Numerical Model of Piezoelectric Lateral Electric Field Excited Resonator as Basic Element of Acoustic Sensors

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Abstract —Nowadays, piezoelectric lateral electric field excited resonators are frequently used for development of various acoustic sensors. But, the adequate theory of such resonators is absent. In this paper, the numerical method of calculation of characteristics of the acoustic oscillations in the piezoelectric lateral electric field excited resonators is developed. The developed method is based on the finite element analysis and allows computing the distribution of the components of the mechanical displacement in the piezoelectric plate and electric potential in the piezoelectric plate and surrounding vacuum at arbitrary frequency of the exciting field. This method allows setting various boundary conditions on various parts of a plate surface, including a condition of mechanical damping of oscillations. This allows calculating the frequency dependence of the real and imaginary parts of the electrical impedance/admittance of the resonator. We analyzed a piezoelectric lateral electric field excited resonator, which is based on a 0.5 mm-thick X-cut lithium niobate plate. Two infinitesimally thin metallic electrodes with width of 5 mm were deposited on top side of the plate. The electrodes were deposited in such a way that the lateral field was oriented along the crystallographic Y-axis. Calculations of electric impedance were carried out for various values of a gap in range 1 - 3 mm between electrodes. These results are in quantitative agreement with experimental data. A brief description of experimental set up is also presented.

Keywords - acoustic resonator; lateral exciting field; finite element analysis; lithium niobate;

I. INTRODUCTION

At present time researchers pay particular attention to the piezoelectric lateral electric field excited resonators because of development of various acoustoelectrical sensors. One of the main problems of the design of such devices is the suppression of undesirable acoustic oscillations and ensuring a high Q-factor of the resonator. Currently, this problem is solved experimentally [1][2] by selection the optimal shape of the electrodes and choosing the area of coverage of the damping coating. However, this process requires a creation of a large amount of experimental samples. Researchers can theoretically estimate the efficiency of such resonators using the Christoffel - Bechmann method, which allows computing the electromechanical coupling coefficient for bulk waves excited by a lateral electric field [3][4]. However, this method does not take into account the finite aperture of the excited waves. Therefore, the problem of more accurate theoretical calculation of characteristics and efficiency of such resonators is considered as urgent.

In this paper, we developed a method for calculating the acoustic oscillations and the accompanying electric field in resonator representing a thin plate of a piezoelectric material with two rectangular electrodes on one side. The developed method is based on the finite element analysis and allows us to find the distribution of components of the mechanical displacement in the piezoelectric plate and electric potential in the piezoelectric plate and its surrounding vacuum at a certain oscillation frequency of the exciting field. This method takes into account the different boundary conditions on different areas of the resonator surface, and in particular, the mechanical damping of the parasitic oscillations, which was used in the [1][2].

In Section II, we give the description of the numerical model of resonator. In Section III, we describe the experimental set up. In Section IV, we make the comparison of theoretical and experimental frequency dependencies of real and imaginary parts of electrical impedance of lateral electric field excited resonator. Finally, Section V presents the conclusions and the future research.

II. THE DESCRIPTION OF NUMERICAL MODEL

In this paper, we consider a piezoelectric plate limited in x and y directions (Figure 1). There are different boundary conditions on different parts of plate surface. Value of time-varying electric potential is given on an infinitely thin electrodes $e1$ and $e2$. The gap between electrodes is G. Special mechanical boundary conditions are specified on areas $d1$ and $d2$. The rest of plate surface is assumed mechanically and electrically free. In the z direction, the plate and electrodes assumed to be unlimited.

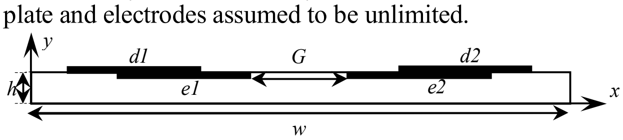

Figure 1. The geometry of the problem

So, we need to find a distribution of mechanical displacements within the plate, as well as the electric potential distribution inside the plate and in the surrounding vacuum. Exciting electric field varies according to harmonic law with a frequency of ω. Since there is no other sources of vibration excitation the solution must also be time-harmonic

 ISBN: 978-1-61208-375-9

with frequency ω. Thus, this problem may be represented as a system of differential equations [5]:

$$L(u_i, \varphi) - f = 0 \qquad (1)$$

where L is a differential operator, u_i is the mechanical displacement components, i=1..3 and φ is the electric potential. So, we need to find functions $u_i(x, y)$ and $\varphi(x, y)$, which satisfy (1). In this work this problem was solved by using the Galerkin's method [5]. For existence and uniqueness of the problem solution of (1), the boundary conditions must also be specified. As electrical boundary conditions, we used the given values of φ on the electrodes *e1* and *e2* and continuous of potential on the rest of boundary. The mechanical boundary conditions are more difficult to formulate properly. In our experiments with the resonator with a lateral field [1][2], the space around the electrodes and partly electrodes were covered with an absorbing varnish. This was done to suppress unwanted vibration modes of the plate and improve the quality of the resonator.

To take into account this fact in the theoretical model of the resonator, the mechanical boundary conditions were formulated as follows. On the surface of piezoelectric plates, except for regions *d1* and *d2*, the mechanical boundary condition is the absence of the normal components of the stress:

$$T_{ij} n_j = 0 . \qquad (2)$$

In regions *d1* and *d2*, where the damping coating was applied, the boundary condition is written as:

$$T_{ij} n_j = i\omega Z_{ij} u_j . \qquad (3)$$

Here, T_{ij} is the tensor of mechanical displacement of piezoelectric plate, n_j is the surface normal, ω is the oscillation frequency, Z_{ij} is the acoustic impedance of damping coating, u_j is the mechanical displacement. This boundary condition is obtained as a generalization of the well known relationship [6] from fluids to anisotropic solids

$$p = Zv . \qquad (4)$$

Here, p is the acoustic pressure, v is the oscillation velocity. When $Z_{ij} \to 0$, this condition becomes the condition of the free surface $T_{ij}n_j = 0$, while $Z_{ij} \to \infty$ this condition becomes the condition of rigidly fixed surface u_j=0. In the present case $Z_{ij} = Z\delta_{ij}$ where Z is the acoustic impedance of varnish.

III. THE DESCRIPTION OF EXPERIMENTAL SET UP

In order to compare the theoretical results with experimental data, the lateral electric field excited resonator on X-cut lithium niobate plate was made [2]. The scheme of this resonator is presented in Figure 2. The shear dimensions and thickness of plate were equal 18×18 mm^2 and 0.5 mm, respectively. Two 200 nm – thick aluminum rectangular electrodes with dimensions of 5×10 mm^2 were deposited on one side of the plate through a special mask in vacuum. The electrodes were deposited in such a way that the lateral field was oriented along the crystallographic Y-axis (Figure 2). This field component excited a longitudinal acoustic wave reflected between the plate sides with the largest electromechanical coupling coefficient [1]. The gap G between electrodes was equal to 1 mm. The area around the electrodes and part of electrodes with width of 3 mm were coated with a damping layer of absorbing varnish with thickness of about 0.2 mm.

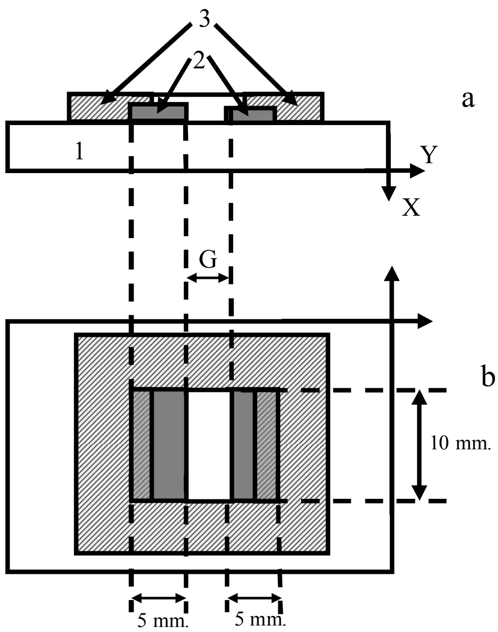

Figure 2. The side (a) and top (b) views of the resonator with the lateral exciting electric field: X – cut lithium niobate plate -1, electrodes -2, and absorbing coating - 3.

The frequency dependences of the real and imaginary parts of electric impedance of resonator were measured using the LCR meter (4285A, Agilent Technologies Inc.). These dependences for pointed above resonator are presented in Figure 4 by dashed lines.

IV. THE COMPARISON OF THE THEORETICAL AND EXPERIMENTAL RESULTS

In accordance with experiment, the calculation was performed for the case when the thickness h and width w of the plate were equal to 0.5 mm and 18 mm, respectively (Figure 1). On the upper surface of the plate, two electrodes *e1* and *e2* were deposited. The lateral electric field was oriented along the crystallographic Y-axis. The width of each electrode *e1* and *e2* was equal to 5mm with the gap G between them of 1 mm. The width of damping regions *d1* and *d2* was of 5 mm and the regions of overlap (*d1-e1*) and (*d2- e2*) were fixed to 3 mm.

Since the above-described method of calculation allows us to find the distribution of all variables and their derivatives for any given frequency, it was possible to build electrical impedance depending on the frequency of this resonator and compare them with experiment. So, we calculated the distribution of the acoustic field and the electric potential in the range f = 6-7 MHz. It is clearly seen in Figure 3 that the maximum amplitude of the acoustic vibrations are located in the gap between the electrodes. These oscillations correspond to the longitudinal bulk acoustic wave propagating in the vertical direction between the boundaries of the plate. This wave is the cause of deep

 ISBN: 978-1-61208-375-9

resonance on frequency dependence of the electrical impedance [1][2] shown on Figure 4.

The theoretical value of the impedance is calculated in accordance with the formula:

$$Z = (\varphi_2 - \varphi_1) / J, \tag{5}$$

Here, $\varphi_2 - \varphi_1$ is the potential difference between electrodes, J is the displacement current:

$$J = \int_S \frac{\partial D}{\partial t} ds \tag{6}$$

This integral is taken over the both top and bottom surfaces of the electrode. The calculated frequency dependencies of real and imaginary parts of electrical impedance are presented by solid lines in Figure 4. The material constants of lithium niobate were taken from [7].

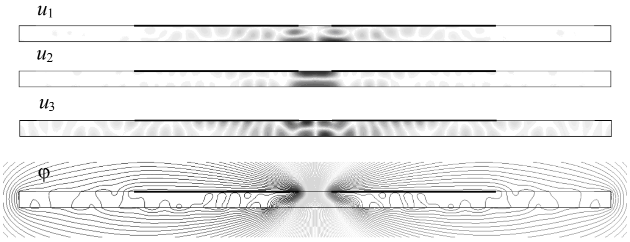

Figure 3. Distribution of the components of mechanical displacement and electric potential in resonator excited by electric field at frequency 6.55 MHz

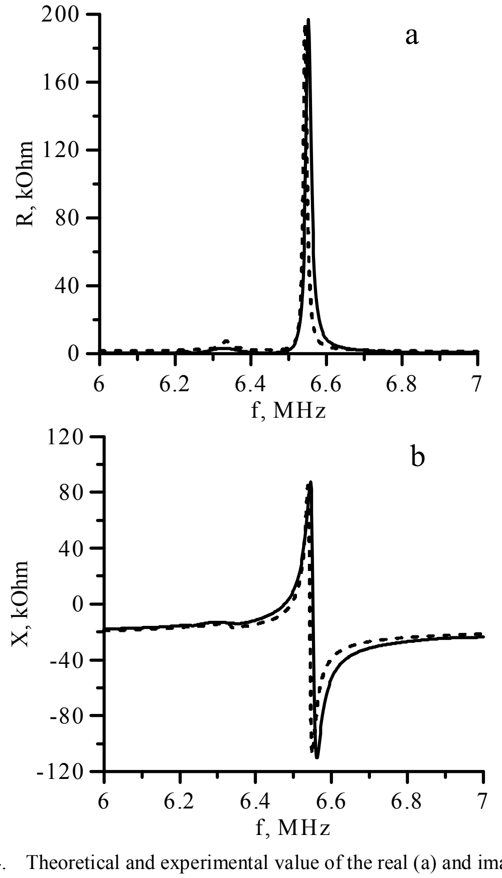

Figure 4. Theoretical and experimental value of the real (a) and imaginary (b) components of the electrical impedance of the resonator with a 1mm gap between the electrodes. Solid line is theory, dashed line is experiment.

One can see from Figure 4 that a good agreement exists between theoretical and experimental dependencies. Therefore, the difference between values of resonant frequency does not exceed 15 kHz. A slightly bigger distinction in absolute values of X is explained by the parasitic electric capacity of the device, which has not been considered in calculation. Moreover, the used material constants taken from [7] may differ from actual ones in the range ±5% (standard error for modern technology of crystal growing process).

V. Conclusion

The obtained results have shown the adequacy of the developed method for the characteristics calculation for resonators excited by a lateral electric field. These results will be used in future to develop sensors of fluid properties.

Acknowledgement

The work was financially supported by the grant of President of Russia MK-5551.2014.9 and the grant of Russian Foundation of the Basic Research 12-02-01057a.

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