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Small size 2-DOF piezoelectric platform for unlimited locomotion

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Abstract. The paper represents a numerical and experimental investigation of a 2-DOF piezoelectric positioning platform that can provide unlimited locomotion in the plane. The platform's operation principle is based on the excitation of the first bending mode of piezoelectric bimorph plates. A numerical investigation of the 2-DOF platform was performed, and it was found out that the suitable vibration mode of the bimorph plates occurs at 23.54 kHz Harmonic response analysis showed that the maximum displacement amplitude of the contact reached 561.12 µm or 2.67 µm/V_{p-p} while an excitation signal of 210 V_{p-p} was applied. The experimental study was performed and showed that maximum linear velocity of 44.45 mm/s or 0.212 mm/s/V_{p-p} were obtained while the load of 55.68g and applied and electrical signal of 210 V_{p-p} was used. In addition, at the same conditions output force of the platform was measured, and it was found that the platform is able to provide 44.16 mN of output force.

1. Introduction

For nova days, modern technologies used in biology, chemistry, physics of light, and other scientific high-resolution imaging systems have massive demand on positioning systems which are able to provide micro and nanoscale motion, positioning in several degrees of freedom, with fast response time and high dynamic characteristics [1-3]. There can be found numerous manipulation and positioning systems which operation are based on electromagnetic, electrostatic, and piezoelectric actuators [4-5]. Piezoelectric actuators have advanced features and able to provide high positioning resolution, have self-locking ability, fast response time, and are magnetic and static field free. Several degrees of freedom systems can be designed using a single piezoelectric transducer [3, 4]. Moreover, piezoelectric actuating devices do not require gearing mechanisms, therefore, no backlash appears during their operation. Usually piezoelectric positioning devices have a simple design based on regular structures so relatively simple driving and control methods, as well as operation electronics, is used [6].

Bansevičius *et al.* introduced a novel concept of multi-DOF actuators, which are able to provide planar and angular motions [7]. Proposed actuators are based on ring and cylinder-shaped transducers and have a simple design. It was shown that angular and planar resolutions of 20 µrad and 5µm can be achieved using cylinder type transducer while resolutions of 10μrad and 1μm resolutions, respectively was reached using ring type transducer.

Vasiljev *et al.* reported on a piezoelectric motor suitable for planar stage positioning XY plane [8]. The shaking beam principle was implemented to design a motor. It is composed of four transducers and a metal frame. Numerical and experimental studies revealed that planar motion resolution of the proposed motor is approximately 1.3μm in X and Y directions.

The aim of this research is to develop a novel design of an ultrasonic piezoelectric 2-DOF platform for unlimited high precision locomotion controlled by a single harmonic signal. Numerical and experimental studies were made, and the feasibility of the platform was validated. Results are discussed, and corresponding conclusions were made.

2. The design and operation principle of the platform

The platform design is based on three rectangular plates, six piezo ceramic plates, a triangle platform, and six thin junction beams. The rectangular plates act as a passive layer of the piezoelectric bimorphs which are formed by gluing piezo ceramic plates on both sides of the plates. The thin junction beams are used to compose piezo ceramic bimorphs and platform to one indissoluble structure. The junction beams are placed and the nodal lines of the first, out of the plane, bending mode of the bimorph plates (B_{20}) in order to reduce structural damping of the plates as well as to isolate vibrations of bimorphs from the platform. Moreover, at the bottom of each bimorph plate are placed sphere-shaped contacts which are used to transfer vibrations of the bimorph plates to the contact surface. The exploded and assembled view of the platform is shown in Fig.1.

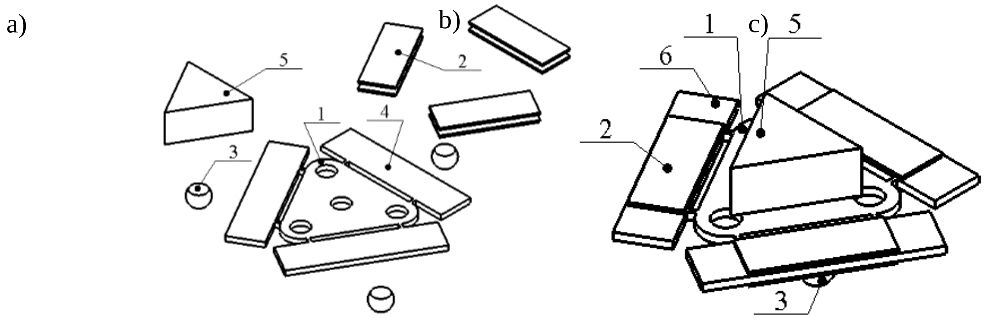

Figure 1. Design of the platform; a – exploited view; b – assembled view; c - prototype the platform; 1 – a platform; 2 – piezo ceramic plates; 3 – spherical contacts; 4 – rectangular plate; 5 – load; 6 – piezoelectric bimorph plate.

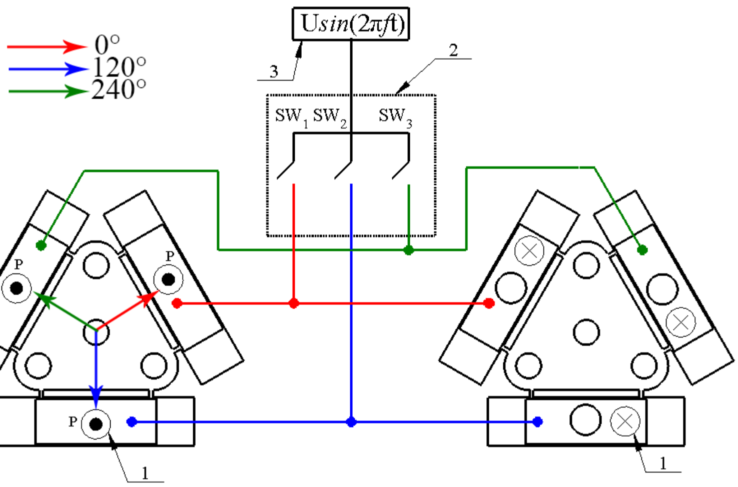

Figure 2 Excitation schematics of the platform; 1 – direction of piezo ceramic polarization; 2 – digitally controlled switch box; 3 – generator

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The operation principle of the platform is based on the excitation of the first, out-of-plane bending mode (B_{20}), of the bimorph plate. Considering that bimorph plate clamping is unsymmetrical i.e. only one edge of the bimorph is fixed to the platform, then out-of-plane vibrations generate an additional displacement component in the Y direction due to unsymmetrical reaction forces. The excitation of the platform motion can be implemented by one harmonic signal, which must be applied to the appropriate piezoelectric bimorph plate. The excitation of one piezoelectric bimorph plate, while others are passive, will ensure the motion of the platform in a direction aligned to the transverse axis of the active bimorph. In addition, the motion direction of the platform can be controlled by switching excitation signals between different bimorph plates using a digitally controlled switch box (Fig.2). The trajectory planning algorithms can be applied in order to obtain the required planar motion of the platform.

3. Numerical investigation of the platform

The numerical investigations of the piezoelectric platform were performed in order to obtain optimal geometrical parameters, indicate electrical and mechanical characteristics as well as evaluate the proposed design. Modal analysis was made to identify natural frequencies and modal shapes of the platform. A frequency response study was performed to calculate impedance and phase-frequency characteristics as well as displacement–frequency characteristics. In addition, motion trajectories of the contacting spheres were analyzed to verify the operation principle. Finite element modeling of the piezoelectric platform was made using Comsol Multiphysics 5.4 software. The following materials were used in the model i.e. stainless steel for the passive layer of the platform and bimorph plates, PZT8 was used for piezo ceramic plates, and finally, alumina oxide ceramic was used for spherical contacts.
Results of the modal analysis revealed that the modal shape showed in Fig. 3a can be used to generate platform locomotion. It can be seen that the bimorph plates have B_{20} deformation mode while the platform body stays passive. Moreover, it can be found that B_{20} mode is modified by non-symmetrical clamping i.e. the bimorph plate not only bends in out of plane direction but also generates displacement in the Y direction. Therefore, the composition of these two displacement components will ensure the planar motion of the platform.

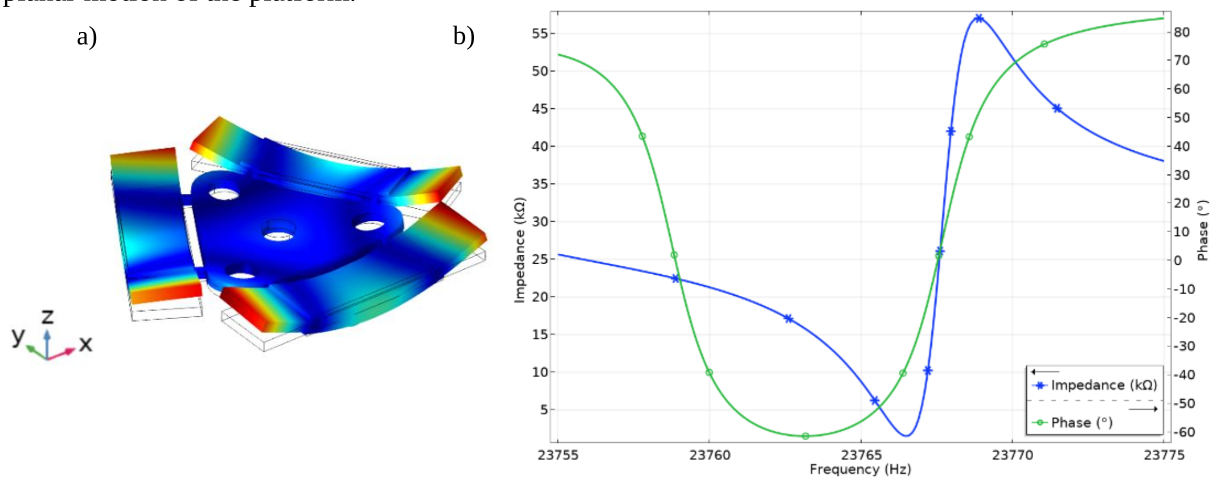

Figure 3. Electro-mechanical characteristics of the platform; a - the modal shape of the platform obtained at a frequency of 23.54 kHz; b - Impedance and phase-frequency characteristics in the frequency range of 23.755 – 23.775 kHz

The next step of the numerical investigation was dedicated to the investigation of the electrical characteristics of the platform. The impedance and phase-frequency characteristics of the platform are shown in Fig 3b.
The impedance graph confirms that the resonant frequency of the platform is obtained at 23.767 kHz (Fig. 3b). The minor mismatch of 220 Hz compared to the natural frequency occurs due to differences in electrical boundary conditions. The impedance value at the resonance frequency is 1.61 kΩ while the mechanical quality factor (Q_m) and effective coupling coefficient (k_{eff}) are 1398.1 and $12.9 \cdot 10^{-3}$, respectively.

The influence of the excited bimorph plate vibrations on the remaining bimorph was analyzed. It was important to evaluate parasitic vibrations of the non-excited plates. The bimorph plates were excited in accordance with the excitation schematics given in Fig. 2. The results are given in Fig. 4, and it can be seen that the contact point located on $Plate_1$ has a displacement amplitude of 561.12µm while contact points located on $Plate_2$ and $Plate_3$ plates have 56.45 µm and 48.19 µm displacement amplitudes, respectively. The difference between displacement amplitudes of the active plate and passive plates is about ten times.

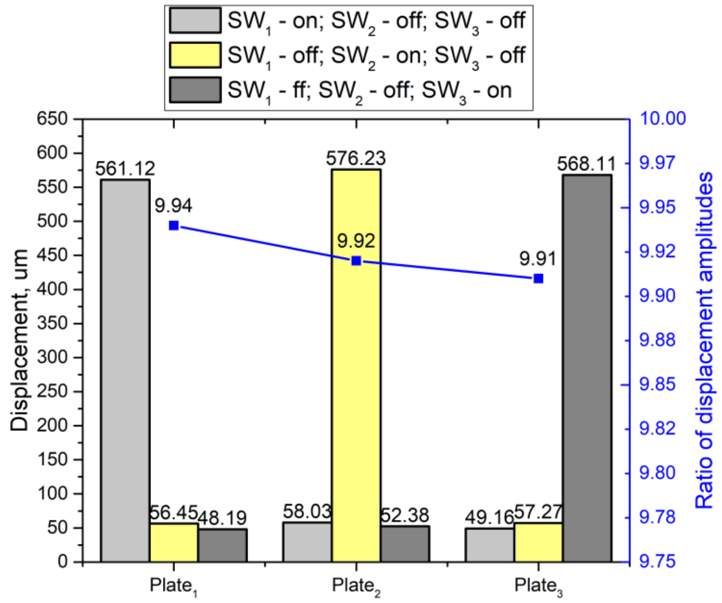

Figure 4. Summary of displacement amplitudes while different plates are excited.

It can be concluded that the excited vibrations of $Plate_1$ will have a minor effect on the vibrations of the passive plates and will not move the platform.

The motion trajectory of the contacting sphere was simulated when excitation voltage of $210V_{p-p}$ was applied to $Plate_1$. The time-domain study was set up for the same numerical model and boundary conditions. It can be seen that the trajectory is closed to the straight line. It indicates that the platform will be driven by implementing the vibro-impact principle. The projection length to the X-axis is 89.9µm, while the projection to Y-axis has a length of 551.1µm.

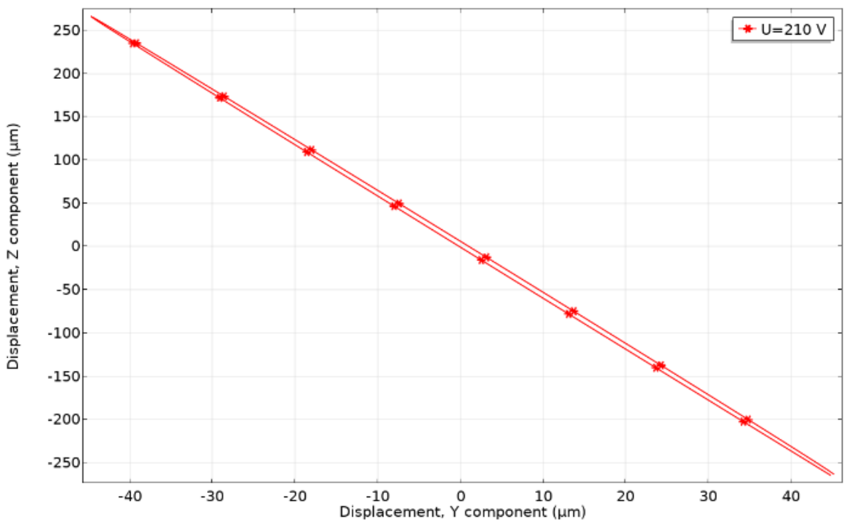

Figure 5. Motion trajectory of contact located on $Plate_1$, excitation voltage is $210V_{p-p}$

4. Experimental investigation of the platform

A prototype piezoelectric platform was made for the experimental study (Fig. 1c). The first stage of the experimental investigation was to measure impedance-frequency and phase-frequency characteristics of the platform. Measurement of each bimorph plate was done separately using impedance analyser.
Analyzing results, it can be noted that the are minor differences in resonant frequencies between bimorph plates (Fig.6). The resonant frequencies of $Plate_1$, $Plate_2$, and $Plate_3$ are 22.47 kHz, 23.04 kHz, and 22.86 kHz, respectively. The differences between resonant frequencies do not exceed 570Hz. Moreover, compared to results obtained during numerical investigation difference between resonant frequencies is 1.29 kHz, respectively. The linear speed of the platform was measured when the different excitation voltage and the preload were applied. Values of maximum linear speed at different load conditions are given in Fig. 7a. The characteristics were measured by digital tachometer DT-2100 (USA) with linear speed measuring function. Fig. 7a shows that the highest platform motion velocities were obtained at $210V_{p-p}$ excitation voltage for all load and plate excitation cases. The results found that the highest linear motion values were obtained while the load was equal to 55.68g, and it reached 44.45 mm/s or 0.182 $mm/s/V_{p-p}$. Moreover, it was found that velocity values at different loads are similar and will ensure even linear motion speed in all directions.

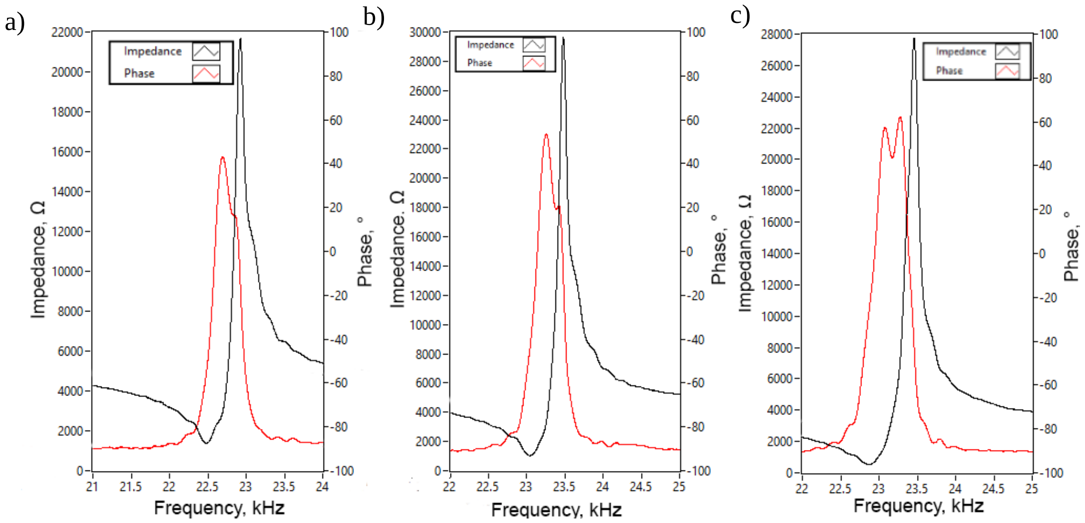

Figure 6. Impedance and phase frequency characteristics of the platform; a – characteristics of $Plate_1$; b – characteristics of $Plate_2$; c – characteristics of $Plate_3$

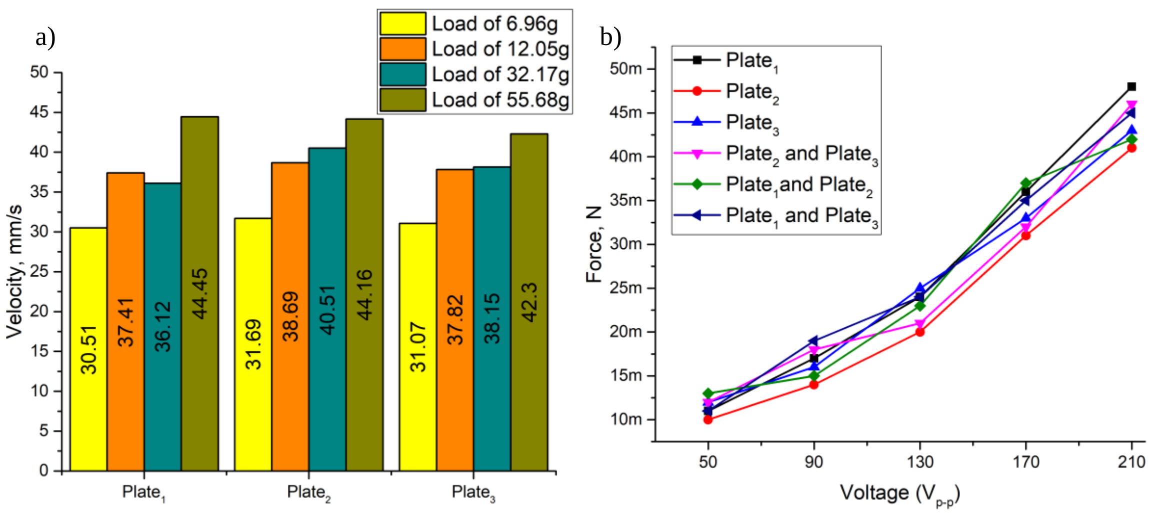

Figure 7. Characteristics of the platform; a – maximum velocity values; b – output force characteristics

The next stage of the experimental investigation was dedicated to an indication of output force characteristics of the platform when the load was set to 32.17g, and different excitation voltages were applied in the range from $50V_{p-p}$ to $210V_{p-p}$. The measurements were performed by an analogical force gauge ATN 0.05 (China). Analysing results, it can be found that the highest output force was obtained at $210Vp_{-p}$ while the average output force is 44.16 mN (Fig.7b). The deviation between values is 34.83μN. Finally, the ratio of the average output force to excitation voltage is $210\mu N/V_{p-p}$. Therefore, on the basis of these results can be found that the output force increment relationship to an increment of excitation voltage is almost linear and well predictable.

5. Conclusions

2-DOF planar motion piezoelectric platform was developed and investigated. The design of the platform is simple and well scalable. The design of the platform is based on three piezoelectric bimorph plates, which were evenly distributed around a triangle-shaped platform. The platform's design provides partial isolation of parasitic vibrations transfer from active plate to passive ones as well as to the platform body. Numerically calculated impedance and phase frequency characteristics showed that the operation frequency of the platform is 23.76 kHz. These results also confirmed results obtained during modal analysis of the platform. Numerical investigations of the platform showed that parasitic vibrations of the unexcited plates are low, and their influence on the planar motion is negligible. Also, it was found that the maximum displacement amplitude of the contact reached 561.12 µm or 2.67 $\mu m/V_{p-p}$ .Experimental investigation of dynamic characteristics showed that that average planar motion reached 44.45 mm/s or 0.212 $mm/s/V_{p-p}$ while excitation voltage amplitude was $210V_{p-p}$ and preload was 55.68g while maximum output force reached 44.16 mN at the same conditions.

Acknowledgment

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