vibration mode. Also, the direction of motion of the carbon fiber tube coincides with the direction of the Z axis.

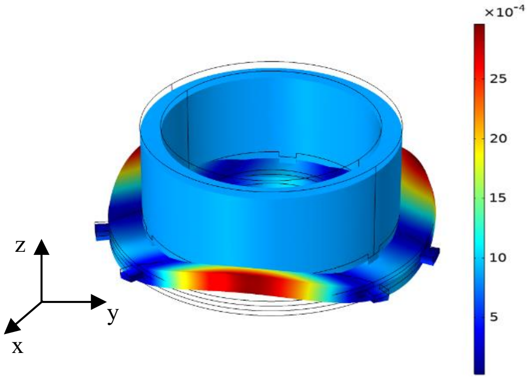


Figure 3 Vibration mode at the frequency of 22.45 kHz

Impedance and phase-frequency characteristics of the actuator were analyzed in the frequency range of 22.41 kHz -22.66 kHz. The simulation was made when one segment of electrodes of both piezo ceramic discs was excited by the voltage of 30 V_{p-p}, while the remaining segments of the piezo ceramic ring were set to open circuit condition. The results are shown in Figure 4. It can be seen that the resonant frequency of B_{03} bending mode was obtained at a frequency of 22.47 kHz. There is a minor difference of 1% between natural frequency and resonant frequency because of the different electrical boundary conditions used in the model.

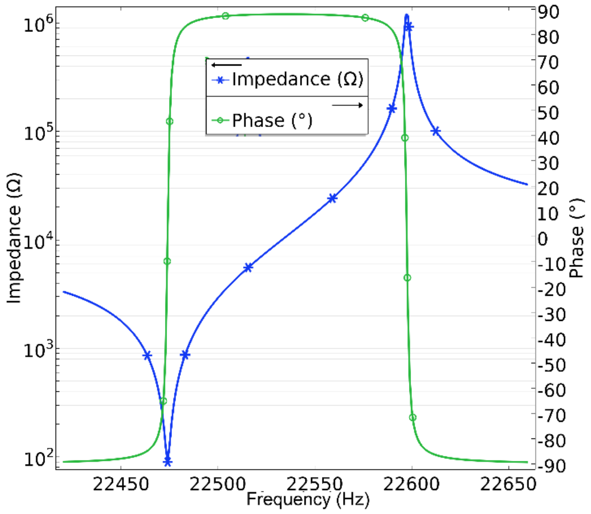


Figure 4 Impedance and phase-frequency characteristics of the piezoelectric actuator in a frequency range of 22.41 kHz – 22.66 kHz

Dependence of the carbon tube top point vibration amplitude from excitation voltage was analyzed when harmonic voltage was applied in the range of 10 – 100 V_{p-p} with the step of 10 V_{p-p} (**Figure 5**). Vibration amplitude in Z direction was investigated in the frequency range of 22.46 kHz - 22.49 kHz when all segments of electrodes were excited using two harmonic electric signals with a phase difference of π. Analyzing the results it can be noticed that vibration amplitudes almost linearly depend on excitation voltage.

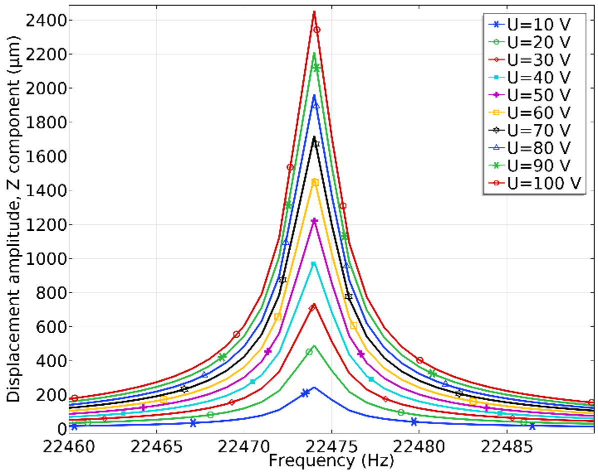


Figure 5 Amplitude - frequency characteristics of the actuator at different voltages

Transient vibrations of the top point located on the carbon tube were analyzed when a saw-tooth and square waveform signal of 30 V_{p-p} was applied at the frequency of 22.47 kHz. Vibrations were analyzed during the time interval from 0 µs to 3.5 ms when the saw-tooth signal was applied. The model is symmetric so only the forward propulsion regime was simulated (**Figure 6**). Results showed that steady-state displacement of the contact point is achieved after 2.73 ms and vibration amplitude of 5.28 µm was achieved.

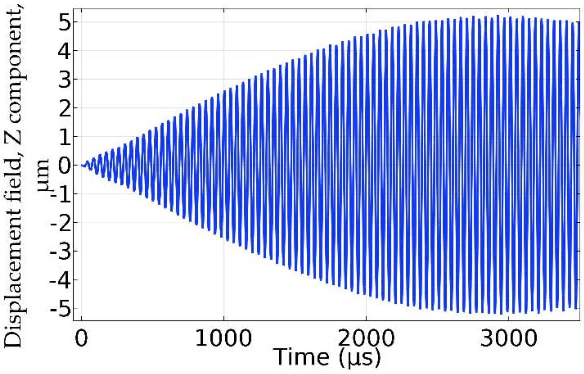


Figure 6 Transient vibrations of the actuator when saw-tooth signal of 30 V_{p-p} is applied.

Transient displacements were also analyzed when square waveform voltage had different duty ratio values i.e. 0.1-0.35 (**Figure 7**). Results showed that saw-tooth like displacement curve biased to the left side is obtained when the duty ratio is within the range of 0.1 – 0.35. It means that the forward and backward motion of the slide will be induced by changing the duty ratio. Also, it can be seen that when the duty ratio is increasing from 0.1 to 0.35, then the vibration amplitude is increasing as well but the displacement curve becomes close to harmonic type (**Figure 7**). It means that difference between contact point velocity and friction force of the forward and backward motion decreases.

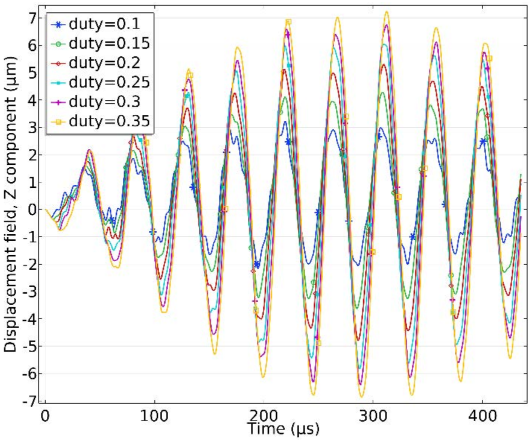
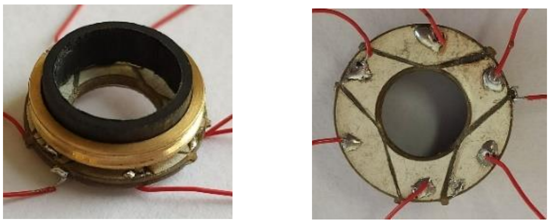


Figure 7 Transient displacements of the carbon fiber tube when the actuator is driven by a square waveform signal with different duty ratios: 0.1-0.35 (a)

4 Experimental study

A prototype of a piezoelectric actuator was made for the experimental study (**Figure 8**). Measurements of electrical and mechanical characteristics were performed to validate the operating principle of the actuator and the results of numerical simulation.



a) b)

Figure 8 Prototype piezoelectric actuator with slider: a side view (a), bottom view (b)

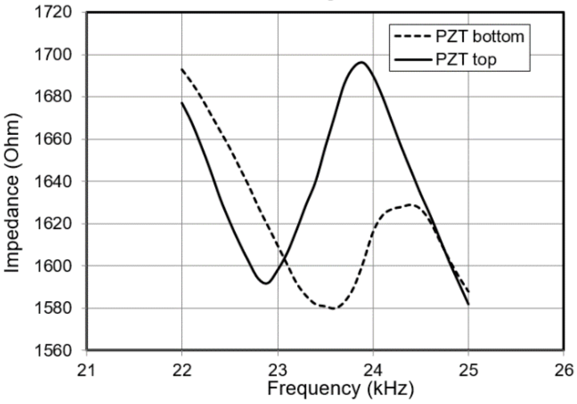


Figure 9 Impedance - frequency characteristics of actuator

Firstly, impedance–frequency characteristics were measured to find the resonant frequency of the actuator (**Figure 9**). Impedance was measured using an actuator without a slider. Separate measurements of the top and bottom piezoceramic disc were made using impedance analyzer HP4129A. The results of measurements show that the resonant frequency of the actuator is 22.89 kHz and 23.45 kHz when the top and bottom piezo ceramic discs are measured, respectively. The error between the measured and calculated resonant frequency does not exceed 4.1%.

The next step of the experimental study was dedicated to measuring vibration amplitudes in the frequency domain. The displacements were measured on the top point of the carbon fiber tube using a Polytec CLV vibrometer while excitation voltage amplitude was set to 5 V_{p-p}. The results are given in **Figure 10**.

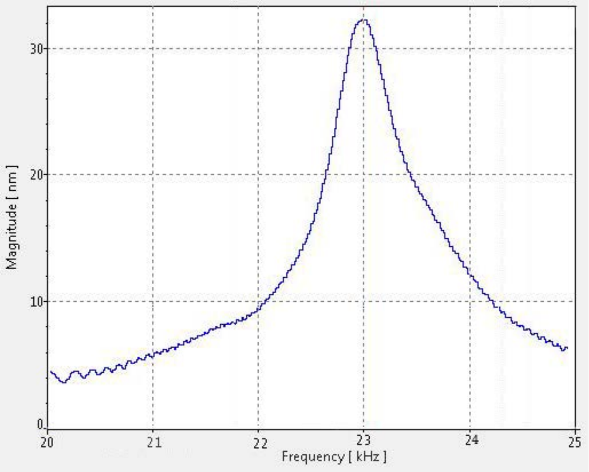


Figure 10 Displacement – frequency characteristics of the actuator

It can be seen that resonant vibrations of the actuator are obtained at the frequency of 22.95 kHz while displacement amplitude is 32.28 nm. Overall, it confirms the results of numerical and experimental investigations of impedance–frequency characteristics. Mechanical output characteristics of the actuator were measured as well. Linear velocity and thrust force of the slider were analyzed as a function of input voltage. The results are shown in **Figure 11.**

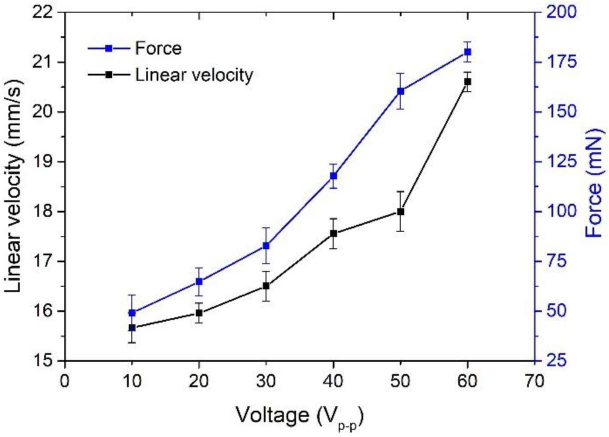


Figure 11 Velocity and force characteristics of the actuator

It can be seen that the lowest velocity value of 15.6 mm/s was obtained while the amplitude of excitation voltage was set to 10 V_{p-p} and the maximum velocity of 20.61 mm/s was reached while the voltage was 60 V_{p-p}. Also, it can be noticed that velocity almost linearly depends on the input voltage. **Figure 11** also shows thrust force dependence from voltage. The highest output force of 180 mN and lowest force of 49 mN were obtained at voltage of 20 V_{p-p} and 60 V_{p-p} respectively.

5 Conclusions

A novel small-sized piezoelectric actuator used for optical lens positioning is introduced and investigated. The results of numerical simulation and experimental study validated the operating principle of the actuator and showed that carbon fiber tube has asymmetric vibrations when a sawtooth or square waveform signals are applied. Results of experimental investigations showed that the highest velocity of the slider reached 20.61 mm/s while the maximum thrust force was 180 mN. Velocity and thrust force almost linearly depend on excitation voltage.

Acknowledgment

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6 References

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