DUAL-MODE QUARTZ RESONATORS SUITABLE FOR TCXO AND OCXO

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Abstract

One of the reasons of TCXO and OCXO thermal frequency instability is existence of thermal gradient between resonator and temperature sensor. Piezoelectric crystal plate and thermo sensor companioning is very difficult technical problem because sensor must be placed in resonator area where amplitude of oscillation is maximal. Only in this case we will have properly information about «own mode» temperature. Unfortunately placing of any external sensor at this surface area will lead to dramatically Q-factor worsening and practically unexercised.

Some years ago the «self temperature sensing» technology based on dual mode excitation using were proposed. This technology have in mind using of simultaneous excitation of «B» and «C» modes or 1-st and 3-rd mechanical harmonic in SC-cut resonators. The second method have low temperature sensitivity and the first method have great one, but disadvantage because in majority of realization it may be obtained as called «activity dips» - oscillation decay at specific temperatures.

It is shown that the reason of B-mode activity dip is acoustic interaction of B-mode with C-mode inharmonic. The algebraic expression describes this phenomenon are shown. The numerically-analytical method of dual-mode resonator modeling is described. This method allows obtain modes parameters (motional resistance, modes frequencies, thermal time constants) as a function of plate sizes, electrode sizes and plate curvature.

The resonator which is not having activity dip of B-mode owing to influence inharmonic components of C-mode

Resonators SC and TD-cut, have suitable properties for creation OCXO on base dual-mode crystal oscillator. These resonators are characterized by the least force sense factor of frequency, the least temperature-dynamic factor of frequency, the most flat site temperature-frequency the characteristic of C-mode in the field of temperatures (70°C … 90°C), fast temperature response of B-mode (about 300 Hz / C° with in the field of temperatures 70°C … 90°C). However for use dual-mode excitation of resonators of a SC-cut the decision of some problems is necessary. One of which is instability of dynamic resistance of the B-mode.

The sharp changes of dynamic resistance of resonators and the corresponding variations of frequency with temperature are a long-standing problem which compels to cull a part of products and to carry out labour-intensive measurements. Many publications [1–4], are devoted to the given problem. These papers describe various mechanisms of activity dips. In the article [4] attempt to classify these mechanisms has been made. It is considered that disturbance of frequency characteristic and activity dips are mostly caused by mechanical communication of the working vibration and some other the vibration which happens to have the same frequency at certain temperature [3,4]. All these works are directed on maintenance of the reference oscillation excitation and on suppression of other modes and do not answer a question how to provide simultaneous stable excitation of two modes. It turned out, that simultaneous excitation the C-mode and the B-mode in an oscillator circuit makes a serious demand to stability of dynamic resistance of both modes. From the ratio of dynamic resistances magnitudes of modes depends a level of components in a spectrum of the oscillator output signal, character of excitation of oscillations (soft or rigid), and also the opportunity of excitation of two oscillations simultaneously.

The idea of application dual-mode excitation, with use of a temperature-sensitive B-mode as the gauge of temperature of the quartz resonator during generator operation, belongs to J. Kusters with co-authors [5,6]. In 1978 it had been tested on breadboard model of the OCXO. The control of a heater was exercised by a difference of frequencies of the B-mode and the C-mode. The measured temperature instability of the generator reached $4 \cdot 10^{-8}$ in an interval -20°C… +80°C, except for an interval between +10°C and +15°C. Unfortunately, the idea has not been developed further. One of the possible reasons could be a failure owing to activity dip of the B-mode. Experiments [7] have been made for research of activity dip. They have shown that the reason of sharp increase of dynamic resistance of temperature-sensitive B-mode for resonators SC and TD-cut in narrow temperature zones is acoustic interaction with inharmonic C-mode with high indexes. These inharmonic electrically are not are excited, and their influence is found out only in acoustic interaction with B-mode. Identification of interfering vibration has been made for ten resonators TD-cut (yxbl/23^{0}25′/34^0) with plano-convex quartz plates in the size 10x7 mm with the rounded off corners. For resonators with radius of sphere R_S=100mm the interfering vibration is f_{374}, for resonators with R_S=150mm – $f_{385.}$ [7]. The assumption has been made: a condition of existence interfering inharmonic (with frequency constant close to frequency constant of C-mode K_{fc}, and value of frequency close to frequency of B-mode) is existence of the corresponding size on thickness. The algebraic formula has been deduced from this assumption for calculation of design data of a plate of the resonator which is not having interfering inharmonic C-mode in the field of existence values of frequencies mode "B" [7]:

$$R_S \geq \frac{l^2}{8h_0(1-A)} + \frac{8h_0(1-A)}{2} \approx \frac{l^2}{8h_0(1-A)} \ , \tag{1}$$

where

A is the relation of frequency factors C-mode and B-mode $A=K_{fc}/K_{fb.}$,

l – length or diameter of a plate,

h_0 – thickness at the center of plano-convex plate of resonator.

Expression (1) has been checked up on 5 plano-convex resonators of a TD-cut of the rectangular form 10x7мм with the rounded off corners and 10 plano-convex resonators of a SC-cut of the round form in diameter of 10 mm both those and others with radius of sphere 300 мм. The specified resonators have been produced with application of already existing industrial equipment. The measurements have shown at all given resonators the stable monotonous characteristic of dynamic resistance B-mode in a working range of temperatures.

Modeling of thickness-shear vibration of quartz plate.

During search the reasons of instability of dynamic resistance B-mode there was a new task: identification of indexes of the most active excited inharmonic modes on experimental spectral characteristics. Given task has been solved by means of numerically-analytical model of thickness-shear vibration [8]. Next by means of enhanced model have been received new interesting results.

The problem of definition of own frequencies and distributions of amplitudes of mechanical displacement of particles, possible fluctuations in quartz plate is actual, difficult task and till now completely is not solved. The analytical methods of the decision developed Tiersten and Stevens [9], not always allow providing necessary accuracy of calculations because of the assumptions accepted in them. Besides, a values of some parameters included in the equations is defined with difficultly.

Attempts of numerical calculation of own frequencies of fluctuations [10] are known. But the grid of finite element method is enough rough. It often happens for multivariate problems at use usual memory sizes of personal computers. It is possible to combine the specified two approaches. The analytical formulas are applied for formation of the design equations which then will be solved numerical methods. From a three-dimensional task it is possible to pass to two-dimensional task, having set thickness of plate by the equation of a surface. The analysis of analytical expressions with use of decomposition in a mathematical row is made. Influence of members of row on an end result is investigated. Owing to this it is possible to construct numerically-analytical model of sufficient accuracy with acceptable time of calculation. The decision is made by a finite element method. At such approach to a problem, the grid of finite element method will be enough dense and that will allow to receive the decision with sufficient accuracy. The inaccuracy of calculations thus basically will be defined by adequacy of analytical model.

For construction and calculation of model it is necessary to choose corners of a cut of a quartz plate of the resonator; thickness of a plate in the center; temperature at which it is necessary to calculate frequencies of vibrations. To choose a material: natural quartz or it is artificially grown quartz and material constants corresponding them. For this purpose it is possible to take advantage of known data [11]. In consideration of temperature factors of the first, second, third orders for constants of elasticity, for thermal expansion, for density of quartz, in consideration of temperature factors for piezoelectric constants, for dielectric permeability have been calculated corresponding material constants and thickness in the center of plate for the chosen temperature. Then using methods of tensor algebra we shall transform components of tensor of material constants to rotated system of coordinates. [12,13]. This actions are being described in the program, for example in MathCAD environment. Then it is possible to do them repeatedly when it is changed temperature or angle of cutoff or thickness of a plate.

Let's consider one of possible variants of formation of analytical model. On fig. 1 the resonant standing wave (mode) is conditionally shown. It can be is formed addition of two running wave, in opposite directions:

$$\begin{aligned} U_{1y}(y,t) &= A_y Cos[w(t+y/v)] = A_y Cos(wt+xy) \\ U_{2y}(y,t) &= -A_y Cos[w(t-y/v)] = -A_y Cos(wt-xy) \end{aligned} \ . \tag{2}$$

Where A_y – amplitude of fluctuation of a falling wave, ω - circular frequency, v – speed of distribution of a wave in a plate, ξ – the wave factor, circular frequencies being by spatial analogue.

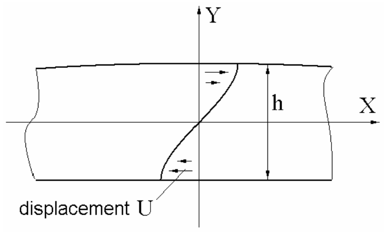


Fig. 1. The conditional image of fluctuations of shift on thickness in section of a plano-convex plate.

Thus, a standing wave:

$$U_y(y,t) = U_{1y}(y,t) + U_{2y}(y,t) = (-2A_y Sinwt)Sinxy \quad (3)$$

For the analysis of spatial amplitudes of displacement it is enough to write down expression in the form of:

$$U_y = A_{yn}\sin(xy),$$

where the maximal amplitude of displacement of particles of a quartz plate is equal

$$A_{yn} = \left|-2A_y Sin\left(\frac{np}{2}\right)\right|, \quad n = 1, 3, 5,\ldots$$

For the decision we shall use system of coordinates of piezoelectric crystal plate: axis X will be directed along length of a plate, axis Y – along its thickness, and axis Z – along width. We shall use standard numbering axes of coordinates at which axis X has number 1, Y – 2, and Z – 3. Let's designate amplitudes of components of displacement of particles of plate surface for an any point on surface of crystal plate through A_k (k = 1..3) (components of displacement), and thickness of a plate in the given point will be designated through h. We shall consider, that fluctuations submit to the sine wave law of distribution on thickness of a plate with node in median plane. Then it is possible to write down following relations for components of displacement of particles U_i:

$$U_i = A_i \sin(\xi_i\, y), \quad (4)$$

where $\xi_i = n\pi/h + \eta_i$, n – number of a harmonic, η_i – the unknown small additive to propagation constant (wave number) that necessary for maintenance of boundary conditions on a surface of the resonator.

At small changes of thickness $\eta_i y << 1$ on a surface of a plate (where $y = h/2$) it is possible to use the following assumption:

$$\sin(\xi_i h/2) \approx -(-1)^{(n+1)/2}, \ \cos(\xi_i h/2) \approx \eta_i(h/2)(-1)^{(n+1)/2}. \quad (5)$$

It is possible to neglect synchronous change of a sign in expressions (2) at change of number of a harmonic, and it is being written down in another view:

$$\sin(\xi_i h/2) \approx 1, \ \cos(\xi_i h/2) \approx -\eta_i h/2. \quad (6)$$

For each point of quartz plates six component of relative deformation is received: r_1=dx(Ux), r_2=dy(Uy), r_3=dz(Uz), r_4=dz(Uy)+dy(Uz), r_5=dx(Uz)+dz(Ux), r_6=dx(Uy)+dy(Ux). We shall apply a following designation: the symbols located in an index after a comma, designate a partial derivative of this size on corresponding coordinate, for example, for example dx(Uy)=$U_{2,1}$. Vector of deformations is being defined according to expressions:

$$\boldsymbol{r} = \{\ U_{1,1},\ -\eta_2,\ U_{3,3},\ U_{2,3}-\eta_3,\ U_{3,1}+U_{1,3},\ U_{2,1}-\eta_1\ \}^t. \quad (7)$$

Components of strain tensor are being defined by the formula: $T_p = \hat{C}_{pq} r_q$, where $\hat{C}_{pq}$ – tensor of effective factors of elasticity of quartz in system of coordinates of piezoelectric crystal plate (take into account piezoelectric effect).

Hereinafter at a designation of indexes the following rule of names is used: indexes with names i, j, k accept values from 1 up to 3, and indexes with names p, q accept values from 1 up to 6.

In view of these approximations, the basic equation of the form of fluctuations of mode along a surface for own frequencies of thickness-shift fluctuations is being written in the form:

$$T_{i1,1} + T_{i3,3} + \hat{C}_{pi2}\Lambda_p + \rho\omega^2 U_i = 0\ , \quad (8)$$

где ω – own frequency of mode, ρ – density of quartz, Λ – array (gradient of deformation), Take into account approximation (6), we shall write down expressions:

$$\Lambda = -\{\ \eta_{1,1},\ U_2(n\pi/h)^2,\ \eta_{3,3},\ \eta_{2,3} + U_3(n\pi/h)^2,\ \eta_{3,1} + \eta_{1,3},\ \eta_{2,1} + U_1(n\pi/h)^2\ \}^t. \quad (9)$$

The system of the equations (7) should be added by boundary conditions on a surface of the resonator:

$$T_{2i} = U_i\,\omega^2\, ms\ , \quad (10)$$

where ms – surface density of an covering electrode.

The equations (8) and (10) together with expressions (7) and (9) make system of 6 equations. The decision of this system in the modal analysis gives own frequencies of modes and distribution of amplitudes of displacements. The equation of a surface of the plano-convex resonator in view of possible ellipsoid forms is expressed through thickness in the center of a plate h_0, half-axles (radiuses) R_{SX}, R_{SY}, R_{SZ} and coordinates x and z:

$$h = h_0 - R_{SY}\left(1 - \sqrt{\left(1 - \left(\frac{x}{R_{SX}}\right)^2 - \left(\frac{z}{R_{SZ}}\right)^2\right)}\right). \tag{11}$$

The formula for calculation of dynamic resistance of modes through amplitudes of displacement is made, with use of expression for potential energy of the deformation carried to unit of volume. It is known, volumetric density of the potential energy is reserved during elastic deformation when Hooke law still is not broken. Energy of one layer with a thickness equal λ/4 is used. The number of layers with thickness λ/4 is equal two for the first mechanical overtone and for the subsequent overtones 2n. At transition to equivalent electric parameters of oscillatory system we shall take advantage of the equation for *Q-factor* and equation of equivalence of energy. The current through the resonant tank can be output through density of displacement current. In consideration of orthogonal components of displacement of corpuscles (A_i amplitudes of components of displacement of particles) also that *e* - a tensor of piezoelectric constants, we will finally write equation:

$$R = \frac{n\int_S rh\left(A_1^2 + A_2^2 + A_3^2\right)ds}{8Q\left(\int_{Se}\frac{1}{h}\left(e_{26}A_1 + e_{22}A_2 + e_{24}A_3\right)ds\right)^2} w_0 . \tag{12}$$

Expressions (7-12) data arrays of material constants and geometrical parameters of a quartz plate and electrodes are a ground of a tendered numerically-analytical model of thickness-shear modes of quartz bars. The model allows to determine eigenfrequencies of thickness-shear modes resonators, allows to learn influence of geometrical parameters, allows to demonstrate allocating of amplitudes of displacement of particles, allows to select optimally the form and the sizes of electrodes for modes of oscillations. Program FlexPDE was used for the decision of these equations.

Results are displayed in table 1 for two resonators with different radius of sphere. Frequencies and motional resistance were metered by means of the analyzer of parameters of electronic circuits “NETWORK ANALYZER 250B” with the software of company Saunders and Associates Inc. Value of h_0 (thickness at the center of plano-convex plate of resonator) was adjusted in breaking points ±0,3 % for model Measured meaning of Q-factor (for C-mode C311) is used for computation of dynamic resistance by means of expression (28) for all modes of each resonators. Value of Q-factor of C-mode C311 defines surface quality of a quartz bar. It is enough for a qualitative analysis of meanings of motional resistance of inharmonic modes.

Table 1. Results for comparison

№ Mode	Calculated Frequency, kHz	Index Mode	Calculated Motional Resistance, Om	Measured Frequency, kHz	Measured Motional Resistance, Om
	Resonator TD-cut (yxbl/23°25’/34°) R_S=100 mm и $Q_{C311} = 0.825\cdot10^6$				
1	10100,36	C311	198	10100,400	196,6
4	10302,89	C313	595	10295,724	636
6	10332,18	C331	778	10315,266	660
11	10494,9	C315	2913	10495,7646	1947
13	10522,63	C333	2088	10507,968	3795
	11057,9	B311	162	11004,88	132
	Resonator TD-cut (yxbl/23°25’/34°) R_S=300 mm и $Q_{C311} = 1,1\cdot10^6$				
1	9999,819	C311	103	9999,825	95,4
4	10117,93	C313	843	10118,502	587
6	10134,67	C331	1400	10136,598	4700
11	10229,93	C315	8797	10246,122	8146
	16624,83	C511	236	16633,880	288
	10947,05	B311	87	10904,67	56

It is visible that, calculated values of frequency have comparable accuracy versus measured values (table 1). Calculated motional resistance has adequate accuracy for research. The result of calculation of 18 own modes of oscillations for a plano-convex quartz bar of the TD-cut with radius of sphere R_S=100 mm on frequency f_{311}=10.1 MHz is shown (Fig. 2). Not all shown modes can be energized by supply of a signal with appropriate frequency. In particular, modes at which the even number of maxima is recoated by the square of electrodes will not be excited. Modes with the dynamic resistance above negative resistance of the connected oscillator will not be excited. But if frequency of a working mode appears close to frequency of one of such modes there can be an acoustical coupled oscillation with sorbtion of energy of working oscillation and increase in dynamic resistance.

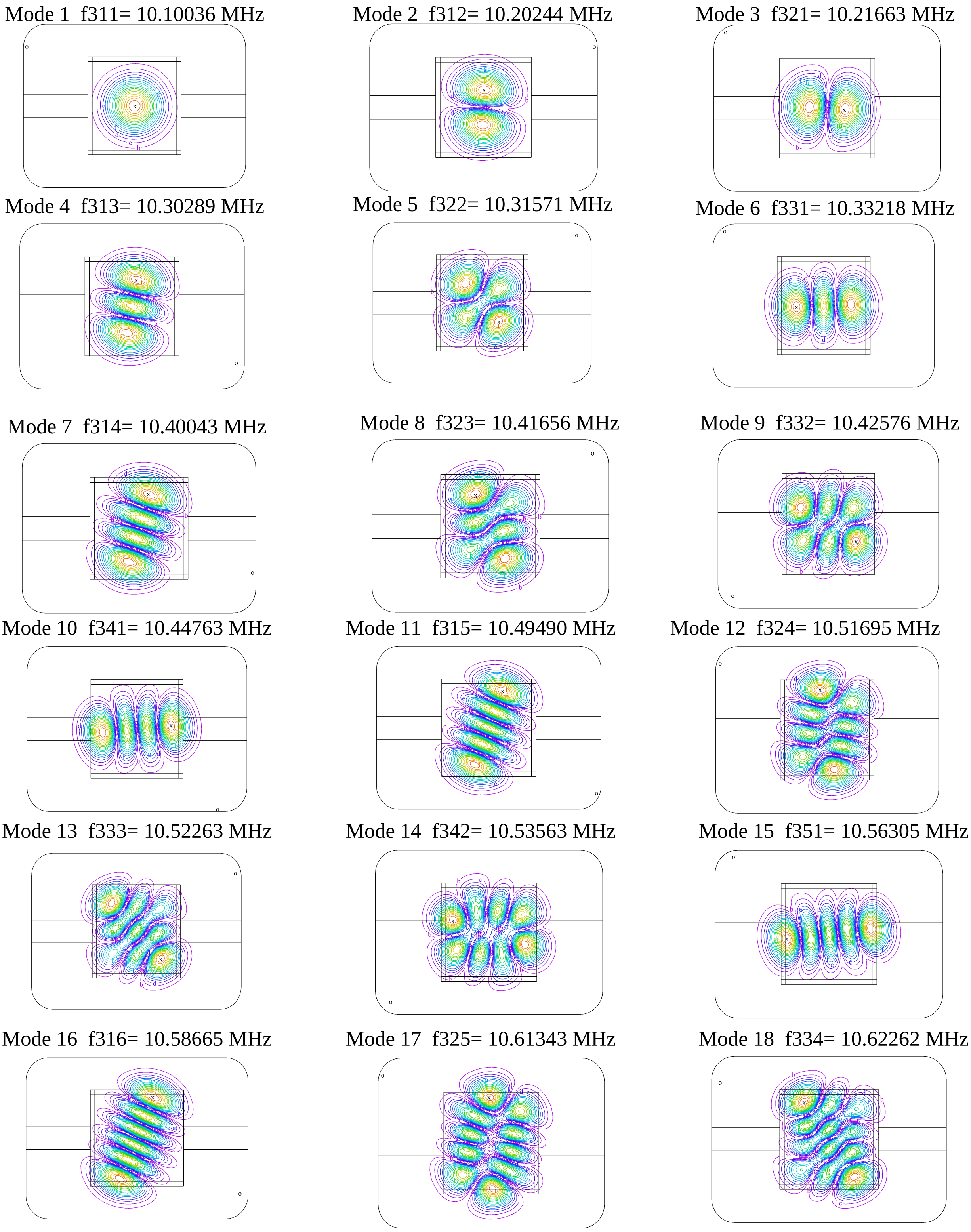


Fig. 2. Modes of thickness-shift oscillations of quartz bar TD-cut (1-18 modes).

The ideal spherical form of a quartz bar has $R_S=R_{SX}=R_{SY}=R_{SZ}$. Making an ideal sphere is difficultly. It is possible the surface to present by means of the equation эллипсоида (11). Influence of a deviation from sphericity of a surface on frequency and dynamic resistance was investigated by means of the presented model. Dependence of values of frequency and dependence of values of dynamic resistance for mode C333 are shown (Fig. 3, 4). Deviations of a size of a radius (semiaxisis) of ellipsoid in limits ± 5 % have been applied with an invariable thickness h_0 in the plate centre and invariable two other semiaxises R_S=100 mm.

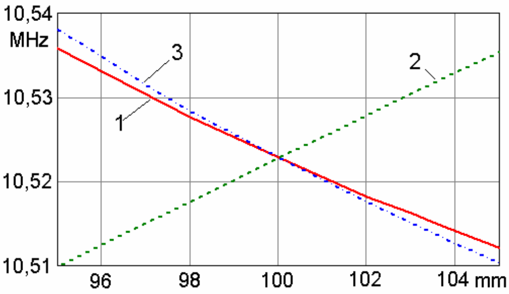


Fig. 3. The diagram of dependence of frequency of mode C333 from a deviation of sizes semiaxises of ellipsoid from sphere: 1 – via R_{SX}, 2 - via R_{SY}, 3 – via R_{SZ}

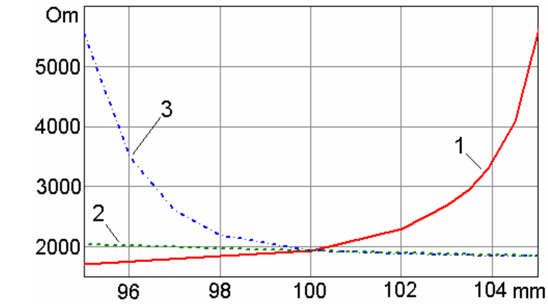
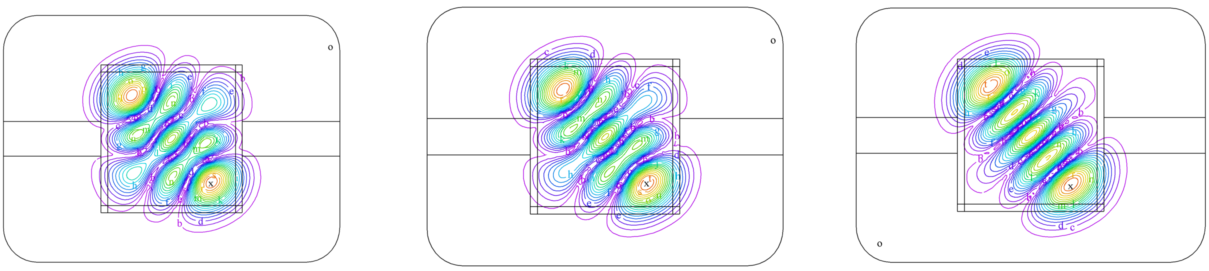


Fig. 4. The diagram of dependence of motional resistance of mode C333 from a deviation of sizes semiaxises of ellipsoid from sphere: 1 – via R_{SX}, 2 - via R_{SY}, 3 – via R_{SZ}

Distribution of displacement amplitudes of particles on the surface of crystal plate for mode C333 is shown by the Fig. 5. It is necessary to note that change of motional resistance of C-mode via radiuses of ellipsoid (in limits ± 5 %) are not exceeded by 1 % and frequency of C-mode on ± 180 ppm while frequency of mode C333 varies on ±1330 ppm (Fig. 3).



R_{SX}=98 mm R_{SX}=100 mm R_{SX}=102 mm

Fig. 5. Change of arrangements of lines of amplitudes of mode C333 via R_{SX} with an invariable thickness in the plate centre (h_0=const, $R_{SY}=R_{SZ}=R_S$=100 mm).

Distribution of displacement of particles of a surface of a plano-convex plate of the TD-cut with radius of sphere R_S=300 mm for vibrations of a basic C-mode and for vibrations thermosensitive B-mode is show on Fig. 6. Vibrations of a thickness-shift of thermosensitive B-mode are orthogonal to vibrations of basic C-mode (see a vector of displacement of particles of a quartz plate on Fig. 6). Calculation of distribution of displacement of particles has allowed to describe localization of the spatially-combined temperature gauge of the quartz resonator, constructed on thermosensitive B-mode, relative C-mode and with use of thermal model of the resonator to receive thermal transfer characteristic and thermal time constants of C-mode and B-mode depending on temperature of the resonator [14]. Distribution of temperatures to surfaces of TD-cut quartz plate in 8 seconds after jump of temperature on 1 °C in holder is shown (Fig. 7). It is made by means of thermal model of a quartz plate of the resonator [14].

The temperature of area of the quartz plate was calculated by the instrumentality of two models: model of own frequencies of thickness-shift vibrations and thermal model of quartz plate. This area influences on frequency of mode. Calculation of instant distributions of temperature was used for an estimation of size of a thermal time constant. Distinction of thermal time constants does not exceed 3 % for transducers of temperature on the basis of the B-mode and C-mode. Considerable dependence of size of a thermal time constants from resonator initial temperature is revealed.

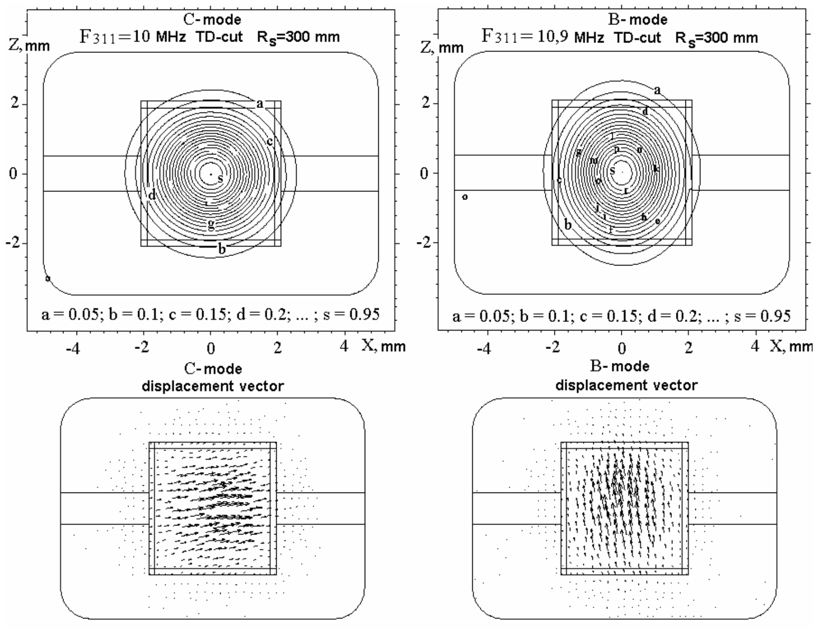


Fig. 6. Location of levels of amplitude of displacement of particles of a surface of quartz plate and vectors of displacement for vibrations C-mode and B-mode.

Change of size of a thermal time constants (τ) of quartz temperature-frequency transducers can reach two times and more at initial temperature of quartz plate -50°C and +100°C. It is made without the account of time of distribution of heat through holder of quartz plate. Exact value depends on the plate form (for example, round or rectangular) and a quartz cut. The analysis has shown that change τ from initial temperature of quartz plate is defined basically by dependence of a specific heat capacity of quartz and its heat conductivity from temperature.

The received result is necessary for considering at use of dynamic temperature compensation in quartz oscillators. The concept of thermal time constant of nonlinear temperature-frequency transducers strictly is not defined. On Fig. 8 the equivalent scheme of thermal model of the transducer is shown.

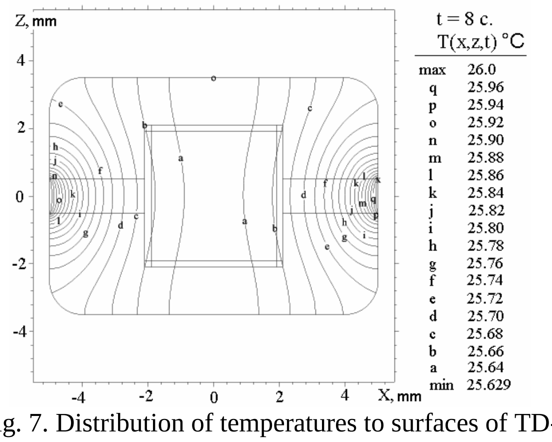
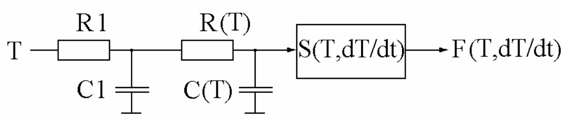


Fig. 7. Distribution of temperatures to surfaces of TD-cut quartz plate in 8 seconds after jump of temperature on 1 °C in holder.



T - temperature; R1C1 – thermal time constant of terminals, balloon and holder together; R(T)C(T) – thermal time constant of quartz plate; S(T,dT/dt) – temperature-frequency characteristic of the quartz transducer; F(T,dT/dt) – output frequency of the gauge.

Fig. 8. The equivalent scheme of thermal model of the quartz transducer.

The system effectiveness of compensation of a constructional heat error has been investigated on three-dimensional thermal model of OCXO. The compensation was carried out by means of the additional sensor of temperature on B-mode of resonator SC-cut. Modeling has shown improvement of static accuracy thermostating, has shown reduction of settling time of temperature of the resonator by 5-20 % in comparison with other schemes of temperature regulators without dynamic indemnification.

Conclusions

The results of research work:

- It is experimentally proved, that the reason of sharp increase of motional resistance on the frequency of B-mode in narrow temperature band is acoustic interaction of modes.
- Identification of interfering vibration is made. It inharmonic components of C-mode with a high index (for investigated resonators it f_{374} and f_{385} depending on radius of sphere of a plano-convex quartz plate).
- Conditions of existence of interfering vibration are determined. Algebraic expression to define the geometrical sizes of the resonator which is not having activity dip of B-mode owing to influence inharmonic components of C-mode is deduced.
- The resonators corresponding to this algebraic condition are made. These resonators have stable dynamic resistance in a wide range of temperatures.
- The presented Numerically-analytical calculation method in this article has approximately the same accuracy of calculations, as classical formula Tiersten, however unlike the analytical approach allows to consider influence of edges of crystal plate, has no restriction because of the form of electrodes and the law of change of thickness (at preservation condition of little these changes).
- This approach allows to receive results directly in a graphic view with any forms of crystal plate and electrodes. Model has allowed making the qualitative analysis of dynamic resistance of modes.

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