PAPER • **OPEN ACCESS**

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To cite this article: A eponis *et al* 2022 *IOP Conf. Ser.: Mater. Sci. Eng.* **1239** 012015

IOP Conf. Series: Materials Science and Engineering 1239 (2022) 012015 doi:10.1088/1757-899X/1239/1/012015

5DOF planar – rotary motion piezoelectric robot

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Abstract. A novel resonant type five degrees of freedom (5DOF) mobile piezoelectric robot is proposed and analysed. The piezoelectric robot performs unlimited linear working motion in the plane and rotates the positioning table or sphere about three axes independently. The piezorobot can be used for precise positioning or transportation of small objects and make complicated locomotion trajectories. The piezoelectric robot is designed as a compound structure and includes a piezoelectric ring and a special ring-shaped bronze layer. Electrodes of the piezoelectric ring are divided into six equal sections. Excitation of the piezoelectric robot is performed by using a single switched harmonic signal applied to the particular electrode. The operation principle of the piezoelectric robot is based on the excitation of the third radial vibration mode of the piezoelectric ring. The numerical and experimental study was performed, and the operating principle was validated. The maximum linear velocity of 18.8 mm/s and rotational speed of 31.3 rpm were achieved when load of 25.1g and excitation voltage of 200 V_{p-p} were applied.

1. Introduction

Modern high-precision mechatronic systems include different types of actuators and motors, such as piezoelectric, magnetostrictive, electrostatic, electromagnetic, etc. Piezoelectric devices have advanced features and can be used as sensors and actuators at the same time because of the direct and indirect piezoelectric effect [1]. Mechanical vibrations of the actuator excited by electric signal can be transferred into continuous linear or rotational motion of the slider or rotor [2]. Also, the actuator can move itself on the plane. These unique features allow the development of multipurpose mobile piezoelectric robots that can manipulate the positioning object, move into a particular location with high accuracy and perform different tasks. Piezoelectric robots have a simple design, good controllability, and can achieve high resolution [3]. The size of piezo robots can be minimized up to a millimetric scale. Vibration amplitude and waveform of mechanical vibration of the contacting legs can be easily controlled by electric signals. The electric circuit can be configured to actuate or damp mechanical vibrations, therefore a wide range of the control parameters are used to control the piezoelectric robot in a proper way.

Moreover, multi-degrees of freedom (MDOF) piezoelectric robots can be designed using a single piezoelectric actuator. The structural design of the robot and electrode topology must be optimized to construct MDOF piezoelectric robot. The piezoelectric actuator must generate the elliptical oscillation trajectories of the contact points or impact contact surface at an inclined angle in order to obtain the locomotion of the robot. The inertial driving principle can be used to drive robot by employing asymmetric vibrations. Elliptical motion can be generated using mode superposition, shifted phase excitation, or vibro-impact principle, while asymmetric vibrations of the contact point is obtained applying square or triangle waveform electric signal. MDOF ultrasonic piezoelectric systems face the problem of the excitation of the particular single degree of freedom independently. The whole solid system vibrates when any zone of the actuator is excited. It complicates control of MDOF piezoelectric robot locomotion, and a closed-loop feedback system, shunting, and out-of-phase excitation are required.

There are reports on piezoelectric robots used for planar motion and carry a payload [4-8]. Robots have different designs and are based on the cylinder, disc, or plate type bimorph piezoelectric transducers. It was shown that disc and cylinder type piezoelectric robots can achieve controllable 2DOF planar motion and rotate about the vertical axis [4, 5]. Robots with plate-type bimorph actuators can provide linear locomotion [6, 7] or planar motion [8]. However, there is no piezoelectric robot with a single actuator that could provide planar locomotion as well as rotate payload about two axes.

This study presents a novel design of a 5DOF piezoelectric robot. Numerical analysis based on finite element modeling was performed, and the operating principle was validated. A prototype motor was made, and an experimental study confirmed the feasibility of the robot. Finally, the corresponding conclusions are made.

2. Design and operation principle

The piezoelectric robot is designed as a compound structure and consists of a piezoelectric ring and ring-shaped metal layer (Fig.1). Both parts are glued using epoxy. The top electrode of the piezoelectric ring is divided into six equal sections, while the bottom electrode is common and used for grounding. The polarization direction of the ring is aligned with the thickness of the ring. The ring-shaped metal layer is divided into the same six sections as the piezoelectric ring. The thickness of the ring at the two adjacent sections is different. This was done to make the vibration amplitudes of the adjacent sections different when one of the sections is excited by an electric signal. Moreover, each section of the metal ring is separated by gaps to minimize vibration energy transfer to the neighboring sections. Totally six alumina spherical balls are used as contacting structures between the robot and surface (Fig 1). Three balls are glued on the top surface of the piezoelectric ring and are used for rotation of a sphere, while the other three balls are glued at the bottom and are employed to obtain the planar motion of the robot. All balls were placed in the middle of the corresponding section.

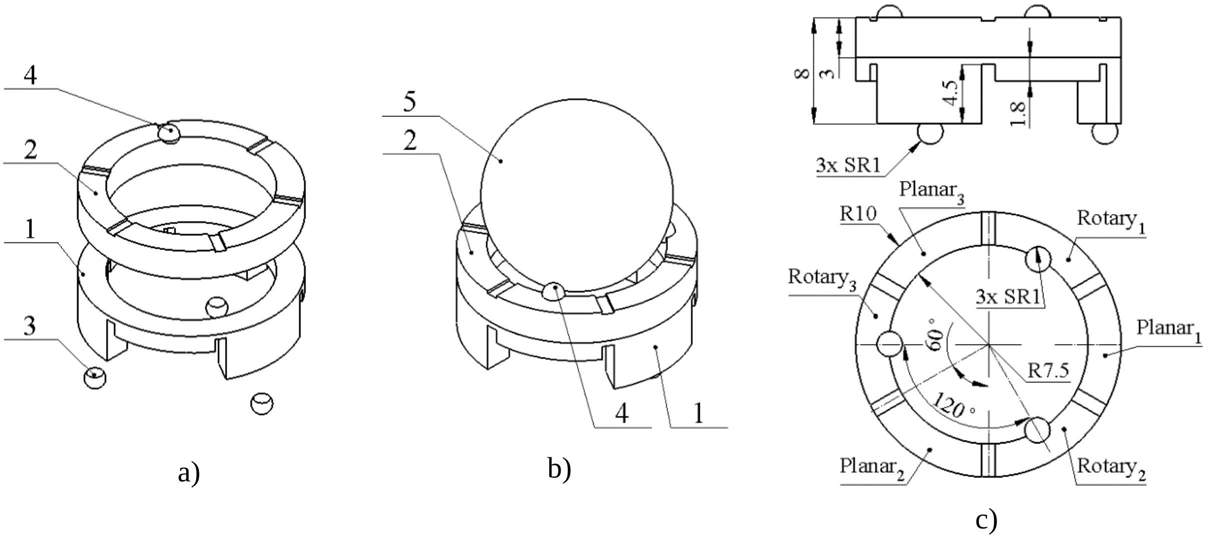

Figure 1. Design of piezoelectric robot: a - exploited view; b - assembled view of the robot with a sphere; c – sketch of the robot. 1 – bronze ring; 2 – piezoceramic ring; 3 – spherical contacts for planar motion; 4 – spherical contacts for rotary motion; 5 – spherical rotor.

The operation of the robot is based on the 3rd radial vibration mode of the ring-shaped structure using d_{31} piezoelectric effect. In order to implement flexible control of a particular degree of freedom, the structure of the robot is divided into six sections. Excitation of the piezo robot is performed by using a single switched harmonic signal applied to the particular electrode. Such individual excitation of the electrode allows achieving planar or rotary motion in an appropriate direction.

Locomotion control of the robot as well as control of the sphere rotation, can be implemented using digitally controlled switching and a single harmonic signal. Figure 2 shows excitation schematics of the robot using a single generator and two switching boxes used to control payload rotary motion and planar motion of the robot, respectively. Locomotion along the X axis is obtained by switching on SW5, and reverse motion is generated by switching SW4 and SW6. Movement in the Y direction is generated by switching SW5 and SW6, while reverse motion is obtain using SW4 and SW5. A similar switching principle is applied to obtain rotation of the sphere about the X and Y-axis. In order to achieve rotation about the Z-axis, three signals shifted by 120 degrees must be used. Special trajectory planning algorithms can be used to generate the required planar or rotational motion [4]. The amplitude of the electric signal, duration time, and sequences of switching control allows achieving needed motion of the piezoelectric robot and payload. High displacement and rotation resolution of the robot can be achieved by applying burst type electric signal.

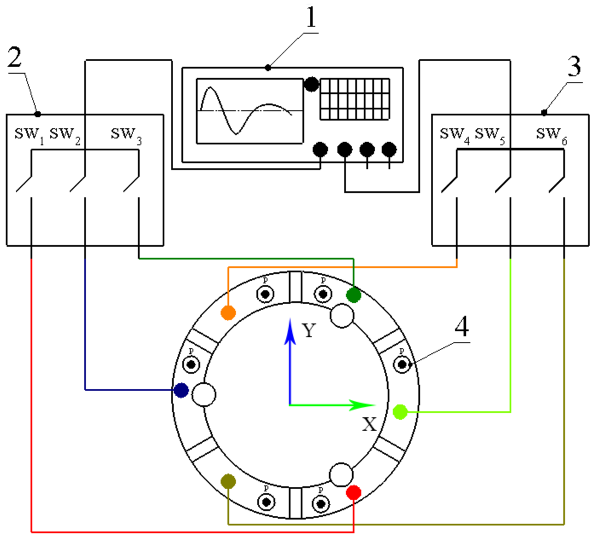

Figure 2. Excitation schematics of the robot: 1 – generator, 2 – switching box for control of payload rotary motion 3 – switching box for control of planar motion, 4 – electrode and polarization direction.

3. Numerical modelling

Numerical calculations of the piezoelectric robot was performed to analyse modal shapes and make frequency response analyses. The finite element model of the robot was built using Comsol Mutiphysics 5.4. The following materials were used i.e., beryllium bronze was used for the passive layer of the robot, PZT8 piezo ceramic was used for the piezoelectric ring, and alumina oxide was used for contacting balls. The adhesive layer was neglected in the model. The model of the robot was not clamped while all electrodes were grounded when modal frequency analysis was performed.

3.1 Results

The operational modal shape of the piezoelectric robot is shown in Figure 3a when it vibrates at the frequency of 58.085 kHz. The 3rd radial vibration mode is dominating in this shape. The anti-nodes of the modal shape are located in the sections used for planar motion, while sections used for rotation are in the nodes of modal shape. The impedance of the robot was analysed in a frequency range of 57.60 – 58.20 kHz in order to analyse the losses of the system (Fig. 3b). It can be seen that the lowest impedance value of 1.19 kΩ is obtained at the resonant frequency of 58.01 kHz. Based on the impedance graph mechanical quality factor Q_m of the robot was calculated and it was found that Q_m = 1055.54. The effective coupling coefficient k_{eff} is 0.0435. These results show that the piezoelectric robot has low mechanical loss at the operating frequency.

Harmonic response analysis was performed by analysing displacement amplitudes of the six spherical contacts in the frequency range from 58.0 kHz till 58.2 kHz with the step of 2.5 Hz when the voltage of 200 V_{p-p} was applied to a single electrode. This type of excitation evaluates planar and rotational possibilities in one direction (Fig. 4). Calculations were performed when the robot was preloaded by the force of 0.546N. Results of simulation show that a peak of displacement amplitude of 3.88 µm is obtained at the frequency of 58.088 kHz. This peak value corresponds displacement amplitude of the spherical contacting ball located in the section that was excited by an electric signal. It must be noted that other contacting balls have significantly lower amplitudes of vibrations.

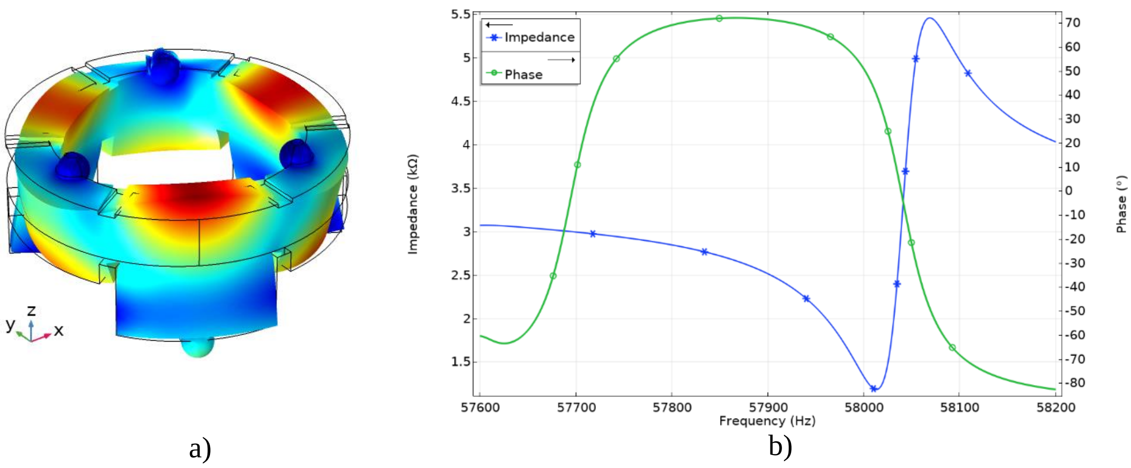

Figure 3. The modal shape of the actuator at 58.085 kHz (a) and dependence of impedance and phase versus frequency (b).

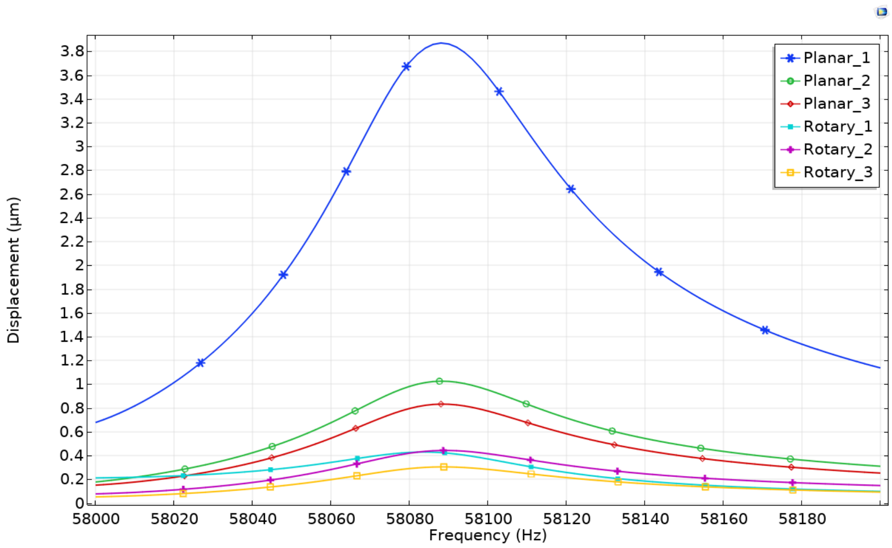

Figure 4. Amplitude – frequency characteristics of the different contact points of the robot.

It was already mentioned in the introduction that the MDOF ultrasonic piezoelectric systems face the problem of the excitation of the particular single degree of freedom independently because the whole system vibrates when any zone of the actuator is excited. Therefore, a more detailed numerical analysis was performed to compare the amplitudes of the vibrations of the spherical contacts located in the excited zone and the amplitudes of the remaining contacting balls. The particular single electrode was excited by the harmonic voltage of 200 $V_{p-p,}$ and amplitudes of all spherical contacts were analysed. The results are shown in figure 5. It can be seen that difference between vibrations amplitudes of the spherical contacts used for planar motion is up to 4.02 times and planar – rotational is up to 12.9 times (Fig.5a). A similar comparison was made between the vibration amplitudes of the spherical contacts used for rotary motion and the remaining spherical contacts. It was found that the difference is up to 4.3 times and 11.2 times, respectively. Obtained results show that the influence of the contacting spheres located on non-excited sections makes a small influence on the driving direction defined by the exciting section. Therefore, it can be concluded that the direction of locomotion or rotation of the spherical payload can be controlled by applying an electric signal to the corresponding electrode.

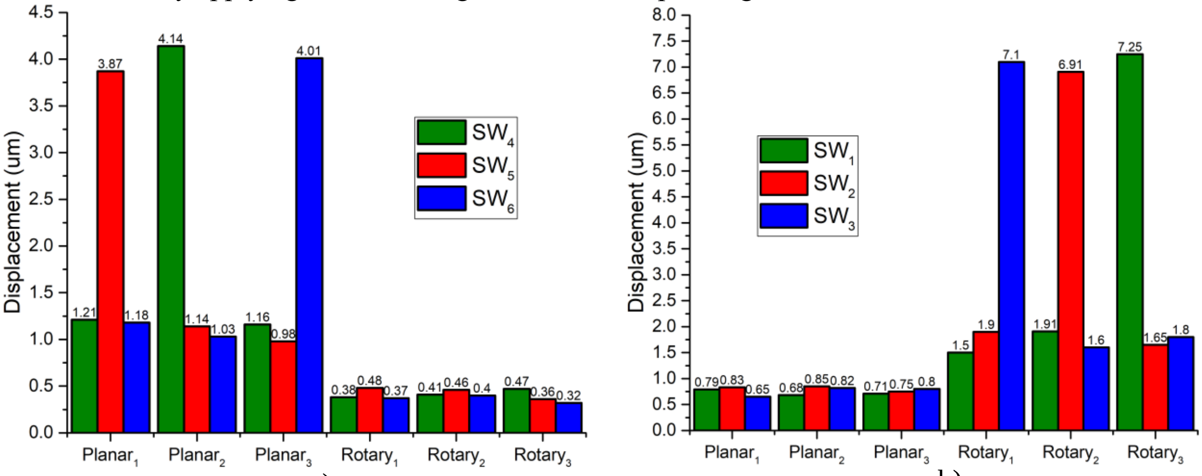

Figure 5. Comparison of the vibration amplitude of the spherical contacts used for planar motion (a) and rotational motion (b).

4. Experiments

An experimental study of the piezoelectric robot was performed to validate the operating principle and to measure electrical and mechanical characteristics. A prototype was made and is shown in figure 6a. Impedance–frequency characteristic of the robot was measured without preload. Analysing results, it can be seen that resonant frequency was obtained at the frequency of 59.65 kHz (Fig. 6b). The difference between calculated and measured frequency is 2.68%. The measured mechanical quality factor Q_m is 950.12 while the effective coupling coefficient k_{eff} is 0.058. The difference does not exceed 2.5% compared with the results obtained from the numerical study.

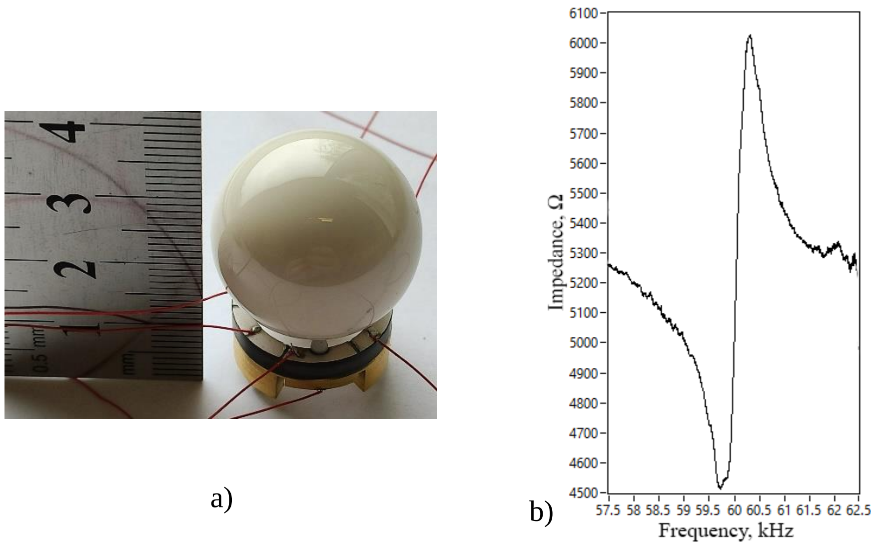

Figure 6. Prototype of the piezoelectric robot with a sphere (a), the measured impedance of piezoelectric robot in the frequency domain (b).

Measurements of the linear and rotation velocity were performed when different preload and voltage was applied. The preload force was obtained using spheres with different weights. Figure 7 shows average linear and rotation velocity when the voltage from 80 V_{p-p} to 200 V_{p-p} was applied. It can be seen that velocity almost linearly depends on the driving voltage and is increasing with the increase of preload. This can be explained by the fact that as the load increases, the friction force between contacting balls and planar surfaces increases, so the robot moves at a higher speed. The maximum average linear speed of 18.8 mm/s was obtained at the preload of 0.251 N while the voltage of 200V_{p-p} was applied. Accordingly, the highest rotation speed of 31.3 RPM was obtained at the same conditions.

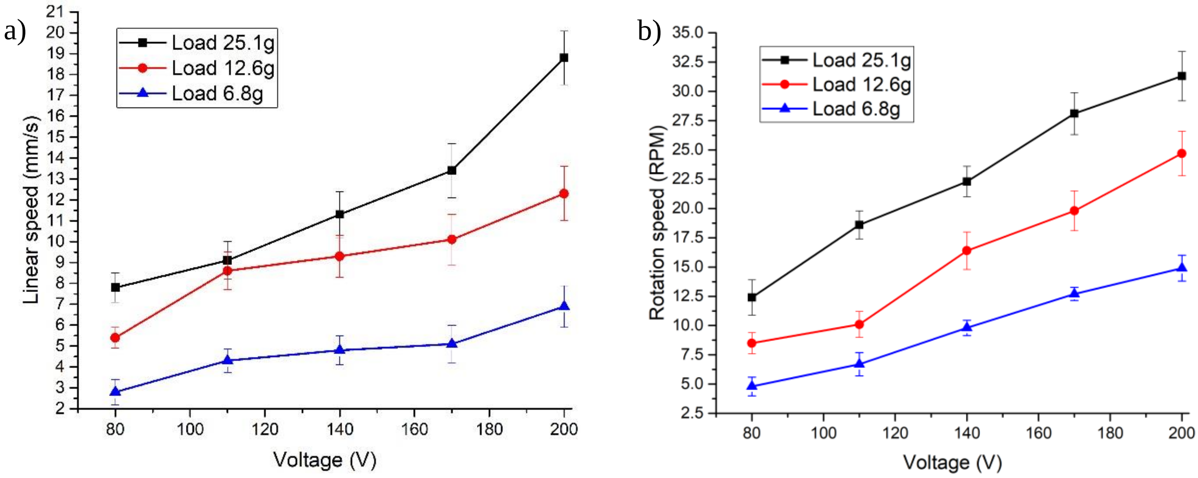

Figure 7. Measured average linear (a) and rotation (b) velocity of the piezoelectric robot

5. Conclusions

A novel 5-DOF piezoelectric robot was developed and investigated. Results of the numerical and experimental study confirmed that the robot can perform planar locomotion and rotary motion of the payload. Motion control is performed by switching the harmonic signal applied to the six electrodes of the piezoelectric ring. The maximum average rotation speed of 31.3 RPM and linear velocity of 18.8 mm/s was obtained during the experimental study when the voltage of 200 V_{p-p} was applied.

Acknowledgment

This research was funded by the European Social Fund according to the activity “Promotion of postdoctoral fellowships studies” of Measure No. 09.3.3-LMT-K-712-19-0082.

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