Development and investigation of micro- and nanostructures of metamaterials to form the necessary characteristics and coefficients of piezoelectric elements

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Abstract. The development and research of micro and nanostructures for the manufacture of ultrasonic piezoacoustic elements has been carried out. The structures obtained in this work have practical applications for the manufacture of piezoelectric and piezoacoustic elements, in particular, for using in liquid flowmeters as receivers and emitters of an ultrasonic signal. A structure of nanocells was obtained that was different from standard piezoelectric elements (disk, cylinder), but with the same coefficients, characteristics, and radiation pattern.

1. Introduction

The piezomaterials are of great interest because of their unique properties since the discovery of the direct and inverse piezoelectric effect of single crystals by the Curie brothers in 1880 and 1881. And the discovery of the possibility of polarizing ceramic material with an electric field in 1946 led to the widespread distribution of piezoelectric and piezoelectric elements. The ability of piezoelectric materials to convert mechanical energy into electrical energy and vice versa allows them to be used in ultrasonic measurements, in pressure measurements, in medicine, in flow detectors, seismic sensors and energy collection systems. In addition, applying an AC voltage to the material causes it to vibrate and thus creates mechanical waves with the same frequency as the electric voltage, which can be used in micro-positioning devices, such as attenuators, scanning tunnelling microscopes, etc. Similarly, if mechanical vibration is used, a charge of a proportional size and the same frequency will be generated [1]. In some problems, piezoelectric materials are indispensable, since without this physical process it will be impossible to make studies or measurements.

But all the characteristics, coefficients, and piezoelectric constants of existing standard piezoelectric elements, such as a disk, cylinder, etc., are dictated by their structure and chemical composition. This leads to the fact that the properties of the piezoelectric elements, such as the radiation pattern or conversion coefficient, remain constant for the whole wide range of tasks. It is necessary to find such technical solutions in which the maximum response of the piezoelectric element is achieved, or to seek a compromise between the efficiency of the piezoelectric element and the complexity of the entire system design. In non-trivial problems, the necessary radiation pattern, which will correspond to the best signal emission result, cannot be obtained with standard piezoelectric elements. Even the addition of impurities to the crystallographic structures of piezoelectric materials cannot lead to the possibility of dynamically adjusting the piezoelectric constants in certain directions, since the set of alloying components is limited, and any changes to the geometry of standard piezoelectric elements, in an attempt to obtain the desired characteristics, will lead to a change in the electrical and acoustic properties. One way to avoid losing the necessary parameters is to use metamaterials with a specific geometry to create piezoacoustic and piezoelectric elements. In this case, it will be possible to select material for a given geometry, and not vice versa [1].

With a certain structure of the connection of the nanocells (3 - 200 nm) of the piezoelectric materials, electromechanical bonds are formed, in which the piezoelectric properties are improved by changing parameters such as the electromechanical coupling coefficient, conversion coefficient, quality factor, piezoelectric module, etc. Due to these improvements, the efficiency of piezoelectric elements is significantly increased. These nanocells are three-dimensional (3D) structural nodes, as shown in Figure 1 [1].

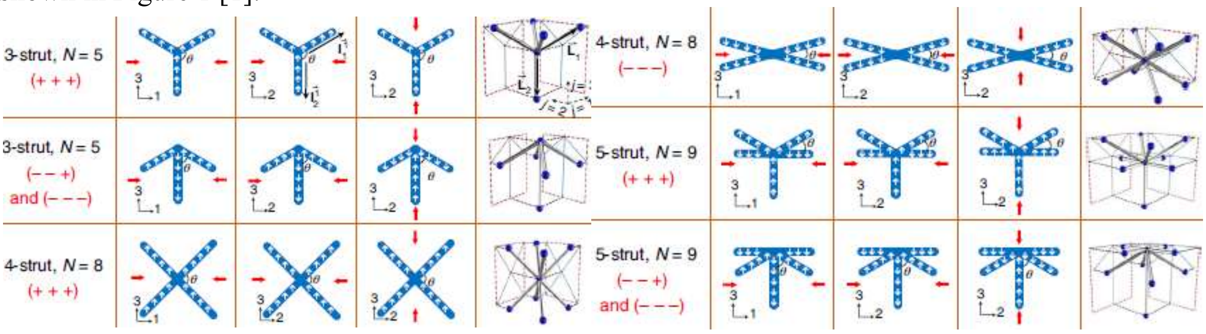


Figure 1. Three-dimensional structural units [1].

Nanocomposite piezoelectric metamaterials from these structures achieve a high conversion coefficient and a piezoelectric voltage coefficient, and also have a high flexibility of characteristics, which is not achievable using standard piezoelectric and piezoelectric elements [3].

When using these structures, the field of application of piezoelectric elements significantly expands and their efficiency increases several times. There is the possibility of manufacturing piezoelectric elements with the necessary geometry for the user based on the task.

The purpose of this work is to obtain new structures to form the necessary characteristics.

2. Piezoelectric elements

One of the standard versions of piezo-acoustic elements are discs of various diameters (figure 2).

Figure 2. Standard piezoacoustic element with a diameter of 4 mm for a frequency of 1 MHz.

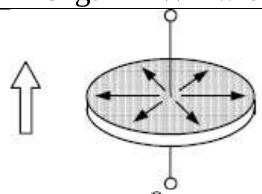
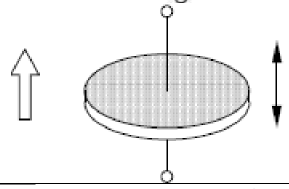
This element has certain characteristics and coefficients, which are key parameters. For this type of piezoelectric elements, there can be the following modes, presented in table 1[12].

The main coefficients and characteristics for piezoelectric elements, which determine their properties and are determined by the structure, geometry and impurities [2]:

1. Dielectric constant
2. Conversion coefficient
3. Dielectric loss factor
4. Quality factor of the elastic system
5. Frequency constant
6. Electromechanical coupling coefficient
7. Coefficient of the piezoelectric charge

8. Piezoelectric voltage factor
9. Coefficient of elastic compliance
10. Rate of aging
11. Curie point

Table 1. Piezoelectric Element Mods [12].

Piezoelectric modes of vibration					
Vibration mode	Dimensions			Constants to be calculated	
	L - length	W - width	D - diameter	Piezoelectric	Mechanical
Radial mode			D > 10 Th	$k_p, \varepsilon_{33}^S, \varepsilon_{33}^T$	σ^E, S_{12}^E, Q_p
Thickness extension mode			D > 10 Th	k_T, ε_{33}^S	$C_{33}^D, C_{33}^E, S_{13}^E, Q_T$

To describe these constants, it is necessary to consider elements as 3D objects with three possible directions of action of forces and three rotation axes, as shown in Figure 6. Also in this figure, directions (1 - 6) are numbered [3].

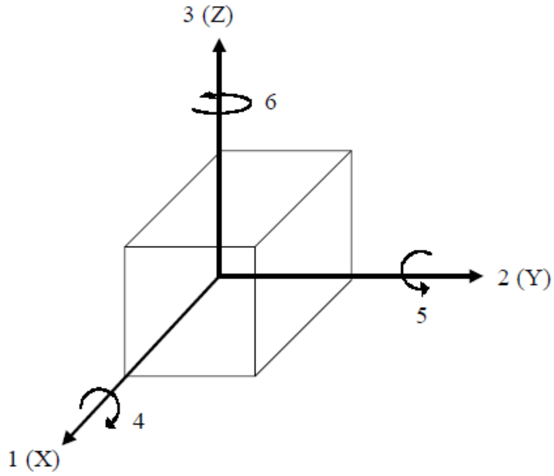


Figure 3. Stress application directions [12].

All characteristics and constants are indicated in accordance with the position of the electrodes on the cell, the direction of the applied voltage or load, the direction of shear, etc. Examples of these designations are presented in table 2 [12].

3. Modeling

Figure 3 shows a model of a standard piezoelectric element, which is used as a receiver and transmitter of an ultrasonic signal.

Figure 4 shows a micro-cell, which is used as a structural unit for constructing a new piezoelectric element (this cell was used in [1], a microscope image of the structure from these cells is shown in Figure 5 [1]).

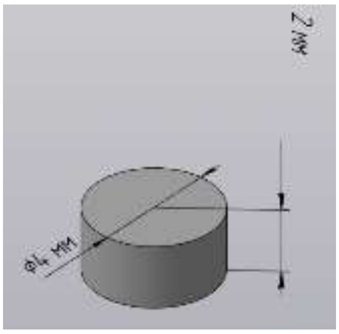


Figure 4. Piezoelectric element.

Table 2. Designations [12]

Relative dielectric constant $\varepsilon_3^S/\varepsilon_0$ and $\varepsilon_1^T/\varepsilon_0$	K_3^S: S → All strains in the material are constant or mechanical deformation is blocked in any direction; 3 → Electrodes are perpendicular to 3 axis
	K_1^T: T → All stresses on material are constant or no external forces. 1 → Electrodes are perpendicular to 1 axis.
Electromechanical coupling factor	k_p → Stress or strain is equal in all directions perpendicular to 3 axis
	k_{15} → Stress or strain is equal in all directions perpendicular to 3 axis ↳ Electrodes are perpendicular to 1 axis.
Piezoelectric charge coefficient	d_h → Hydrostatic stress or stress is applied equally in all directions.
	d_{33} → Applied stress,or piezoelectrically induced strain is in 3 direction ↳ Electrodes are perpendicular to 3 axis.
Piezoelectric voltage coefficient	g_{15} → Applied stress,or the piezoelectrically induced strain is in shear form around 2 axis. ↳ Electrodes are perpendicular to 1 axis.
	g_{31} → Applied stress,or the piezoelectrically induced strain is in 1 direction. ↳ Electrodes are perpendicular to 3 axis.
Elastic compliance	S_{36}^E: E– Compliance is measured with closed circuit. 36– Stress or strain is shear around 3 direction ↳ Strain or stress is in 3 direction.
	S_{11}^D: D– Compliance is measured with open circuit. 11– Stress or strain is in 1 direction ↳ Strain or stress is in 1 direction.

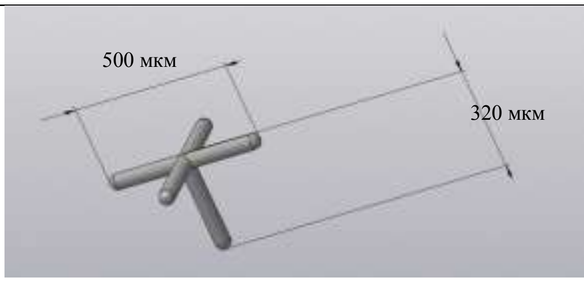


Figure 4. Microcell.

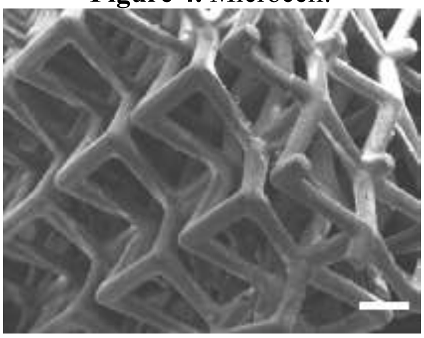


Figure 5. Microcell piezoelectric structure [1].

The piezoelectric element shown in Figure 6 was constructed from these cells with the same geometric parameters as the standard one. In this sample, the upper and lower platforms of the model were chosen as electrodes for positive and negative potentials.

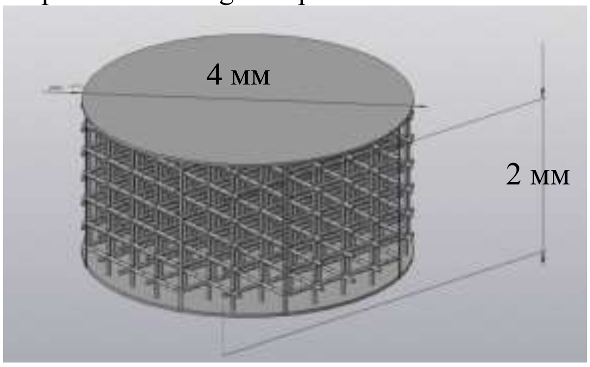


Figure 6. Piezoelectric element design.

The standard model (Figure 3) and designed (Figure 6) were modeled under conditions of creating a potential difference between their surfaces. Figure 7 shows the deformation diagrams of element when applying a voltage of 5V.

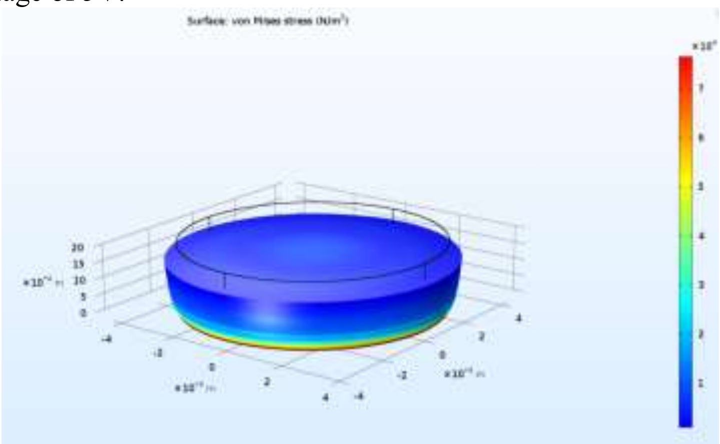


Figure 7. Standard element deformation diagram.

4. Conclusion

A theoretical study of the constants and coefficients for piezoelectric elements was carried out, as well as the influence of various physical properties on the characteristics and response of piezoelectric and piezoelectric materials. It was found that the dielectric constant, conversion coefficient, dielectric loss coefficient, Q factor of the elastic system, frequency constant, electromechanical coupling coefficient, piezoelectric charge coefficient, piezoelectric stress coefficient, elastic compliance coefficient, aging rate and Curie point for the piezoelectric element depend on its structure and composition.

The processes of the piezoelectric effect for a standard piezoelectric element with a diameter of 4 mm and a thickness of 2 mm were simulated, as well as a piezoelectric element constructed from microcells with preserved geometric parameters. A unit cell option was proposed for piezoelectric material structures from which a non-standard element was assembled.

This element allows you to achieve different characteristics and efficiency compared to standard piezoelectric elements, while maintaining the same overall dimensions. The use of various configurations of microcells to create structures of piezoelectric materials allows you to change the properties, parameters and characteristics of piezoelectric elements made from these structures.

5. Acknowledgments

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