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The sensor for measuring the micro-displacements based on the piezoelectric resonator with lateral electric field

B.D. Zaitsev*, A.P. Semyonov, A.A. Teplykh, I.A. Borodina

Kotel'nikov Institute of Radio Engineering and Electronics of RAS, Saratov Branch, Saratov 410019, Russia

A R T I C L E I N F O

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A B S T R A C T

Theoretical and experimental studies of the influence of a thin metal film on the characteristics of a piezoelectric resonator with a lateral electric field showed the possibility of creating a micro-displacement meter in the range of 10–300 μm. For the experiments, two resonators based on the plates of PZT piezoceramics with a thickness of 3.56 and 4.46 mm with resonant frequencies of ~96 and ~260 kHz for both resonators were used. It has been experimentally established that in both cases, with an increase in the width of the gap between the free side of the piezoelectric resonator and thin aluminum film, the frequency of the parallel resonance and maximum value of the real part of the electrical impedance increase and reach saturation. Besides, it has been shown that the relative change of these values with a change in the width of the gap in the range 10–300 μm increases with decreasing the thickness of the resonator. In this case, the frequency of the series resonance practically does not change. It has been also established that the sensitivity of the resonator to the presence of a conducting film at the resonant frequency of ~96 kHz is significantly higher in comparison with the resonant frequency of ~260 kHz. The experimental results are in the qualitative agreement with the theoretical data.

1. Introduction

For 10–15 years, piezoelectric resonators with a lateral exciting electric field have aroused great interest among researchers and are increasingly finding their use as various types of sensors [1–9]. The electrodes of such resonators are located on one side of the piezoelectric plate, and the electric field is concentrated not only in the piezoelectric plate, but also penetrates beyond its limits. Consequently, a change in the electrical boundary conditions in the immediate vicinity of the free side of the resonator can lead to a change in its characteristics. Recently in [10,11] the effect of the conductivity of a film located near the free side of X-cut lithium niobate resonator on its characteristics was investigated. In these works, the possibility of developing the mechanical displacement sensors in the range 0.2–2 mm for continuous monitoring of deformations and detection of cracks in various constructions and structures was shown. However, in some cases, to analyze the stress state of some constructions, one needs to determine precision micro displacements in a narrower range. From a physical point of view, for this purpose, the material of the resonator should have a higher dielectric constant. In this regard, PZT piezoceramics is very promising material for creating resonators [12], which is characterized by a higher dielectric constant and a high electromechanical coupling coefficient compared with lithium niobate. A study of the effect of films with different conductivities located near a resonator with a lateral electric field based on PZT ceramics on its characteristics near the resonant frequency of 96 kHz was also carried out [13]. However, the characteristics of a series resonance and influence of the resonator thickness on its parameters were not investigated. At that the influence of conducting film on the characteristics of another pronounced resonance near the frequency of 260 kHz was not taken into account.

The purpose of this work is the theoretical and experimental studies of the influence of a thin metal film set near a piezoelectric resonator with a lateral electric field based on PZT ceramics on its characteristics in order to develop a micro-displacement meter in the range of 10–300 μm. The particular attention was paid to the study of a series and parallel resonances of all resonances and the influence of the plate thickness.

2. The methodology of the experiment and the experimental results

To carry out experiments, two resonators with a thickness of 3.56 and 4.46 mm and with shear dimensions of 18 × 20 mm^2, were fabricated on the plane-parallel plates of the PZT piezoceramics. One side of each plate was covered with an aluminum film with a gap in the center 2 mm wide, i.e. both halves of the coating served as electrodes. The

* Corresponding author at: Kotel'nikov Institute of Radio Engineering and Electronics of RAS, Saratov Branch, Zelyonaya str., 38, Saratov 410019, Russia.
E-mail address: zai-boris@yandex.ru (B.D. Zaitsev).

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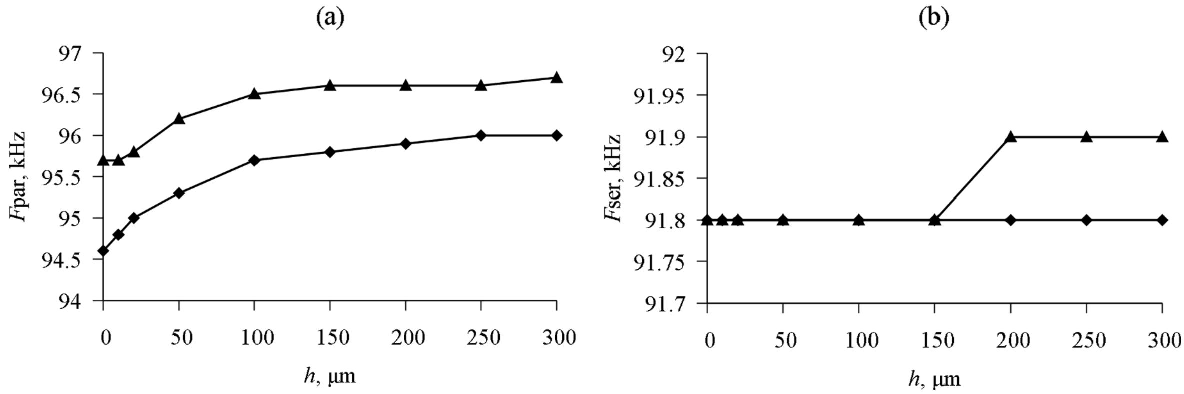

Fig. 1. Experimental dependences of the frequency of parallel (a) and serial (b) resonances on the width of the gap *h* for resonance near the frequency of 96 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

polar axis of the piezoelectric plate was oriented perpendicular to the gap between the electrodes along a shear dimension of 18 mm. The resonator was connected to the LCR parameter meter 4285A (Agilent, USA) and the frequency dependences of the real and imaginary parts of the electrical impedance and admittance were measured in the ranges 75–150 kHz and 200–500 kHz. The presence of two resonances near frequencies ~96 and ~260 kHz was found for both resonators. To ensure a specified gap between the free side of the resonator and a glass plate with an aluminum film, a micrometric device was used, which allows to set the width of the gap with an accuracy of 10 µm [10,11]. The frequency dependences of the real and imaginary parts of the electrical impedance of the resonators were measured in the above frequency ranges for different values of the width of the gap between the resonator and the aluminum film. The frequencies of parallel and series resonances, as well as the maximum values of the real parts of impedance and admittance, were determined from these dependencies.

Figs. 1–4 show the measured dependences of the frequencies of the parallel and serial resonances, as well as the maximum values of the real parts of electrical impedance and admittance on the width of the gap near frequencies 96 kHz and 260 kHz for resonator No. 1 and resonator No. 2 with thicknesses of 3.56 and 4.46 mm, respectively. It can be seen from Fig. 1 that the frequency of the parallel resonance F_{par} increases with increasing width of the gap width *h* and reaches saturation (Fig. 1a). In this case, the frequency of the series resonance F_{ser} remains almost constant (Fig. 1b). Fig. 2 shows the dependences of the maximum value of the real part of the electrical impedance R_{max} (a) and the admittance G_{max} (b) on the gap width *h* for the resonators under consideration. It can be seen that with an increase in the width of the gap, the indicated values monotonously increase and reach saturation. In this case, the main change in R_{max} and G_{max} is observed when the gap width varies from 10 to 100 µm. Table 1 presents the experimental relative changes of F_{par}, F_{ser}, R_{max}, and G_{max} with a change in the gap width from 300 to 10 µm.

Figs. 3 and 4 show similar dependences for the second resonance near 260 kHz, which are of a similar nature excluding the value of G_{max}, which practically does not depend on the width of the gap *h*. Table 2 presents the experimental relative changes of F_{par}, F_{ser}, R_{max}, and G_{max} with a change in the width of the gap from 300 µm to 10.

From Tables 1 and 2, it can be concluded that with decreasing resonator thickness, its sensitivity to the presence of a conducting film increases for both resonances. This means that with a decrease in the thickness of the resonator plate, the coefficient of electromechanical coupling K^2 increases. This can be confirmed by the Table 3, which shows K^2 for all values of the resonant frequency and the thickness of the resonator. The measurement of series (F_{ser}) and parallel (F_{par}) resonant frequencies had allowed us to find an effective electromechanical coupling coefficient K^2 using the known formula [14]:

$$K^2 = (\pi/2)^2(F_{par} - F_{ser})/F_{ser}. \quad (1)$$

3. Results of the theoretical analysis

A theoretical analysis of the effect of a metal film on the characteristics of a resonator with a lateral electric field based on PZT piezoceramics was also carried out. Using the finite element method, two resonators were analyzed for which the geometrical dimensions and geometry of the electrodes in the plane “polar axis – normal to the plate” corresponded to the experimental samples. Along an axis perpendicular to this plane, the structure was considered to be unlimited. We have found the distribution of the components of the mechanical displacement inside the piezoplates, as well as the electric potential inside the piezoplates and in the surrounding vacuum. The analysis

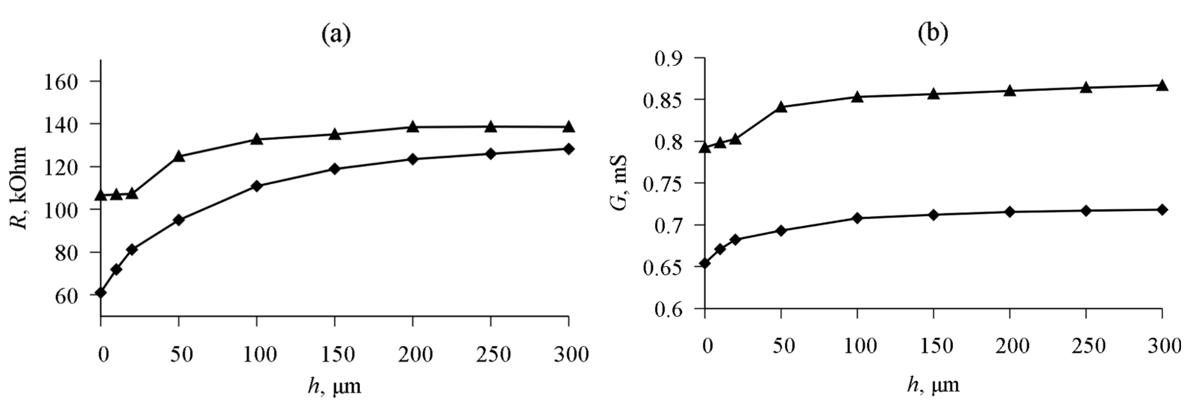

Fig. 2. Experimental dependences of the maximum values of the real part of the electrical impedance (a) and admittance (b) on the width of the gap *h* for a resonance near the frequency of 96 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

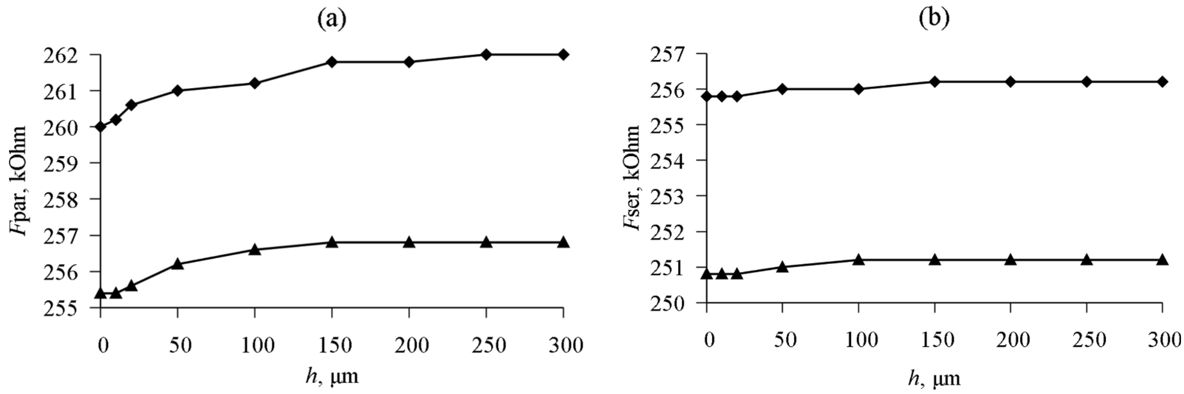

Fig. 3. Experimental dependences of the frequencies of parallel (a) and serial (b) resonances on the width of the gap *h* for a resonance near a frequency of 260 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

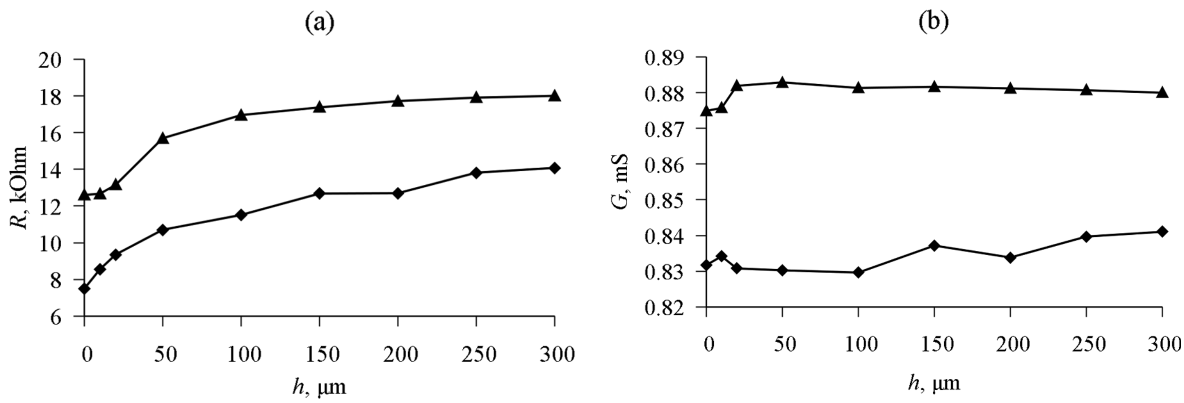

Fig. 4. Experimental dependences of the maximum values of the real part of the electrical impedance (a) and admittance (b) on the width of the gap *h* for a resonance near a frequency of 260 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

Table 1
Experimental and theoretical values of the relative change of F_{par}, F_{ser}, R_{max}, and G_{max} with a change in the width of the gap from 300 to 10 µm for the first resonance (~96 kHz).

	$\Delta F_{par}/F_{par}$, %	$\Delta F_{ser}/F_{ser}$, %	$\Delta R_{max}/R_{max}$, %	$\Delta G_{max}/G_{max}$, %
Resonator No. 1, experiment	1.5	0.1	52	8.9
Resonator No. 1, theory	8.9	1.3	96	72
Resonator No. 2, experiment	1	0.1	23	8.6
Resonator No. 2, theory	9.4	1.8	93	71

Table 2
Experimental and theoretical values of the relative change of F_{par}, F_{ser}, R_{max}, and G_{max} with a change in the width of the gap from 300 to 10 µm for the second resonance (~260 kHz).

	$\Delta F_{par}/F_{par}$, %	$\Delta F_{ser}/F_{ser}$, %	$\Delta R_{max}/R_{max}$, %	$\Delta G_{max}/G_{max}$, %
Resonator No. 1 experiment	0.7	0.16	46.7	1
Resonator No. 1 theory	2.3	3.2	44.5	2.4
Resonator No. 2 experiment	0.5	0.16	30	0.6
Resonator No. 2 theory	4.4	4.3	24.5	6.2

Table 3
Experimental values of the electromechanical coupling coefficients for both resonators and resonances.

Thickness of resonator, mm	F_{par}, kHz	K^2, %
3.56	~96	11.7
4.46	~96	11
3.56	~260	5.5
4.46	~260	4.8

showed that the electric field penetrates in the vacuum on a depth substantially smaller than the thickness of the resonator. Then the situation was analyzed when a metal plane with a zero electric potential was located at the some distance near the free surface of the resonator. The characteristics of the parallel and series resonances were studied for two types of plate oscillations with a change in the gap width from 0 to 300 µm. The calculation results are presented in Figs. 5–8. The theoretical results obtained for the two plate thickness values (3.56 and 4.46 mm) qualitatively correspond with the experimental results. As the gap width increases, the resonance frequencies F_{par} and F_{ser}, as well as

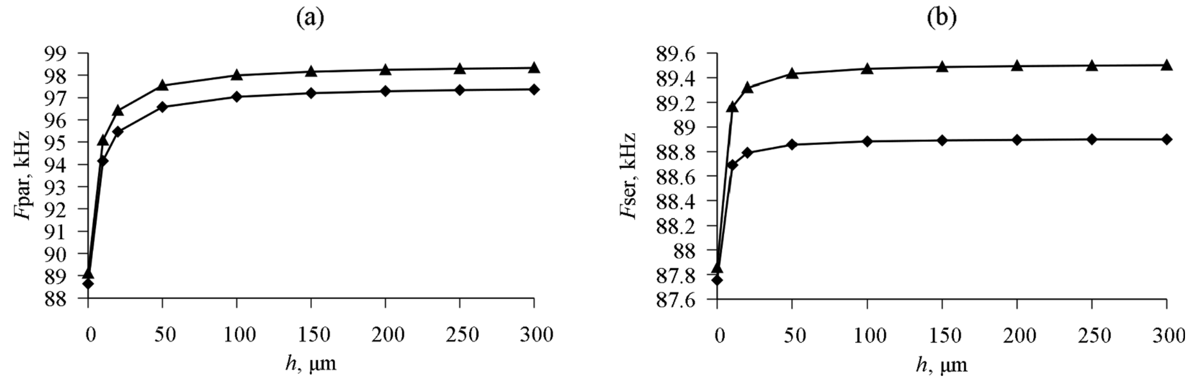

Fig. 5. Theoretical dependences of the frequency of parallel (a) and serial (b) resonances on the width of the gap *h* for resonance near the frequency of 96 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

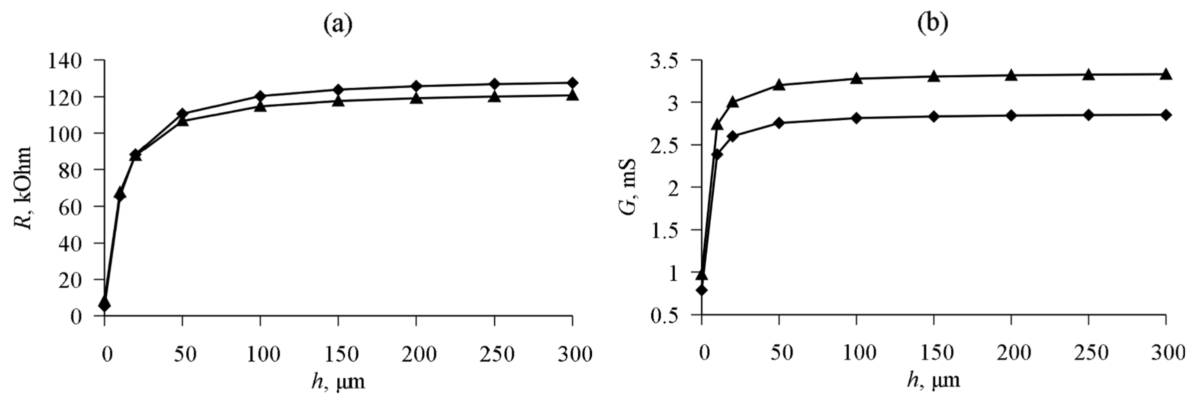

Fig. 6. Theoretical dependences of the maximum values of the real part of the electrical impedance (a) and admittance (b) on the width of the gap *h* for a resonance near the frequency of 96 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

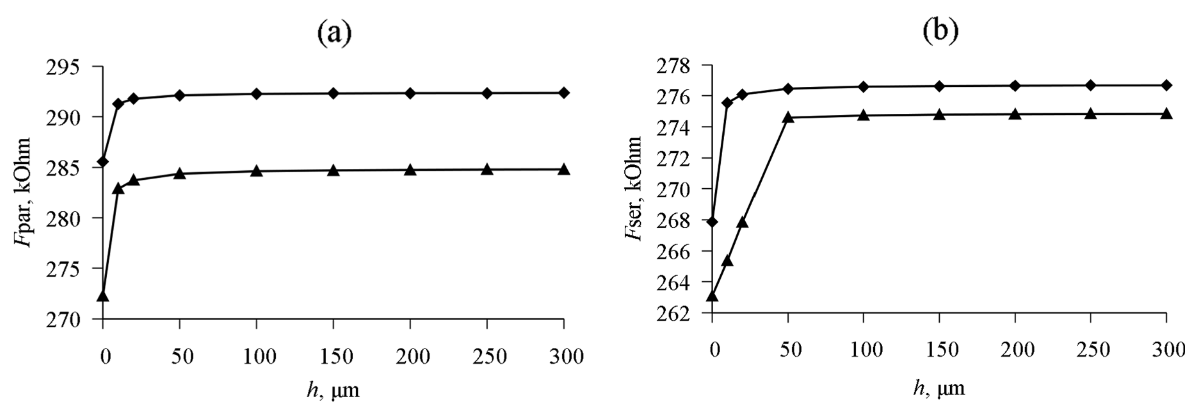

Fig. 7. Theoretical dependences of the frequency of parallel (a) and serial (b) resonances on the width of the gap *h* for a resonance near the frequency of 260 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

the value R_{max} monotonously increase and reach saturation for both resonances near ~96 and ~260 kHz. In this case, the largest change in these values corresponds to the interval of 0–100 μm. For resonance near ~96 kHz, the value of G_{max} monotonically increases with increasing gap and also reaches saturation. But for resonance near ~260 kHz, the value of G_{max} in the interval from 0 to 20 μm undergoes a certain jump, after which it slightly changes (Fig. 8b). The nature of this jump is not clear from a physical point of view. Most likely, this is a program effect associated with the commensurability of the gap width with the size of the finite element of the method used. The theoretical values of the relative changes in F_{par}, F_{ser}, R_{max}, and G_{max} with a change in the gap width from 300 μm to 0 are presented in Tables 1 and 2 for the resonant frequencies ~96 and ~260 kHz.

4. Comparison of the theoretical and experimental results

Comparison of the results of a theoretical and experimental study of the influence of a thin metal film located near a piezoelectric resonator with a lateral electric field based on PZT piezoceramics showed their qualitative correspondence each other. It is established that with increasing width of the gap between the free side of the resonator and the substrate with a metal film, the frequencies of parallel and series resonances, as well as the maximum values of electrical impedance and admittance, monotonously increase and tend to saturation. It has been shown theoretically and experimentally that with decreasing thickness of the piezoelectric plate, the sensitivity of the resonator to the presence of a metal film increases.

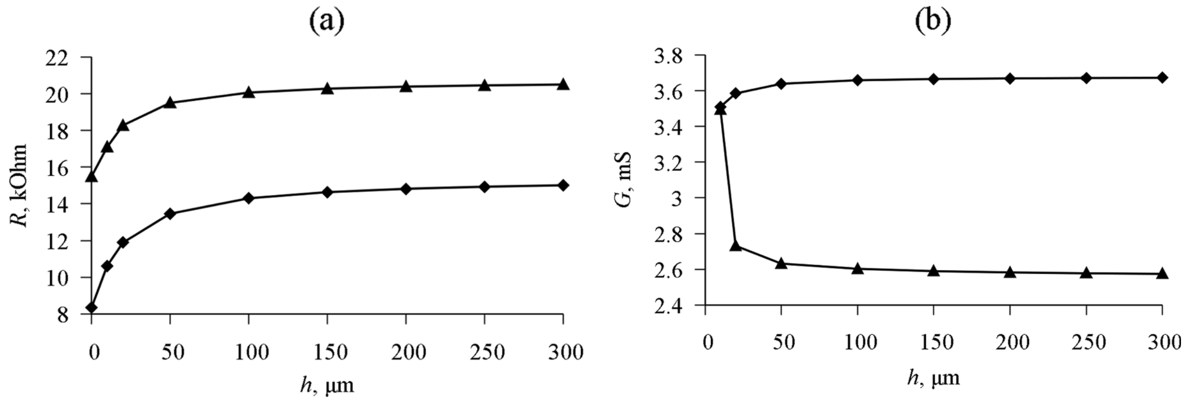

Fig. 8. Theoretical dependences of the maximum values of the real part of the electrical impedance (a) and admittance (b) on the width of the gap *h* for a resonance near a frequency of 260 kHz. Rhombus and triangles refer to resonators with a thickness of 3.56 and 4.46 mm.

However, theoretical and experimental results differ. The discrepancy between these data is due to the following factors. First, a simplified two-dimensional resonator model was used in the theoretical analysis. Secondly, the material constant of piezoceramics [8,13] used in the calculation may differ from their real values. Thirdly, the discrepancy between the experimental and theoretical data is also due to the fact that in the experiment it was impossible to maintain an ideal plane-parallel gap between the side of the resonator and the film.

5. Conclusion

The effect of a thin metal film located near a piezoelectric resonator with a lateral electric field based on PZT piezoceramics on its characteristics was studied theoretically and experimentally. It is shown that with increasing width of the gap between the free side of the resonator and the substrate with a conductive metal film, the frequencies of parallel and series resonances, as well as the maximum values of electrical impedance and admittance monotonously increase and tend to saturation. It has been established that with a decrease in the thickness of the piezoelectric plate, the sensitivity of the resonator to the presence of a conducting film increases. The relative changes in the resonant frequency and real part of the impedance on this frequency were ~1% and 30–50%, respectively, with a change in the gap width in the range of 0–300 µm. Frequency of series resonance changed only by 0.1%. Experimental results qualitatively correspond to theoretical data. The results of this work can be used to create contactless micro-displacement meters in the range of 10–300 µm with high accuracy due to significant change in the real part of the impedance on the resonant frequency. Previously the results of [10] have shown the possibility of the development of a contactless displacement sensor in the range of 0.2–2 mm based on the lithium niobate resonator. As a whole, such sensors can be used for continuous monitoring of deformations and cracks in buildings, bridges and other constructions in wide range and as motion sensors.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ultras.2019.105973.

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