DOI: 10.17725/rensit.2023.15.355

The investigation of resonators with longitudinal and lateral electric fields with various shear dimensions

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Received November 24, 2023, peer-reviewed November 30, 2023, accepted December 03, 2023, published December 06, 2023.

Abstract: **The influence of the diameter of a disk resonator with a radial electric field made on the basis of PZT-19 piezoceramics and the shear dimensions of a resonator with a lateral electric field (LFE) based on PZTNV-1 piezoceramics on their main characteristics, such as the frequencies of parallel and serial resonances and maximum values of the real parts of electrical impedance and admittance has been studied experimentally and theoretically.**

Keywords: **radial oscillations, resonators with a lateral electric field, resonators with a longitudinal electric field, parallel resonance, series resonance, electrical impedance and admittance**

UDC: 534.231, 534.6.08

Acknowledgments: The work was carried out with the financial support of the Ministry of Education and Science of the Russian Federation (state assignment FFWZ-2022-0002).

For citation: Boris D. Zaitsev, Alexander P. Semyonov, Andrey A. Teplykh, Irina A. Borodina. The investigation of resonators with longitudinal and lateral electric fields with various shear dimensions. *RENSIT: Radioelectronics. Nanosystems. Information Technologies,* 2023, 15(4):355-360e. DOI: 10.17725/rensit.2023.15.355.

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1. INTRODUCTION

Piezoelectric resonators are widely used in various fields of science and technology, both as passive components of electronic equipment [1] and as various sensors. These sensors are used to study the properties of various liquids [2-8] and films [9-10], to analyze various gases in the air [11-15], to record specific biological reactions in aqueous environments [16-18], to create micro-movement detectors [19], etc.

It was previously shown that changing the electrical boundary conditions near the free side of a piezoelectric resonator with a lateral electric field affects its parameters [19]. However, in practice during measuring the characteristics of resonators of this type in a wide frequency range, there are often the resonances the nature of which is either unclear or difficult to analyze theoretically. In addition, it should be noted that the features of excited oscillations in resonators must be analyzed not only theoretically, but also the theoretical data must be confirmed by experimental results. In this work, the features of mechanical vibrations in a disk resonator with a longitudinal exciting electric field and in a rectangular resonator

with a lateral electric field are studied when their shear dimensions change.

The purpose of this work is to investigate the influence of the shear dimensions of a piezoceramic disk resonator with a longitudinal electric field and a piezoceramic rectangular resonator with a lateral electric field on their main characteristics.

2. EXPERIMENTAL PROCEDURE AND EXPERIMENTAL RESULTS

2.1. The study of a disk resonator with a longitudinal electric field

To carry out the research, a disk resonator with a longitudinal electric field based on piezoceramics PZTNV-1 (Aurora-ELMA LLC, Volgograd) with a diameter of D = 21.9 mm and a thickness of 1.945 mm was used. During the entire experiment, the diameter of the disk resonator was changed by mechanical processing from 21.9 mm to 14 mm in steps of ~1 mm. For each value of the disk resonator diameter, the frequency dependences of the real and imaginary parts of the electrical impedance were measured. From the measured frequency dependences, the maximum values of the real parts of the electrical impedance and admittance, as well as the resonant frequencies of parallel and series resonances were determined. The dependences of the resonant frequencies of parallel (f_{par}) and series (f_{ser}) resonances on the resonator diameter (D) are presented in **Fig. 1**. The maximum values of the real parts of the electrical impedance (R_{max}) and

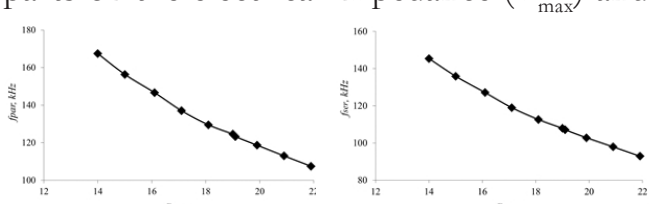

Fig. 1. *Experimental dependences of the frequencies of parallel fpar (left) and serial fser (right) resonances on the diameter of disk D of a resonator with longitudinal electric field made on the basis of PZTNV-1 piezoceramics*

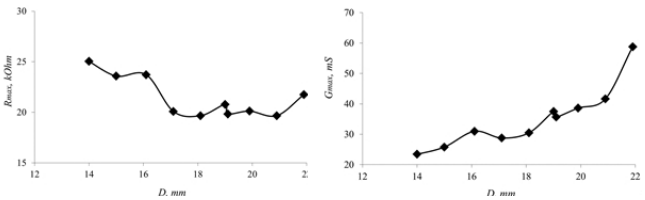

Fig. 2. *Experimental dependences of the maximum values of the real parts of the electrical impedance Rmax (left) and admittance Gmax (right) on the diameter of the disk D of the resonator with longitudinal electric field made on the basis of piezoceramics PZTNV-1.*

admittance (G_{max}) as function of diameter D are shown in **Fig. 2**. Fig. 1 shows that as the diameter decreases, the frequency of both parallel and series resonances increases. The total relative change in these values is 56% and 57%, respectively. The maximum value of the real part of the electrical impedance (R_{max}) does not change as the disk diameter decreases from 22 to 17 mm, but then increases slightly as the diameter decreases from 17 to 14 mm (Fig. 2 (left)). The total relative change in this value is 25% when the disk diameter changes from 17 to 14 mm. The maximum value of the real part of the electrical admittance (G_{max}) decreases from 60 to 20 mS with a decrease in the resonator diameter from 22 to 14 mm (Fig. 2 (right)). The total relative change in the maximum value of the real part of the electrical admittance is 60%. Such a change in the characteristics of the disk resonator, especially the resonant frequency of the parallel resonance, with a decrease in its diameter indicates the excitation of mechanical vibrations of the radial type.

2.2. The investigation of a resonator with a lateral electric field

The resonator with the lateral electric field was manufactured in laboratory conditions from a rectangular PZT-19 piezoceramic plate with a thickness of 2.566 mm and shear dimensions of 19.9×17.86 mm². Two rectangular aluminum electrodes with

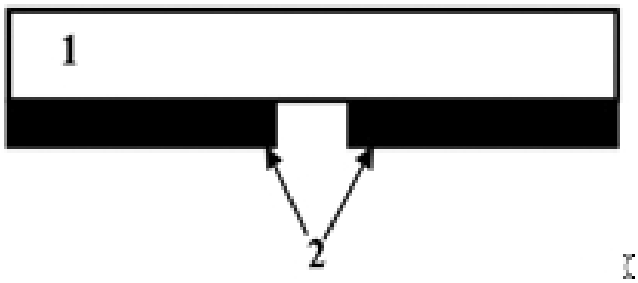

Fig. 3. *Layout of the resonator with lateral electric field: 1 – plate of piezoceramics PZT-19, 2 – electrodes.*

dimensions of 19.9×6.9 mm2 and a gap of 4 mm between them were applied to one side of the piezoceramic plate (**Fig. 3**). The polar axis of the piezoelectric was oriented perpendicular to the gap. During the experiment, the largest shear dimension (H) of the piezoceramic plate along the gap was changed by mechanically grinding from 19.9 to 14.8 mm with a step of ~1-2 mm. This process allowed to maintain the parallelism of opposite faces and the integrity of the resonator electrodes. For each plate length (H) of the resonator probe, the frequency dependences of the real and imaginary parts of the electrical impedance were measured in the operating range of 50-300 kHz. From these dependencies, the values of the resonant frequencies and the maximum values of the real parts of the electrical impedance corresponding to each length of the resonator were determined for the three observed resonances in a given frequency range. The dependences of the maximum value of the real part of the electrical impedance and the resonant frequency of the parallel resonance on the length of the resonator for the three observed resonances are presented in **Figs 4, 5, 6.** Figs 4, 5, 6 show that as the plate length decreases from 19.9 to 14.8 mm, an increase in the resonant frequency is clearly observed for the three observed parallel resonances in the selected operating range. The maximum value of the real parts of the electrical impedance

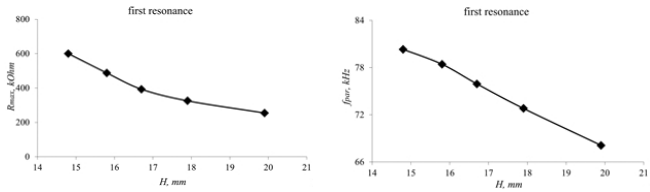

Fig. 4. *Experimental dependences of the maximum value of the real part of the electrical impedance R_{max} (left) and the frequency of parallel resonance f_{par} (right) on the length H of the piezoceramic plate of the resonator with lateral electric field for the first observed resonance.*

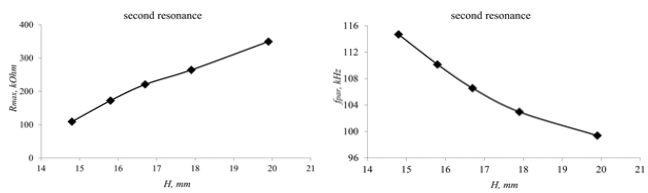

Fig. 5. *Experimental dependences of the maximum value of the real part of the electrical impedance R_{max} (left) and the frequency of parallel resonance f_{par} (right) on the length H of the piezoceramic plate of the resonator with lateral electric field for the second observed resonance.*

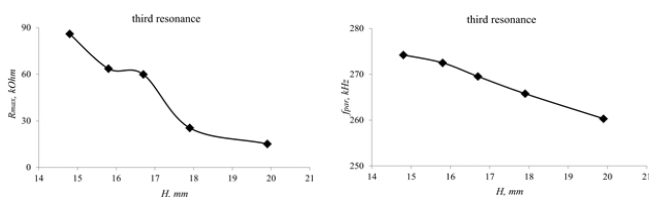

Fig. 6. *Experimental dependences of the maximum value of the real part of the electrical impedance R_{max} (left) and the frequency of parallel resonance f_{par} (right) on the length H of the piezoceramic plate of the resonator with lateral electric field for the third observed resonance*

increases with decreasing plate length for the first and third resonances (Figs. 4, 6) and decreases for the second resonance (Fig. 5). Relative changes in these values are presented in **Table 1**.

Table 1

Relative changes in the resonant frequency and the maximum value of the real part of the electrical impedance of the resonator with lateral electric field for each

Value	First resonance	Second resonance	Third resonance
f_{par}	18%	15%	5%
R_{max}	136%	69%	460%

3. THEORETICAL ANALYSIS OF THE INFLUENCE OF THE SHEAR DIMENSIONS OF RESONATORS ON THEIR CHARACTERISTICS

Theoretical analysis of the characteristics of the resonator with longitudinal electric field for various values of its diameter was carried out using a two-dimensional finite element method [10]. The dependences of the resonant frequencies of parallel and series resonances (**Fig. 7**) and the maximum values of the real parts of the electrical impedance and admittance (**Fig. 8**) on the diameter of the resonator were plotted. Comparison of dependencies in Fig. 1 and Fig. 7, and ones in Fig. 2 and Fig. 8 indicates good agreement between the theoretical data and the experimental results. During the calculations, the material constants for the PZTNV-1 piezoceramics were taken from the reference book [20]. A similar theoretical analysis for the resonator with lateral electric field was not carried out, since the two-dimensional finite element method used does not allow taking into account the size of the resonator in the third dimension, which changed during the experiment.

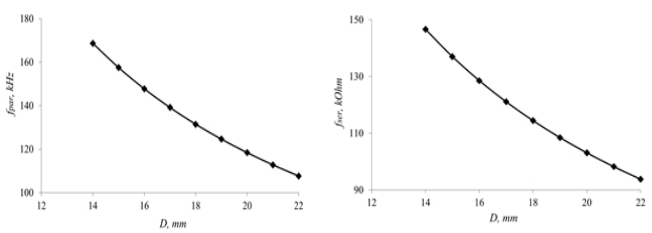

Fig. 7. *Theoretical dependences of the frequencies of parallel f_{par} (left) and series f_{ser} (right) resonances on the diameter of the disk D of the resonator with longitudinal electric field made on the basis of PZTNV-1 piezoceramics.*

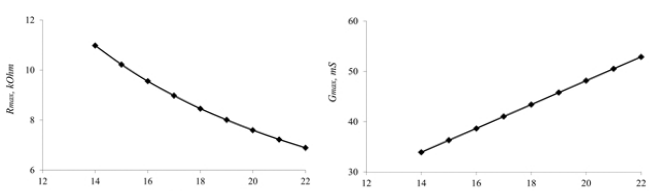

Fig. 8. *Theoretical dependences of the maximum values of the real parts of the electrical impedance R_{max} (left) and admittance G_{max} (right) on the diameter of the disk D of the resonator with longitudinal electric field made on the basis of piezoceramics PZTNV-1.*

4. CONCLUSION

The influence of the diameter of a resonator with a longitudinal electric field, made of PZTNV-1 piezoceramics, on its main characteristics, such as the resonant frequencies of parallel and series resonances and the maximum values of the real parts of the electrical impedance and admittance, has been studied experimentally and theoretically. It has been established that a change in the characteristics of a disk resonator with a decrease in its diameter indicates the excitation of mechanical vibrations of the radial type, which is confirmed by theoretical analysis. Theoretical analysis was carried out using the finite element method. In addition, the influence of the shear dimensions of a resonator with lateral electric field made on the basis of PZT-19 piezoceramics on its characteristics was experimentally studied. These characteristics are the parallel resonance frequency and the maximum value of the real part of the electrical impedance. It has been shown that decreasing the length of the resonator with lateral electric field from 19.9 to 14.8 mm leads to an increase in the frequencies of all observed parallel resonances. In this case, the maximum value of the real part of the electrical impedance increases with decreasing plate length for the first and third resonances and decreases for the second one.

REFERENCES

1. Khomenko I.V., Kosykh A.V., Quartz resonators and self-oscillators. Omsk: Publishing house. Omsk State Technical University, 2018, 160 p. (in Russian).

2. Zao Z., Qian Z., Wang B., Kuznetsova I., Ma T., Yong Y.-K. Design considerations for frequency shifts in a laterally finite FBAR sensor in contact with the Newtonian liquid // IEEE Trans. on Ultrasonics, Ferroelectrics and Frequency Control, 2020, v.67, #11, pp. 2402-2412, https://doi.org/10.1109/TUFFC.2020.3006186
3. McCann D.F., McCann J.M., Parks J.M., Frankel D.J., M. Pereira da Cunha and Vetelino J.F. A lateral-field-excited LiTaO3 high frequency bulk acoustic wave sensor // IEEE Trans. on Ultras., Ferroel., and Freq. Contr., 2006, vol. 56, no. 4, pp. 779–787.
4. Zaitsev B.D., Shikhabudinov A.M., Teplykh A.A., Kuznetsova I.E. Liquid sensor based on a piezoelectric lateral electric field-excited resonator // Ultrasonics, 2015, vol. 63, pp. 179–183.
5. Borodina I.A., Zaitsev B.D., Teplykh A.A. Influence of the conductivity of a liquid contacting with a lateral electric field excited resonator based on PZT ceramics on its characteristics // Ultrasonics, 2020, vol. 102, 106059, DOI: 10.1016/j.ultras.2019.106059
6. Zaitsev B.D., Semyonov A.P., Teplykh A.A., Borodina I.A. A new liquid sensor based on a piezoelectric resonator with a radial electric field // Ultrasonics, 2022, vol. 119, 106603, https://doi.org/10.1016/j.ultras.2021.106603,
7. Zaitsev B.D., Borodina I.A., Teplykh A.A. Compact liquid analyzer based on a resonator with a lateral excitation electric field // Ultrasonics, 2022, vol. 126, 106814, https://doi.org/10.1016/j.ultras.2022.106814,
8. Semyonov A., Zaitsev B., Teplykh A. and Borodina I. The Effect of Glycerol-Based Suspensions on the Characteristics of Resonators Excited by a Longitudinal Electric Field // Sensors. 2023. vol. 23, P. 608
9. Kuznetsova I.E., Zaitsev B.D., and Shikhabudinov A.M. Elastic and viscosity properties of nanocomposite films based on low – density polyethylene // IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control, 2010, vol. 57, № 9, pp. 2099 – 2102.
10. Teplykh Andrey, Zaitsev Boris, Semyonov Alexander and Borodina Irina The Study of the Acoustic Characteristics of Chitosan Acetate Film Using a Radial Electric Field Excited Resonator // Sensors, 2023, vol. 23, P. 1808, https://doi.org/10.3390/s23041808
11. Kuznetsova I., Zaitsev B., Krasnopolskaya L., Teplykh A., Semyonov A., Avtonomova A., Ziangirova M., Smirnov A., Kolesov, V. Influence of humidity on the acoustic properties of mushroom mycelium films used as sensitive layers for acoustic humidity sensors // Sensors. 2020. vol. 20, P. 2711
12. Zaitsev B.D., Teplykh A.A., Fedorov F.S., Grebenko A.K., Nasibulin A.G., Semyonov A.P., Borodina I.A. Evaluation of Elastic Properties and Conductivity of Chitosan Acetate Films in Ammonia and Water Vapors Using Acoustic Resonators // Sensors, 2020, vol. 20, pp. 2236; doi:10.3390/s20082236.
13. Liu K., Zhang C. Volatile organic compounds gas sensor based on quartz crystal microbalance for fruit freshness detection: A review, Food Chem., 2021, 334, 127615.doi:10.1016/j.foodchem.2020.127615.
14. Wang L. Metal-organic frameworks for QCM-based gas sensors: A review,

Sensors Actuators, A Phys., 2020, 307, 111984. doi:10.1016/j.sna.2020.111984

15. Gorbachev I., Smirnov A., Ivanov G., Avramov I., Datsuk E., Venelinov T., Bogdanova E., Anisimkin V., Kolesov V, Kuznetsova I. Langmuir-Blodgett films of arachidic and stearic acids as sensitive coatings for chloroform HF SAW sensors // Sensors, 2023, vol.23, p.100, 10.3390/s23010100.
16. Guliy O.I., Zaitsev B.D., Semyonov A.P., Alsowaidi A.K.M., Teplykh A.A., Karavaeva O.A., Borodina I.A. Microbial acoustic sensor test-system based on a piezoelectric resonator with a lateral electric field for kanamycin detection in liquid // Ultrasonics, 2022, vol. 120, 106651, https://doi.org/10.1016/j.ultras.2021.106651,
17. Hartz Jequil S. R., Emanetoglu Nuri W., Howell Caitlin, and John F. Vetelino Lateral field excited quartz crystal microbalances for biosensing applications, Biointerphases, May 2020. DOI: 10.1116/6.0000144
18. Gorbachev I.A., Smirnov A.V. Biosensor based on Langmuir-Blodgett film with alcohol oxidase enzyme // Radioelektronika, Nanosistemy, Informacionnye Tehnologii, 2023. V.15.#3, p. 307-316e, https://doi.org/10.17725/rensit.2023.15.307
19. Zaitsev B.D., Semyonov A.P., Teplykh A.A., Borodina I.A. The sensor for measuring the micro-displacements based on the piezoelectric resonator with lateral electric field // Ultrasonics, 2019, vol. 99, https://doi.org/10.1016/j.ultras.2019.105973
20. Piezoceramic transducers. Measurement methods and calculation of parameters. Reference book. Edited by S. I. Pugachev. Leningrad, 1984, 256 p. (in Russ.)