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Distribution of the Surface Current Density in the Plate of a Quartz Resonator

Stanislav Prystupa
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
s.prystupa@lntu.edu.ua

Anatolii Tkachuk
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
a.tkachuk@lntu.edu.ua

Yosyp Selepyna
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
y.selepyna@lntu.edu.ua

Sergiy Moroz
Department of Electronics and Telecommunications Lutsk National Technical University
Lutsk, Ukraine
s.moroz@lntu.edu.ua

Ihor Vynnychenko
Taras Shevchenko National University of Kyiv
Kyiv, Ukraine
ingvar80@ukr.net

Oleg Zabolotnyi
Innovation Park Lutsk National Technical University
Lutsk, Ukraine
o.zabolotnyi@lntu.edu.ua

***Abstract* — The basis of most thermostated quartz oscillators is quartz resonators of two-turn cuts TD, SC, and AT. Resonators based on crystalline elements of these cuts, compared to resonators based on the most popular AT cut, have the main advantage – less influence of climatic and mechanical influences on the frequency, which explains their widespread use. At the same time, double-turn cut resonators have one significant drawback - insufficient mono-frequency, associated with a higher quality factor and low dynamic resistance of the side oscillation (mode B) compared to the main oscillation (mode C). Since the frequency of the secondary oscillation is only ~10% higher than the frequency of the main one, the oscillator circuit has to be complicated by introducing additional selective elements into it, mainly resonant circuits based on inductors. The purpose of the work is a theoretical study of the physical properties of the quartz element of the resonator, namely the calculation of the surface current density on the surface of the crystal element in different modes of oscillation. It has been established that the distributions of current densities over the surface of the piezoelectric element of the side mode B and the working mode C differ from each other and are asymmetrical relative to the center of the piezoelectric element.**

***Keywords* — generator, resonator, quartz, oscillation, mode**

I. INTRODUCTION

Oscillation generators are one of the main elements of many modern electronic devices and systems. The main requirements for them are high requirements for stability and reference frequency. At the same time, in modern radio engineering and electronics, generators must have small dimensions and mass, be high-frequency, and well as reliable, and resistant to various mechanical loads or vibrations [1, 2]. According to the functions performed by quartz generators, their use in modern radio technical devices takes first place to ensure the high reliability of quartz resonators. Several scientific and technical tasks during development, production, and operation are required to meet high-reliability requirements. Unification of the design and parameters of quartz resonators, mechanization of production processes, improvement of crystal manufacturing technology, and creation of perfect complexes of measuring and testing equipment are of great importance in this regard [3].

It is important to ensure the proper reliability of the operation of quartz resonators in devices and systems by choosing the correct scheme and observing the modes and conditions of their use. In addition to the well-known areas of application of quartz resonators, such as generators (heterodynes and calibrators of reference frequencies) and filters (rejector, bandpass), they are often used as high-precision sensors for pressure, acceleration, temperature. The use of quartz resonators makes it possible to obtain high-frequency stability with a simple design. Quartz resonators are used mainly at fixed frequencies, but in some cases, it is possible to control the frequency of quartz resonators in a certain range (with direct frequency modulation of quartz generators or with temperature compensation of the frequency) [4].

II. LITERATURE REVIEW

The operation of the quartz resonator is based on the piezoelectric effect that occurs on the quartz plate. Only low-temperature quartz, which has piezoelectric properties, is suitable for making resonators. Quartz is a polymorphic modification of silicon dioxide SiO_2 and occurs in nature in the form of crystals and pebbles. About 12% of quartz is free in the earth's crust, in addition, in the form of mixtures with other quartz minerals, more than 60% of quartz (mass fraction). Both natural and synthetic quartz crystals are used to manufacture resonators [5]. Optical and piezoelectric synthetic quartz is used in electronics, telecommunications devices, optics and telemetry, remote control, and automatic control systems, and radar and radio navigation equipment. To create the piezoelectric effect, the piezoelectric material is placed between two metal plates. To create an electric charge on the plates, a mechanical force should be applied. It is the application of mechanical forces to the metal plates that leads to the accumulation of electric charge on them. In this way, the piezoelectric effect acts as a mini-generator [6]. Quartz (silicon dioxide) is the most widely used natural piezoelectric material. A plate of low-temperature quartz is cut from the crystal in a certain way. It is the angle at which this plate is cut from the crystal that determines the electromechanical properties of the resonator. Then, by applying layers of nickel, platinum, gold, or silver, current-conducting electrodes are attached to this plate on both sides, to which conductors are attached [7]. The entire structure is placed in a small hermetic package (Fig. 1).

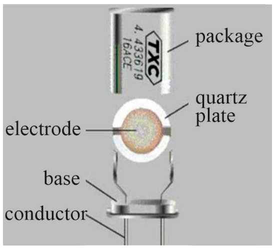


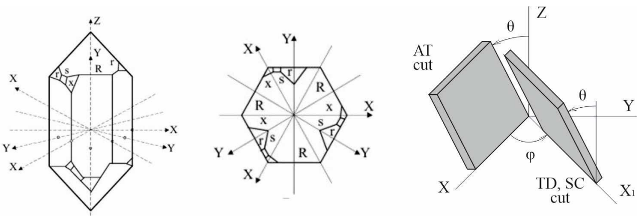
Fig. 1. Structure of a quartz resonator.

The parameters of the resonator depend on the type of cut: frequency, temperature stability, resistance to resonance, and the absence or presence of parasitic resonance frequencies, thus forming an oscillating system that has its resonance frequency [8].

If an alternating voltage of a given resonant frequency is applied to the metal electrodes of the plastic of the quartz resonator, resonance will occur, and the amplitude of the plate's harmonic oscillations will increase. At the same time, the resistance of the resonator is greatly reduced. A similar phenomenon is observed in a sequential oscillatory circuit. Due to the high Q-factor of these oscillations, the energy losses in the resonator when it is excited at the resonance frequency are insignificant.

III. Research Methodology

A quartz crystal is an anisotropic body, and its physical properties are different in different directions. To describe the physical properties of quartz in technology, a crystallographic coordinate system (Figure 2) is used, in the direction of which it has certain (characteristic for each axis) properties. For the manufacture of quartz resonators, piezo elements can be cut from a quartz crystal at different angles relative to the crystallographic axes. This orientation of the piezoelectric element is called a slice. There is a concept of initial orientations, when all faces of the piezo element are parallel to the crystallographic axes (Fig. 2a). Conventional designation of the initial orientation of the piezo element consists of two letters (*X*, *Y* or *Z*): the first indicates which axis parallel to the thickness of the piezoelectric element, the second - which of the axes is parallel to its length. By means of a series of consecutive rotations of the piezo element around its edges to different angles, it is possible to obtain a variety of orientations – oblique sections. Resonators of two-turn sections: TD-section and SC-section have gained application. The basis for their execution is the AT-section. TD and SC-sections differ by the angle φ of rotation counterclockwise around the crystallographic axis Z (Fig. 2b). Angle φ for section AT = 0°, for TD = 23°, for SC = 22°. The rotation angle around the crystallographic axis X is θ, which depends on the value of the thermostating temperature of 33.5...35.5°C.



a) b)

Fig. 2. Crystallographic axes of quartz a), example of a two-turn section of a quartz b) Source: [8].

The designation of the orientation of a piezo element with faces forming angles with crystallographic axes consists of the designation of the primary orientation, to which one, two, or three letters (*l*, *b*, *s*) are added, indicating which directions (along the length, thickness or width) the edges of the piezo element are used as the axes of the first and subsequent turns from the initial position orientation The angles of the first, second, and third turns of the piezo element around these axes are denoted by the letters α, β, and γ, respectively, which are placed through diagonal lines. The numbers that are placed instead of these letters show the magnitude of the rotation angles. The angle of rotation is considered positive if the rotation is counter-clockwise.

Here Z is the optical axis, which coincides with the longitudinal axis of the crystal. In this direction, the piezoelectric effect is not manifested, the electrical conductivity is higher than in the perpendicular direction, and there is no double refraction of the light beam. The X axis is electric, directed parallel to one of the faces of the prism, there are three X axes in the quartz crystal. In the direction of the X-axis, mechanical forces cause an intense generation of electrical charges. The Y axis is mechanical, directed perpendicular to the XZ plane, there are also three Y axes [8].

To obtain quartz resonators, piezoelectric elements (plates, bars) are cut from a quartz crystal at different angles relative to the crystallographic axes. This orientation of the piezoelectric element is called a slice. There is a concept of initial orientation – when all faces of the piezoelectric element are parallel to the crystallographic axes. The conventional designation of this initial orientation of the piezoelectric element consists of two letters (*X*, *Y*, or *Z*): the first indicates which axis is parallel to the thickness of the piezoelectric element, and the second - which of the axes is parallel to its length. By making several consecutive turns of the piezoelectric element around its edges to different angles, a large number of different orientations are obtained, which are called oblique sections [9].

The designation of the orientation of a piezoelectric element with faces forming angles with crystallographic axes consists of the designation of the primary orientation, to which one, two, or three letters (*l*, *b*, *s*) are added, indicating which directions (along the length, thickness or width) the edges of the piezoelectric element are used as the axes of the first and subsequent turns from the position of the initial orientation. The angles of the first, second, and third turns of the piezoelectric element around the axes are denoted by the letters α, β, and γ, respectively, which are placed through diagonal lines. The numbers that are placed instead of these letters show the magnitude of the rotation angles. The rotation angle is considered positive if the rotation is counter-clockwise [8, 10]. Each slice of quartz is characterized by a frequency coefficient N, which relates the resonant frequency f_q of the piezoelectric element to the dimension a, which determines the frequency, through the relation $N = f_q \cdot a$.

For some types of quartz resonators, the frequency factor N is determined by two dimensions of the piezoelectric element. The value of the coefficient N depends on both the physical properties and the orientation of the piezoelectric element. By the numerical value of the frequency coefficient, the frequency range of the piezoelectric element on certain sections is estimated, or, conversely, by the given frequency f_q of the resonator, the geometric size of the piezo element a can be determined. During longitudinal oscillations, the quantity that determines the frequency is the length of the piezo element. During oscillations of the form of thickness shift or contour shift, the size that determines the frequency is the thickness and the contour dimensions, respectively.

The lower limit of frequency range of any cut is limited by the possibility of using quartz resonators of large sizes and mechanical strength. The upper limit of the cut-off range depends on the level of production technology, which provides the possibility of creating piezo elements with sufficiently small dimensions to generate the appropriate frequencies. During a change in the frequency of stresses applied to the resonator, intense resonances are observed at frequencies close to the frequencies of the main oscillation and the frequencies of their overtones. These oscillations are called anharmonic overtones (angharmonics, parasitic oscillations). Their appearance is caused by the two-dimensional propagation of elastic waves and their interference with the emergence of standing waves. This is caused by reflection from the edges of the elastic element, the edges of the electrodes, and the fastening elements. Figure 3 shows examples of the distribution of the amplitudes of the shear modes of the thickness-shear oscillations of the TD-section quartz plate [8].

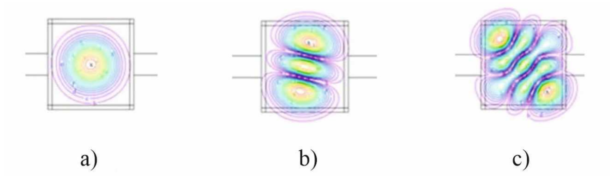


Fig. 3. Examples of the distribution of the amplitudes of shifts of the oscillation modes of the TD-cut quartz plate with the operating frequency at the third overtone: a – the third mechanical overtone Mode f311 = 10.10036 MHz; b – anharmonic Mode f313 = 10.30289 MHz; c – anharmonic Mode f333 = 10.52280 MHz [11].

The relative displacement amplitudes of parts of the piezo element surface (Fig. 4) are shown in the form of closed-level lines. In the center, the relative amplitudes are maximum. The following vibrations are used in piezoelectric resonators: compression-stretching along the length, width, and thickness; shift in thickness and width; bending in thickness and width; torsion along the length [8, 12]. The choice of longitudinal or transverse vibration modes depends on their Q-factor, thermal sensitivity, and stability. Overtones of high orders (3, 5, 7, 9) are used in quartz generators to obtain reference oscillations in the range of 30...200 MHz and higher.

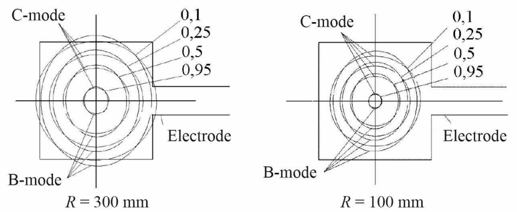


Fig. 4. The location of the amplitude levels of the displacements of the piezoelectric element surface particles for B-mode oscillations (f_b311) relative to C-mode (f_c311) in TD-section resonators according to the third mechanical harmonic with different radius of curvature of the surface R.

Mechanical vibrations of solid bodies, which are caused by the spread of elastic deformations of a certain type in them, are distinguished by the type of deformation: compression-tension, shear (shear vibrations), bending (bending vibrations), torsion (torsional vibrations). The first two are considered the simplest; bending and torsion are sometimes considered as special cases of inhomogeneous compressive-tensile and shear deformations, respectively. Compression-tension and shear waves can propagate both in an unlimited medium and bodies of limited forms. Waves of bending and torsion can exist and propagate only in a limited environment [13]. To achieve the goal, it is necessary to calculate the spectrum of oscillations and fields of surface current density of crystal elements of two-turn sections and conduct theoretical studies of these piezo elements [14, 15].

IV. Research Methodology

To describe the physical properties of the quartz element of the resonator, it is necessary to choose a convenient coordinate system X_1, X_2, and X_3 from the boundary conditions and symmetry of the crystal lattice. Next, it is necessary to select an elementary volume in the environment and consider the forces acting on the boundary of the selected cube [16]. This is a set of multidirectional forces applied to a unit of surface, or stress T_j (Fig. 5).

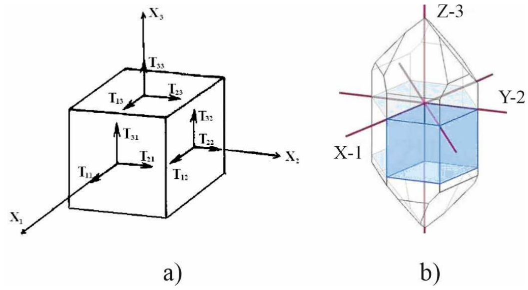


Fig. 5. Components of elastic stresses acting (a) on an elementary cube (b).

Inside a quartz elementary cube with sides parallel to the X, Y, and Z axes, each face is subject to a force that can be decomposed into three components. The indices denoting the direction along the axis will be denoted as X – 1, Y – 2, and Z – 3. Stress tensors are denoted by symbols T_{11}, T_{21}, T_{31}, T_{22}, T_{12}, T_{32}, T_{33}, T_{13}, T_{23}. Components T_{11}, T_{22}, and T_{33} correspond to tensile forces, the rest to shear forces. Since the stress is uniform and the body is in equilibrium, equal components act on the opposite faces. Therefore, $T_{12}=T_{21}$, $T_{13}=T_{31}$, $T_{23}=T_{32}$, respectively. Otherwise, shear moments will be created on the faces of the cube. Together, these components form the mechanical stress tensor [17].

Mechanical stresses in a quartz crystal are described by the mechanical stress tensor T_{ij}:

$$T = \begin{Vmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{Vmatrix} \tag{1}$$

Hooke's law for an anisotropic elastic medium in the absence of the piezo effect:

$$T_{ij} = c_{ijkl} r_{ki} \tag{2}$$

i, j, k, l = 1, 2, 3; T_{ij}, c_{ijkl}, r_{ki} – stress tensors, modulus of elasticity, and deformation, respectively.

The deformations in the crystal are described by the deformation tensor r:

$$r = \begin{Vmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{Vmatrix}, \tag{3}$$

r_{ki} – components of the strain tensor:

$$r_{kt} = \frac{1}{2}\left(\frac{\partial u_k}{\partial x_1} + \frac{\partial u_1}{\partial x_k}\right), \tag{4}$$

u_i – displacement components in the selected coordinate system.

Based on (2), the equality holds:

$$r_{\kappa l} = r_{lkn} \tag{5}$$

With such symmetry of the strain tensor, it is possible to switch from two-index notations to one-index ones:

$$\begin{cases} r_p = r_{kl},\ k = 1;\ p = k \\ r_p = 2r_{kl},\ k \neq 1;\ p = 9 - k - 1 \end{cases} \tag{6}$$

The set of elasticity constants (moduli) c_{ijkl} forms a tensor of the fourth rank. Based on the hypothesis that the use of offset electrodes can improve the monofrequency resonators. For this, the calculation of the surface current density on the surface of the quartz element without taking into account the electrodes was performed [18]. Let us consider the components of the vector of elimination of the standing wave of the thickness-shear oscillation:

$$u_i = A_i \cdot \sin(\omega \cdot t) \cdot \sin\left(\frac{n\pi}{h} \cdot y\right) \tag{7}$$

From (4), (6) and (7), we get the 6th component of the deformation vector:

$$\begin{cases} r_1 = 2\cdot\sin(\omega\cdot t)\cdot\sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_x}{\partial x}; \\ r_2 = 2\cdot\sin(\omega\cdot t)\cdot\left(\sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_y}{\partial y} + \frac{n\pi}{h}\cos\left(\frac{n\pi}{h}\cdot y\right)\cdot A_y\right); \\ r_3 = 2\cdot\sin(\omega\cdot t)\cdot\sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_z}{\partial z}; \\ r_4 = 2\cdot\sin(\omega\cdot t)\cdot\left(\sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_z}{\partial y} + \frac{n\pi}{h}\cos\left(\frac{n\pi}{h}\cdot y\right)\cdot A_y + \sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_y}{\partial z}\right); \\ r_5 = 2\cdot\sin(\omega\cdot t)\cdot\sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\left(\frac{\partial A_x}{\partial z} + \frac{\partial A_z}{\partial x}\right); \\ r_6 = 2\cdot\sin(\omega\cdot t)\cdot\left(\sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_x}{\partial y} + \frac{n\pi}{h}\cos\left(\frac{n\pi}{h}\cdot y\right)\cdot A_x + \sin\left(\frac{n\pi}{h}\cdot y\right)\cdot\frac{\partial A_y}{\partial z}\right). \end{cases} \tag{8}$$

Divergence of electric induction:

$$\frac{\partial D_i}{\partial x_i} = \varepsilon_{ik}\frac{\partial E_k}{\partial x_i} + e_{ip}\frac{\partial r_p}{\partial x_i} = 0 \tag{9}$$

To simplify the calculations, we will assume that term $\frac{\partial E_k}{\partial x_i}$ is not equal to 0, only $\frac{\partial E_2}{\partial y}$. If expression (9) is integrated over y, then the expression for the stress component E_2 will be equal to:

$$E_2 = -\frac{1}{\varepsilon_{22}}\int e_{ip}\frac{\partial r_p}{\partial x_i}dy - C_1. \tag{10}$$

The field strength, expressed in terms of potential, is equal to:

$$E_2 = -\frac{\partial \varphi_2}{\partial y}. \tag{11}$$

Since serial resonance is considered in the calculation, the potential difference on the two sides of the oscillating element is equal to 0. Thus, from (11) at plate thickness h, we obtain:

$$\int_{-h/2}^{h/2} E_2 dy = -\int_{-h/2}^{h/2}\left(\frac{1}{\varepsilon_{22}}\int e_{ip}\frac{\partial r_p}{\partial x_i}dy\right)dy - hC_1 = 0 \tag{12}$$

Substituting (10) (11) we get the value of C_1:

$$C_1 = \left(\begin{array}{l} \frac{2h}{\varepsilon_{22}n^2\pi^2}\left(\begin{array}{l}\frac{\partial^2(e_{11}A_x + e_{16}A_y + e_{15}A_z)}{\partial x^2} + \frac{\partial^2(e_{35}A_x + e_{34}A_y + e_{33}A_z)}{\partial z^2} + \\ \frac{\partial^2((e_{15}+e_{31})A_x + (e_{14}+e_{36})A_y + (e_{13}+e_{35})A_z)}{\partial x\partial z}\end{array}\right) \\ -\frac{e_{26}A_x + e_{22}A_y + e_{24}A_z}{h\varepsilon_{22}} \end{array}\right)\cdot\sin(\omega\cdot t) \tag{13}$$

In dielectrics, there is a bias current, the density of which is equal to:

$$J_2 = \frac{dD_2}{dt} = \frac{d(\varepsilon_{22}E_2 + e_{2p}r_p)}{dt} = \frac{d\left(-\int e_{ip}\frac{\partial r_p}{\partial x_i}dy - \varepsilon_{22}C_1 + e_{2p}r_p\right)}{dt} \tag{14}$$

Since the bias current will be present on the quartz surface, we will call it surface current. If we ungroup the multipliers before e_{ip}, we get the value of the surface current density:

$$J_i = \omega \cdot e_{ip} \cdot K_{ip} \tag{15}$$

The K_{ip} coefficients are integrated through the thickness of the components of the deformations, which take into account the distribution of the amplitude of mechanical shifts on the surface of the plate. Thus, it is possible to calculate the value of the current through the resonator:

$$I_e = \int_{S_e} JdS_e = \omega_0\int_{S_e}(e_{ip}K_{ip})dS_e \tag{16}$$

Based on formulas (15) and (16), the surface current density on the surface of the quartz piezo element was calculated for modes B and C. The FlexPDE software was used to calculate the surface current density. It is a flexible software system for obtaining numerical solutions of individual or related sets of partial differential equations in one, two, or three dimensions plus time constraints. The result of the calculation is shown in Figure 6.

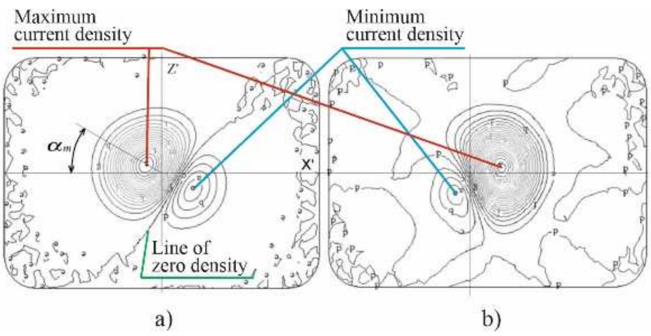


Fig. 6. Surface current density on the surface of the crystal element for mode C (a) and mode B (b) of a TD-section piezo element with a radius of curvature of 100 mm.

Figure 6 shows the difference in the distribution of the surface current density on the same side of the piezo element for modes B and C, and the point of the maximum and minimum value of the surface density is also noted. The surface current density on the front and back sides of the TD-cut plate with a radius of curvature of 300 mm operating on the third mechanical harmonic and the surface current density of other designs of crystal elements were also calculated (Table 1).

TABLE I. RESULTS OF CALCULATING THE SURFACE CURRENT DENSITY OF A QUARTZ ELEMENT

Results of calculating the surface current density of a quartz element	**Maximum current density J_{max}**	**Distance from the center of the quartz element to J_{max}, mm**	**The distance from J_{max} to the zero line of the current density, mm**	**Displacement relative to the X axis, angle $\alpha°$**	**Displacement relative to the Y axis, angle $\beta°$**	**The diameter of the element's active zone**
TD R=300mm Mode B	$-0.31 \cdot J_{max}$	0.93	1.63	27	64	5.41
TD R=300mm Mode C	$-0.18 \cdot J_{max}$	0.69	1.60	27	69	4.76

The calculation results (Fig. 6) showed the current density displacement relative to the plate's center and the presence of regions of positive and negative values. The magnitude of the displacement from the center of the plate increases with the increase in the order of the mechanical harmonic and the increase in the angle of rotation around the crystallographic axis Z. The increase in the harmonic number and the decrease in the radius of curvature lead to an increase in the area with the value of the current density of the opposite sign on each side of the quartz element.

V. CONCLUSIONS

For a theoretical study of the properties and parameters of a quartz resonator, a mathematical model of a quartz element is considered. The basis of such a model is the strain tensor, which is formed for the elementary volume of the quartz element. Its description requires 6 independent components. Using the methods of differentiation and integration, it is possible to determine the field strength for the elementary volume and the value of the current passing through the resonator. The calculation results showed that the nature of the surface current density distribution on the back of the piezo element is symmetrical with respect to its geometric center and has the opposite sign. When working on the fifth and third harmonics, there is a noticeable effect of the asymmetry of the surface current density distribution on the lens oscillating elements of the TD, SC, AT sections. It was established that the location of the point of maximum surface density, the line of zero current density, the sizes of positive and negative areas of surface density, and their levels depend on the shape of the quartz element, the harmonic number, and the cut angle. It can also be noted that the radius of curvature of the KE has little effect on the angle α_t. The location of the point of maximum surface density, the line of zero current density, the sizes of positive and negative areas of surface density, and their levels depend on the shape of the quartz element, the harmonic number, and the cut angle. The analysis of the results of mathematical modeling of the oscillations of crystal elements of different mechanical harmonics, crystallographic orientations, and shapes showed that the distribution of the surface current density has a displacement from the center of the piezo element, which increases with an increase in the order of mechanical harmonics and an increase in the angle of rotation around the crystallographic axis Z.

Based on the research conducted, the principles of spatial selection of oscillations based on the coherence of the shapes and locations of the electrodes in the current density fields are planned to be developed.

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