Design, Simulation and Optimization of PZT-5A Cantilever Piezoelectric Pressure Sensor

ABSTRACT

Aims: The main aim of this research work is

- To design a mathematical model of the sensor and validate with the 3D model simulation of the sensor in COMSOL Multiphysics simulator and
- To optimize the sensor for maximizing its sensitivity.

Study design: In the methodology, we design and utilizePZT-5A piezoelectric in shear mode as the piezoelectric is attached on a cantilever structure. The various factors affecting the sensitivity of the sensor are investigated after validating the mathematical model with the simulated values.

Place and Duration of Study: This study is done in the Department of Electronics and Communication Engineering, Rajiv Gandhi University, Arunachal Pradesh at COMSOL Simulation Laboratory during 2022 to 2023.

Methodology: In this study, a cantilever structure is considered for the mechanical structure. The stress distribution on the structure is calculated for the applied pressure range from 0 to 1000 Pa. Later, the output voltage of the sensor is calculated. This mathematical model is validated with the COMSOL multiphysics simulator. The optimization of the sensor is done in mathematical tool with maximizing function after providing the conditions.

Results: The maximum stress on the sensor structure occurred near the clamped part of the cantilever. The calculated and simulated output sensitivities of the PZT-5A piezoelectric based pressure sensor are-1.6021 mV/kPa and -1.046887 mV/kPa respectively.

Conclusion: We conclude that the PZT-5A piezoelectric based pressure sensor has a linear output with negative gradient as the stress induced on the structure is tensile stress. The various parameters that affect the sensitivity of the sensor arefound to depend on the shape and size of the cantilever structure, Poisson's ratio and Young's modulus, piezoelectric voltage coefficient and piezoelectric material thickness.

Future Scope: In future, this study can be extended by taking different shape and size of the cantilever. The different modes of piezoelectric and different materials may be another future scope of this study.

Keywords: Flexural Rigidity, Linear, Sensitivity, Stress, Voltage Coefficient.

1. INTRODUCTION

Pressure sensorbecomes a very promising device because of its sensitivity and measurement for the pressure of gases or liquids of anysystem.The pressure sensors such as piezoelectric, piezoreistive, capacitive, inductive, and optical sensorshave different sensing mechanisms. Among these sensors piezoelectric pressure sensor don't require any input voltage to the senor. Nowadays, thereare various applications of pressure sensor in, namely 1. Automotive systems: inertial brake lights, car security systems, and air bag systems, rollover detection, electronic door locks, 2. Aerospace: wind tunnel instrumentation, sensors for fuel efficiency and safety, micro-satellites, control systems, inertial guidance systems with micro-gyroscopes, accelerometers, 3. Medical services: disposable blood pressure monitors, respirators, lung capacity meters, controlling medical procedures, apparatus for kidney dialysis, 4. Microbioanalytical systems: capillary electrophoresis and biochip, manufacturing automation, instrumentation, 5. Communications: fibre optic couplings and optical switching, RF relays and switches, tunable resonators, 6. Consumer goods: computers and watches, sensors for exercise equipment, washers with adjustable water levels, athletic footwear with automated cushion control, and 6. Environmental monitoring and control: moisture or humidity, control in water volume[1-2][4][13]. They are also used in energy harvesting and vibration sensing [6-7][9]. The various advantages of piezoelectric pressure sensor are that the sensor can retain tohave low power consumption, more sensitive to input variation, cheap cost of production, enhanced performance & reliability, able to replace bulky parts of traditional electronic appliances, improved reproducibility.Piezoelectric pressure sensor can be used in Internet of things (IoT) devices for improvising the life span of the battery used in IoT.

Piezoelectric materials usually exhibit different piezoelectric coefficient according to their modes of operation. The most common structure used in the piezoelectric pressure sensors are cantilever, bridge and diaphragm. The cantilever piezoelectric pressure sensor is shown in fig. 1.

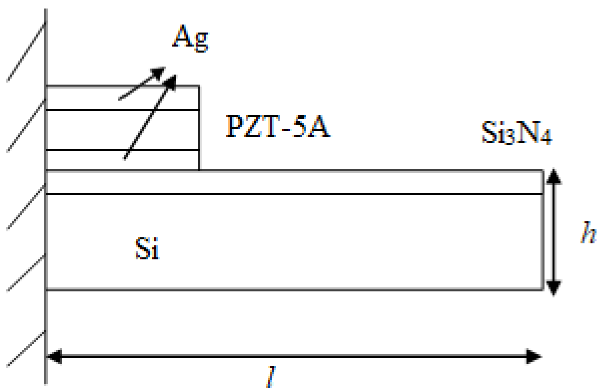

Fig. 1: CantileverPiezoelectric Pressure Sensor.

The piezoelectric output and stress aremutually correlated.The sensing layers are positioned close to the cantilever's fixed edge as maximum stress occurred at the clamped area of the cantilever. The PZT-5A and its composites are used in thin filmdeposition and utilized for different applications [3][8-10][12]. The optimization of the sensor is also very important to maximize the performance with higher sensitivity [5].

This work is organized as follows: in section 2, we consider material and design methodology to describe the mechanical modeling and electrostatic modeling used in the mathematical modeling of the sensor. In section 3, the COMSOL multiphysics simulator's 3D studies of the designed sensor structure and its design structure are described and the numerous factors impacting the sensitivity and optimization of the sensor are presented and analytically compared for the mathematical analysis outputs and 3D analysis outputs. Finally we conclude the work.

2. MATERIAL AND DESIGN METHODOLOGY

Applying the pressure from 0 to 1000 Pa with 100 Pa step size, the design model of a cantilever structure with PZT-5A as the sensing layer is simulatedin COMSOL multiphysics simulator. The dimensions of the 3D model of the proposed PZT-5A piezolectric pressure sensor are tabulated in table 1. Whereas, the materials properties used in PZT-5A piezolectric pressure for this studyare tabulated in table 2.

Table 1: Dimension of the 3D structure of the sensor.

Material	Si	Si_3N_4	Ag	PZT-5A
Length	200 μm	200 μm	50 μm	50 μm
Breadth	50 μm	50 μm	50 μm	50 μm
Thickness	50 μm	3 μm	3 μm	10 μm

Table 2: Material properties used in PZT-5A piezoelectric pressure sensor.

Material	Si	Si_3N_4	Ag	PZT-5A
Density	2320 kg/m^3	3100 kg/m^3	10500 kg/ m^3	7950 kg/ m^3
Young's modulus	160 GPa	250 GPa	83 GPa	79 GPa
Poisson's ratio	0.22	0.23	0.37	0.34

In this study, a model of the sensor is proposed and the mathematical model of the sensor is developed in two steps, i.e. Stress on the cantiliver and Voltage on the surface of the PZT-5A. Secondly, the 3D model of the senosr is simulated and the mathematical model is validated by comparing the simulated and calculated values. Next, the model is optimized for the sensitivity to be maximized. The work flow of this study is illustrated fig. 2.

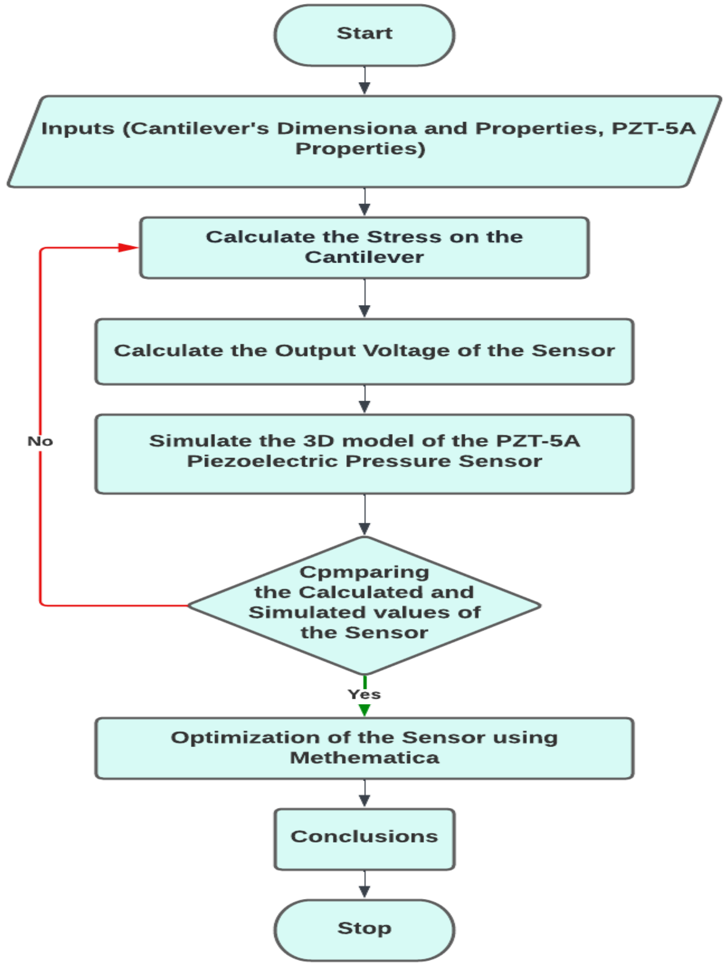

Fig. 2: The work flow of this study.

2.1 Mathematical Model

As mentioned before, the mathematical model has two sections namely, mechanical model and electrostatic model.

In mechanical model, the stress on the cantilever surface is calculated and find the position where the maximum stress occurrs. Let us consider a uniformly load or pressure (*P*) is ditributed on the surface of the cnatilever as shown in fig.1. The mathematical expression for conservation of moment on for the cantilever system is [14-16].

$$-EI\frac{\partial^2 w(x)}{\partial x^2} = Fx - m_0 - \int_0^x \frac{F}{l}(x-s)\partial s, \qquad (1)$$

where, Erepresents the Young's modulus,$w(x)$ is the deflection function of the cantilever in term of x,Irepresents the moment of inertia, Frepresents the total force on the cantilever surface, m_0 represents the moment at the clamped part, $x$represents the position the cantilever,

$l$represents the length of the cantilever and $s$represents the position with small displacement from position x.

Now, integrating and applying the boundary condition, we get

$$-EI\frac{\partial^2 w(x)}{\partial x^2}=Fx-m_0-\frac{F}{l}x(x-0)+\frac{F}{l}(x^2-0), \quad (2)$$

$$=Fx-m_0-\frac{Fx^2}{2l}.$$

The boundary conditions of deflection are given by:

$$\frac{\partial^2 w(0)}{\partial x^2}=0, w(0)=0, \frac{\partial^2 w(l)}{\partial x^2}=0.$$

Applying the above boundary condition to Eq. 2, we get

$$0=Fl-m_0-\frac{Fl^2}{2l},$$

$$\Rightarrow m_0=\frac{Fl}{2}. \quad (3)$$

The putting the value of m_0 into Eq. 2, we get

$$-EI\frac{\partial^2 w(x)}{\partial x^2}=Fx-\frac{Fl}{2}-\frac{Fx^2}{2l},$$

$$\frac{\partial^2 w(x)}{\partial x^2}=\frac{1}{EI}(\frac{Fl}{2}+\frac{Fx^2}{2l}-Fx). \quad (4)$$

The stress $T(x)$equation is given by

$$T(x)=-Ez\frac{\partial^2 w(x)}{\partial x^2},$$

Where z represents the distance from the natural plane. Generally, it is half of the thickness of the cantilever. Now, we get

$$T(x)=-E(-\frac{h}{2})(\frac{1}{EI}(\frac{Fl}{2}+\frac{Fx^2}{2l}-Fx)),$$

$$=\frac{h}{2I}(\frac{Fl}{2}+\frac{Fx^2}{2l}-Fx). \quad (5)$$

The value of $I$is given by [15-16]

$$I=\frac{bh^3}{12}.$$

Now, putting the value of I into Eq.5, we get

$$T(x)=\frac{12h}{2bh^3}(\frac{Fl}{2}+\frac{Fx^2}{2l}-Fx),$$

$$=\frac{3h}{lbh^3}(Fl^2+Fx^2-2lFx),$$

$$T(x) = \frac{3P}{h^2}(l^2 + x^2 - 2lx). \tag{6}$$

To optimize the stress equation, the values of $(l^2 + x^2 - 2lx)$ in Eq. 6 is needto maximize. Now applying maxima and minima operation, we get the maximum value at *x*=0.As the value of *F=PA=Pbl*, we get

$$T(x)_{\max} = T(0) = \frac{3Fl}{bh^2} = \frac{3Pl^2}{h^2}. \tag{7}$$

The optimized value of stress will be given by Eq. 7. In electrostatic model, the sensor's operational mode falls under the transverse mode (g_{31}) in the case of a cantilever beam structure. The output voltage on the piezoelectric surface of the sensor is given by

$$V(x) = g_{31}T(x)t. \tag{8}$$

The sensitivity (S) of the sensor is calculated from the equation:

$$S = \frac{\Delta V}{\Delta P} = \frac{g_{31}t(T(x)_2 - T(x)_1)}{P_2 - P_1}. \tag{9}$$

The sensitivity of the sensor can be improvised by taking the material with higher values of piezoelectric voltage coefficient, higher thickness of the piezoelectric material and higher induced stress values for the given input pressure.

3. SIMULATIONAND DISCUSSION

A 3D model of the sensor as shown in fig. 1 is designed in the COMSOL multiphysics simulator with the dimensions as tabulated in table 1 and simulated for the applied pressure range from 0 to 1000 Pa with step size 100 Pa. In COMSOL, the 3D model is assigned with the respective materials. The structure is configured with fixed constraints, boundary load, ground, terminal etc. After configuration the 3D model is meshing with tetrahedral shape and finer size as shown in fig. 3.

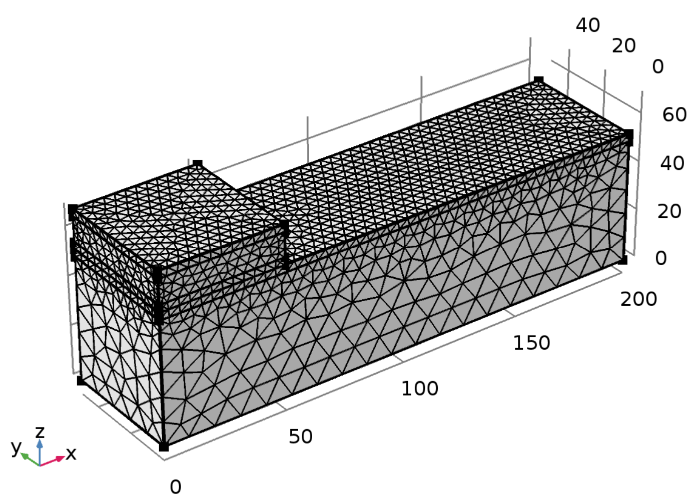

Fig. 3: Meshing of the 3D model of the sensor.

After meshing, the study of the 3D model sensor is done after simulation. The stress distribution on the surface of the piezoelectric pressure sensor is shown in fig.4.

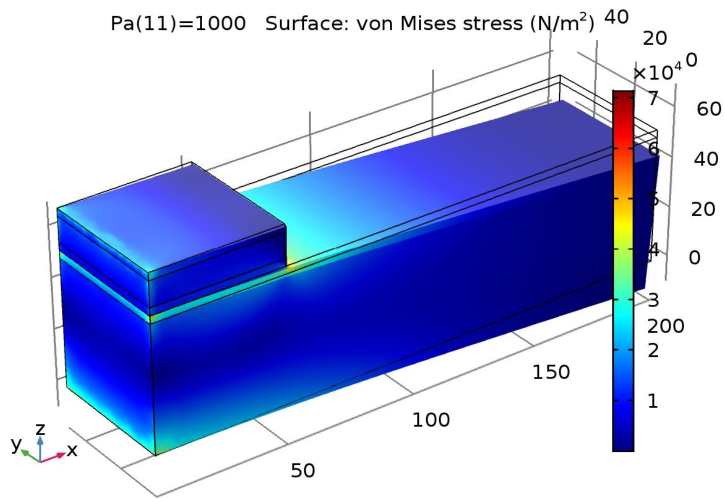

Fig. 4: Stress distribution on the surface of the sensor.

The maximum stress is occurred at the top of the sensor near the clamped part and decreases as the position changes toward the free end of the cantilever. The voltage is distributed on the surface of the piezoelectric pressure sensor as shown in fig.5.

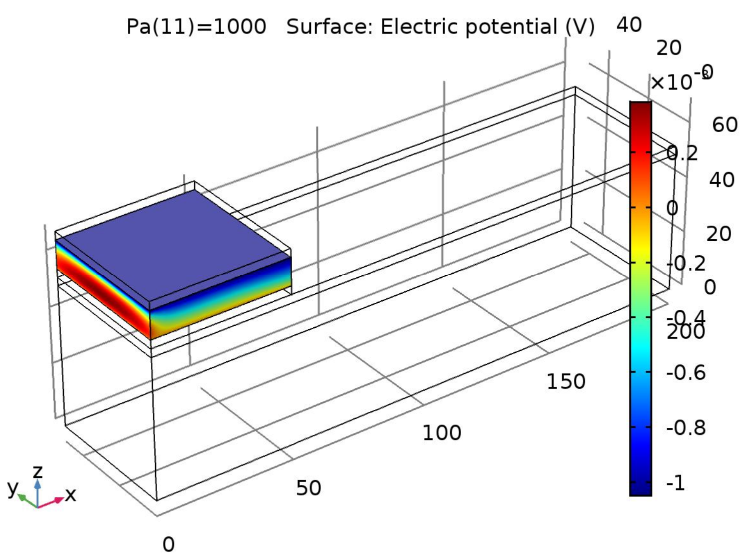

Fig. 5: Voltage distribution on the surface of the piezoelectric material.

The voltage distribution is higher in magnitude on the top surface of the piezolectric material with negative values. This negative value existsas the stress induced on the top surface is tensile stress.

The average output voltage on the upper surafce of the piezoelectric surafce is shown in fig. 6. It is obvious that the output voltage is highly linear with the input pressure with negative slope.

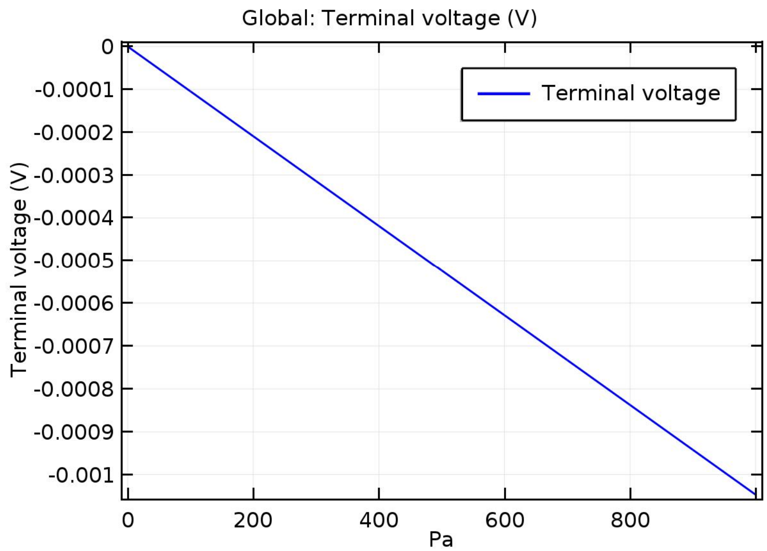

Fig. 6: Simulated output voltage on the surface of the piezoelectric material.

An analytical comparision is peformed between the simulated and calculated values of the output voltage on the surafce of piezolectric pressure sensor. For calculation, Eq. 9 is used at x=50 μm and the values of calculated and simulated values are tabulated in table 3.

Table 3: Simulated and calculated values of output voltage of the sensor.

Pressure	Simulated [mV]	Calculated [mV]
0	0.0	0.0
100	-0.104688	-0.16021
200	- 0.209377	-0.32042
300	-0.314066	-0.48063
400	-0.418755	-0.64084
500	-0.523444	-0.80105
600	-0.628132	-0.96126
700	-0.732821	-1.12147
800	-0.837510	-1.28168
900	-0.942199	-1.44189
1000	-1.046887	-1.6021

The graphical represenstation of the table 3 is shown in fig.7. From the figure, it is seen that the calculated values are found slightly higher than the simulated values. The output voltage magnitudes shoot up with increase in applied pressure but the slope is negative.

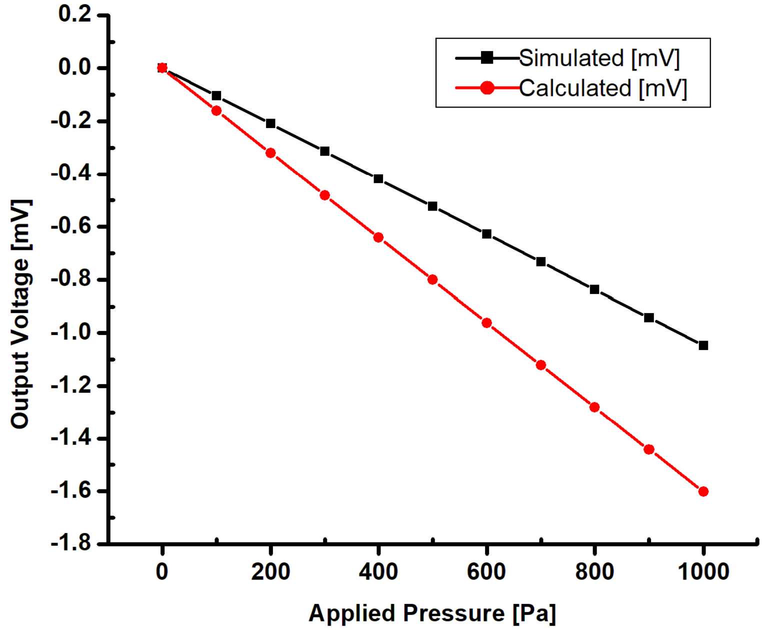

Fig. 7: Comparision of Simulated and Calculated output values.

The simulated and calculated output values are found very close to each other. So, the proposed mathematical model can be used for future application as it is valiated with simulated output values. The sensitivity of the simulated and calculated values are found as-1.046887mV/kPa and -1.6021 mV/kPa respectively.

Optimization of the output voltageis achieved by combining Eq. 6 and Eq. 8 and yields

$$V(x) = g_{31}\left(\frac{3P}{h^2}(l^2 + x^2 - 2lx)\right)t. \qquad (10)$$

The above equation is utilized in Matlab software to maximize the output voltage at$x=0$with various values ofg_{31}, h,l and t.

4. CONCLUSION

The mathematical modelling, simulation, and optimisation of the PZT-5A Cantilever Piezoelectric Pressure Sensor for pressure ranges of 0-1000 Pa are the main topics of this research work. The mathematic model of the sensor is design and validated with the simulated values. According to the mathematical model, the stress on the structure depends on its length, width, thickness as well as its position and the pressure being applied. The stress, the piezoelectric voltage coefficient, and the thickness of the piezoelectric material all influence the sensor's output voltage. The output voltage has a negative slope and increases in magnitude as applied pressure increases. By maximising the stress, voltage coefficient, and thickness of the piezoelctric, the output voltage can be optimised. Therefore, it is important to select a material that has a high piezoelectric coefficient and the highest possible sensor diemenson of the sensor structure. The sensitivity of the simulated and calculated values are found as -1.046887 mV/kPa and -1.6021 mV/kPa respectively.

COMPETING INTERESTS

"Authors have declared that no competing interests exist".

AUTHORS' CONTRIBUTIONS

'Maibam Sanju Meetei' designed the mathematical model and simulation of this work, and wrote the first draft of the manuscript. 'Heisnam Shanjit Singh' analyzed and wrote the second draft of the manuscript. Then both the authors read and approved the final manuscript."

REFERENCES

1. Nurul Amziah Md Yunus, Izhal Abdul Halin, Nasri B. Sulaiman, Noor Faezah Ismail, Ong Kai Sheng. Valuation on MEMS Pressure Sensors and Device. World Academy of Science, Engineering and Technology, International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering. 2015;9:834-842.

2. Maibam Sanju Meetei, Aheibam Dinamani Singh, Swanirbhar Majumder. A Novel Design and Modeling of Beam Bridge Structure Piezoelectric Pressure Sensor Base on ZnO. 5th International Conference on Computers & Management Skills (ICCM 2019).2019:106-110.

3. Haokang Ying, Guangya Ding, Jie Zhao, Jun Wang, Zhiming Liu, Mengqi Zhou, Jianke Ye. Properties of PSN-PZT piezoelectric ceramic powder prepared by fast solid-phase reaction method. Materials Today Communications. 2023;23:106086.

4. Satyaranjan Bairagi, Shahid-ul-Islam, Mohammad Shahadat, Daniel M. Mulvihill, Wazed Ali. Mechanical energy harvesting and self-powered electronic applications of textile-based piezoelectric nanogenerators: A systematic review. Nano Energy. 2023;111:108414.

5. Sang-Mi Chang, Sunghoon Hur, Jiwon Park, Dong-Gyu Lee, Joonchul Shin, Hyun Soo Kim, Sung Eun Song, Jeong Min Baik, Miso Kim, Hyun-Cheol Song, Chong-Yun Kang. Optimization of piezoelectric polymer composites and 3D printing parameters for flexible tactile sensors. Additive Manufacturing. 2023;67:103470.

6. Akinori Tateyama, Yuichiro Orino, Yoshiharu Ito, Takahisa Shiraishi, Takao Shimizu, Minoru Kuribayashi Kurosawa, Hiroshi Funakubo. Simultaneous high-frequency measurement of direct and inverse transverse piezoelectric coefficients of thin films using longitudinal vibration. Sensors and Actuators A: Physical. 2023;354:114265.

7. Yaru Liu, Lei Wang. A robust-based configuration design method of piezoelectric materials for mechanical load identification considering structural vibration suppression. Computer Methods in Applied Mechanics and Engineering. 2023;410:115998.

8. Cherif Othmani, He Zhang, Chaofeng Lü. Effects of initial stresses on guided wave propagation in multilayered PZT-4/PZT-5A composites: A polynomial expansion approach. Applied Mathematical Modelling. 2020;78:148-168.

9. Sang-Hee Yoon, Young-Ho Lee, Seok-Woo Lee, Chan Lee. Energy-harvesting characteristics of PZT-5A under gunfire shock. Materials Letters. 2008;62(21–22):3632-3635.

10. Ezgi Yalcin, Namık Kemal Gözüaçık, Sedat Alkoy, Hüseyin Alptekin Sarı, Mustafa Yunus Kaya, Çınar Öncel, Ebru Menşur. Characterization of 1–3 piezocomposites from PNN-PZT piezoceramics. Sensors and Actuators A: Physical. 2023;357:114389.

11. Yi-Chia Lee, Cheng-Che Tsai, Cheng-Ying Li, Yu-Cheng Liou, Cheng-Shong Hong, Sheng-Yuan Chu. Fabrication and function examination of PZT-based MEMS accelerometers. Ceramics International. 2021;47(17):24458-24465.

12. Jian Guo, Binbin Tong, Jie Jian, Jianguo Chen, Taosheng Zhou, Xunzhong Shang, Jinrong Cheng. Enhanced transduction coefficient in piezoelectric PZT ceramics by mixing powders calcined at different temperatures. Journal of the European Ceramic Society. 2020;40(8):3348-3353.

13. D. Yamini Chowdary, C. Harshitha, Mallika Alapati. Parameters influencing PZT sensing in structural health monitoring. Materials Today: Proceedings. 2022;62(4):1883-1888.

14. Timoshenko S. P., Woinowsky-Krieger, S. Theory of Plates and Shells. Mc Graw Hill; New York:1959.

15. Ugural A. C. Plates and shells: theory and analysis. Boca Raton: London New York;2018.

16. Bao M. Analysis and Design Principles of MEMS Devices. Elsevier Science: Amsterdam Netherlands;2005.