An exact solution of torsional quartz crystal resonators of free-free bar-type

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An exact solution of a partial differential equation including elastic compliance constant s_{56}' , with respect to stress function Ψ has been found for torsional modes of vibration of an arbitrary (singly, doubly, triply) rotated quartz crystal beam with a pair of parallel, free edges. The solution is obtained by relaxing the condition that the edge planes are perpendicular to the main faces of the beam. That is, the edges are off perpendicular by the angle $\theta = \arctan(-s_{56}'/s_{55}')$. The exact solution can reduce the difference of the calculated and measured values of frequency constant for a thickness-to-width ratio. Also, a comparatively large-inclination of the edge cuts is required to reduce the unwanted, complicated mode shapes to simple ones.

Keywords: Torsional vibration, Piezo-element, Supersonic wave, Free vibration, Exact solution, Quartz crystal, Frequency constant

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1. INTRODUCTION

Since a frequency constant of a resonator vibrating in torsion¹⁻³⁾ lies intermediately to those for flexural and length extensional mode resonators, it is very available for realization of miniature resonators of a comparatively low-frequency, *i.e.*, 400 to 600 kHz. In order that one of the authors clarifies frequency temperature behavior of doubly rotated torsional quartz crystal resonators of tuning fork-type which can be approximately regarded as a clamped-free bar, and free-free bar-type, a theoretical and/or experimental examination was performed in detail. As a result, we have already obtained and reported^{1,2)} that a cut angle (ϕ, θ) where gives the first order temperature coefficient $\alpha=0$ and approximately one third of the second order temperature coefficient β for flexural mode quartz crystal resonators, exists for the torsional quartz crystal resonator by combination of the cut angle (ϕ, θ) and a thickness-to-width ratio, the so called TT-Cut classified into the TT(X_1)- and

TT(X_2)-Cuts.

A vibration problem of torsion is equivalent to solving the problem of torsional rigidity C_t . In the previous report²⁾ C_t was derived from stress function Ψ . However, the obtained stress function Ψ is an approximate solution derived neglecting the elastic compliance constant which couples two shear stresses.

In this paper, an exact solution of torsional rigidity C_t for a torsional mode resonator is found and applied to quartz crystal. In analysis procedure, first, a frequency equation is, as already reported,¹⁻³⁾ found to be given as a function of torsional rigidity C_t . Next, a general strain-stress relation is transformed into a simple one from the conditions of resonator shape and dimensions, and from the equation of equilibrium a partial differential equation is derived with respect to stress function Ψ . In addition, the Ψ which satisfies the boundary conditions is derived and torsional rigidity C_t is calculated. Finally, the obtained result is applied to a quartz crystal resonator of free-free bar-type and is com-

pared with the measured ones of the quartz crystal resonator vibrating in torsion. Consequently, the calculated values taking account of s_{56}' are found to agree with the measured ones better than those neglecting s_{56}' .

2. ANALYSIS PROCEDURE

2.1 Frequency Equation

Figure 1 shows a resonator of a beam vibrating in torsion and its coordinate system. The resonator is expressed in the IEEE notation of (YXlt) ϕ/θ and has a dimension of length $2x_0$, width $2z_0$ and thickness $2y_0$. When length $2x_0$ is much larger than width $2z_0$ and thickness $2y_0$, lateral motion for a resonator vibrating in torsion can be neglected.⁴⁾ A resonant frequency f for a torsional resonator is, therefore, given as

$$f = \frac{m}{4(2x_0)} \sqrt{\frac{C_t}{\rho I_0}}, \quad (1)$$

where

- C_t : torsional rigidity
- ρ : density of beam
- I_0 : polar moment of inertia
- $2x_0$: length of beam
- m : even for free-free beam and odd for clamped-free beam.

As can be easily understood from Eq. (1), a vibration problem of torsion is equivalent to solving the problem of torsional rigidity C_t because I_0 is determined by the resonator shape of section.

2.2 Equations of Equilibrium

Now, when displacements in the x , y and z axes direction are taken as u , v and w , the displacements u , v , w can be expressed by

$$\begin{aligned} u &= \tau \Phi(y, z) \\ v &= -\tau xz \\ w &= \tau xy, \end{aligned} \quad (2)$$

where torsion function Φ is a function of y and z ,

Fig. 1 Torsional resonator of a beam and its coordinate system.

and τ is the twist. From the relation of Eq. (2), the strain-components vanish and are

$$S_1 = S_2 = S_3 = S_4 = 0. \quad (3)$$

A general strain-stress relation has the form

$$\begin{aligned} S_1 &= s_{11} T_1 + s_{12} T_2 + s_{13} T_3 + s_{14} T_4 + s_{15} T_5 + s_{16} T_6 \\ S_2 &= s_{21} T_1 + s_{22} T_2 + s_{23} T_3 + s_{24} T_4 + s_{25} T_5 + s_{26} T_6 \\ S_3 &= s_{31} T_1 + s_{32} T_2 + s_{33} T_3 + s_{34} T_4 + s_{35} T_5 + s_{36} T_6 \\ S_4 &= s_{41} T_1 + s_{42} T_2 + s_{43} T_3 + s_{44} T_4 + s_{45} T_5 + s_{46} T_6 \\ S_5 &= s_{51} T_1 + s_{52} T_2 + s_{53} T_3 + s_{54} T_4 + s_{55} T_5 + s_{56} T_6 \\ S_6 &= s_{61} T_1 + s_{62} T_2 + s_{63} T_3 + s_{64} T_4 + s_{65} T_5 + s_{66} T_6, \end{aligned} \quad (4)$$

where s_{qp} is elastic compliance constant. From Eq. (3) the strain-stress relation reduces to

$$\begin{aligned} S_5 &= s_{55}' T_5 + s_{56}' T_6 \\ S_6 &= s_{65}' T_5 + s_{66}' T_6, \end{aligned} \quad (5)$$

where

$$\begin{aligned} s_{qp}' &= \bar{s}_{qp} - \bar{s}_{4q} \bar{s}_{p4} / \bar{s}_{44} \quad (q, p=5, 6) \\ \bar{s}_{qp} &= \tilde{s}_{qp} - \tilde{s}_{3q} \tilde{s}_{p3} / \tilde{s}_{33} \quad (q, p=4, 5, 6) \\ \tilde{s}_{qp} &= \bar{s}_{qp} - \bar{s}_{2q} \bar{s}_{p2} / \bar{s}_{22} \quad (q, p=3, 4, 5, 6) \\ \bar{s}_{qp} &= s_{qp} - s_{1q} s_{p1} / s_{11} \quad (q, p=2, 3, 4, 5, 6). \end{aligned}$$

In addition, the equations of equilibrium yield

$$\begin{aligned} \frac{\partial T_1}{\partial x} + \frac{\partial T_6}{\partial y} + \frac{\partial T_5}{\partial z} &= 0 \\ \frac{\partial T_6}{\partial x} + \frac{\partial T_2}{\partial y} + \frac{\partial T_4}{\partial z} &= 0 \\ \frac{\partial T_5}{\partial x} + \frac{\partial T_4}{\partial y} + \frac{\partial T_3}{\partial z} &= 0. \end{aligned} \quad (6)$$

Since stress-components T_1 , T_5 and T_6 are given as a function of y and z , we find that

$$\frac{\partial T_1}{\partial x} = \frac{\partial T_5}{\partial x} = \frac{\partial T_6}{\partial x} = 0. \quad (7)$$

When length $2x_0$ for a torsional resonator is much larger than width $2z_0$ and thickness $2y_0$, stress-components T_2 , T_3 and T_4 become

$$T_2 = T_3 = T_4 = 0. \quad (8)$$

From Eqs. (7) and (8), the second and third equations of Eq. (6) are always satisfied, so that the equation of equilibrium is given by

$$\frac{\partial T_6}{\partial y} + \frac{\partial T_5}{\partial z} = 0. \quad (9)$$

Equation (9) is satisfied if

$$T_5 = -\frac{\partial \Psi}{\partial y} \quad \text{and} \quad T_6 = \frac{\partial \Psi}{\partial z}, \quad (10)$$

Ψ is stress function. Substitution of Eqs. (2) and (10) into Eq. (5) then yields

$$S_{55}' \frac{\partial^2 \Psi}{\partial y^2} + S_{66}' \frac{\partial^2 \Psi}{\partial z^2} - 2S_{56}' \frac{\partial^2 \Psi}{\partial y \partial z} = -2\tau, \quad (11)$$

($\because S_{56}' = S_{65}'$)

which must hold over the area of the cross section, while the boundary conditions must be satisfied with

$$\begin{aligned} T_5 &= 0 \quad \text{on} \quad z = \pm z_0 \\ T_6 &= 0 \quad \text{on} \quad y = \pm y_0. \end{aligned} \quad (12)$$

Hence, the stress function Ψ is derived from Eq. (11) and the boundary conditions of Eq. (12).

2.3 Stress Function Ψ

Now, we take the stress function Ψ as

$$\Psi = a_n \{1 - b_n \cosh \xi(z + \zeta y)\} \cos \eta y. \quad (13)$$

where a_n , b_n , ξ , ζ and η are constant. Substitution of Eq. (13) into Eq. (11) then gives

$$\begin{aligned} a_n \{ & b_n (S_{55}' \eta^2 - S_{55}' \xi^2 \zeta^2 - S_{66}' \xi^2 \\ & + 2S_{56}' \xi^2 \zeta) \cosh \xi(z + \zeta y) \cos \eta y \\ & + 2b_n (S_{55}' \eta \xi \zeta - S_{56}' \eta \xi) \sinh \xi(z + \zeta y) \\ & \cdot \sin \eta y - \eta^2 S_{55}' \cos \eta y \} = -2\tau. \end{aligned} \quad (14)$$

Accordingly, to hold Eq. (14) at an arbitrary value of $\cosh \xi(z + \zeta y) \cos \eta y$ and $\sinh \xi(z + \zeta y) \sin \eta y$, we should find that

$$\begin{aligned} S_{55}' \eta^2 - S_{55}' \xi^2 \zeta^2 - S_{66}' \xi^2 + 2S_{56}' \xi^2 \zeta &= 0 \\ S_{55}' \eta \xi \zeta - S_{56}' \eta \xi &= 0. \end{aligned} \quad (15)$$

From Eq. (15) ζ and ξ , respectively, become

$$\zeta = \frac{S_{56}'}{S_{55}} \quad (16)$$

$$\xi = \sqrt{\frac{S_{55}'}{S_{66}'}} \frac{1}{\sqrt{1 - \frac{S_{56}'^2}{S_{55}' S_{66}'}}} \eta, \quad (17)$$

so that Eq. (14) is simplified into

$$a_n \eta^2 S_{55}' \cos \eta y = 2\tau. \quad (18)$$

Now when $-y_0 < y < +y_0$, the 2τ of the right term in Eq. (18) can be expanded in a Fourier's series⁵⁾ as follows:

$$2\tau = 2\tau \sum_{n=1,3,5}^{\infty} \frac{4}{n\pi} (-1)^{(n-1)/2} \cos \eta y. \quad (19)$$

Hence, a_n of Eq. (18) can be expressed in the form

$$a_n = \frac{8\tau}{\eta^2 \pi} \frac{1}{S_{55}'} \sum_{n=1,3,5}^{\infty} \frac{1}{n} (-1)^{(n-1)/2}. \quad (20)$$

Next, the constants η and b_n are derived from the boundary conditions. The stress-component T_6 of Eq. (10) becomes

Fig. 2 Sectional view and rotated axes of quartz crystal resonator.

$$\begin{aligned} T_6 &= \frac{\partial \Psi}{\partial z} \\ &= a_n b_n \xi \sinh \xi(z + \zeta y) \cos \eta y, \end{aligned} \quad (21)$$

the boundary condition of $T_6 = 0$ on $y = \pm y_0$ then gives

$$\eta = \frac{n\pi}{2y_0} \quad (n=1, 3, 5, \dots). \quad (22)$$

In addition, since we can not find a solution which satisfies the boundary condition of $T_5 = 0$ on $z = \pm z_0$, the edges are, as illustrated in Fig. 2, off perpendicular by the angle θ . When a resonator vibrating in torsion is rotated about the x -axis, a transformation of an old coordinate system (x, y, z) into a new one (x', y', z') yields

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos \theta & \sin \theta \\ 0 & -\sin \theta & \cos \theta \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}. \quad (23)$$

Accordingly, the transformed stress-components T_5' and T_6' is given by

$$\begin{aligned} T_5' &= T_5 \cos \theta - T_6 \sin \theta \\ T_6' &= T_5 \sin \theta + T_6 \cos \theta. \end{aligned} \quad (24)$$

In addition, the stress-components T_5 and T_6 are transformed into

$$\begin{aligned} T_5 &= -\frac{\partial \Psi}{\partial y} = a_n [b_n \xi \zeta \sinh \xi(z + \zeta y) \cos \eta y \\ & \quad + \eta \sin \eta y \{1 - b_n \cosh \xi(z + \zeta y)\}] \\ T_6 &= \frac{\partial \Psi}{\partial z} = -a_n b_n \xi \sinh \xi(z + \zeta y) \cos \eta y \end{aligned} \quad (25)$$

From the relation of Eq. (25) T_5' reduces to

$$\begin{aligned} T_5' &= a_n [b_n \xi (\zeta \cos \theta + \sin \theta) \sinh \xi(z + \zeta y) \cos \eta y \\ & \quad + \eta \cos \theta \sin \eta y \{1 - b_n \cosh \xi(z + \zeta y)\}] \end{aligned} \quad (26)$$

In Eq. (26), we set

$$\zeta \cos \Theta + \sin \Theta = 0, \quad (27)$$

so that we obtain

$$\Theta = \arctan(-s_{56}'/s_{55}'). \quad (28)$$

Here we note that $z + \xi y = z'/\cos \Theta$, T_5' reduces to

$$T_5' = a_n \eta \cos \Theta \sin \eta y \left(1 - b_n \cosh \frac{\xi}{\cos \Theta} z' \right). \quad (29)$$

From the boundary condition of $T_5' = 0$ on $z' = \pm z_0 \cos \Theta$, we should find that

$$b_n = \frac{1}{\cosh \xi z_0}. \quad (30)$$

From these results, stress function Ψ is given by

$$\Psi = \frac{8\tau(2y_0)^2}{\pi^3} \frac{1}{s_{55}'} \sum_{n=1,3,5}^m \frac{1}{n^3} (-1)^{(n-1)/2} \times \left[1 - \frac{\cosh \xi(z + \xi y)}{\cosh \xi z_0} \right] \cos \eta y. \quad (31)$$

Namely, Ψ of Eq. (31) is an exact solution which includes the elastic compliance constant s_{56}' .

2.4 Torsional Rigidity C_t

Since torsional rigidity C_t is given by a ratio of torsional moment M_t and the twist τ (M_t/τ), the M_t which is defined by the area integration of Ψ , i.e., $2 \int_{-z_0}^{z_0} \int_{-y_0}^{y_0} \Psi dy dz$ is calculated, so that M_t is

$$M_t = \frac{1}{3} \tau \frac{1}{s_{55}'} (2y_0)^3 (2z_0) \left[1 - \frac{192}{\pi^5} \left(\frac{y_0}{z_0} \right) \times \sqrt{\frac{s_{66}'}{s_{55}'}} \sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \left(1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \right) \times \sum_{n=1,3,5}^m \frac{1}{n^5} \cosh \left(\frac{n\pi}{2} \sqrt{\frac{s_{55}'}{s_{66}'}} \sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \frac{1}{\sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}}} \right) \times \tanh \left(\frac{n\pi}{2} \sqrt{\frac{s_{55}'}{s_{66}'}} \sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \frac{z_0}{y_0} \right) \right]. \quad (32)$$

Here, we note that the constant m must be so determined that it fulfills the convergent condition of M_t . Namely, it may need the following relation

$$\sqrt{s_{55}' s_{66}' - s_{56}'^2} > m s_{56}', \quad (33)$$

From the relation of Eq. (32) torsional rigidity C_t is given by

$$C_t = \frac{1}{3} \frac{1}{s_{55}'} (2y_0)^3 (2z_0) \left[1 - \frac{192}{\pi^5} \left(\frac{y_0}{z_0} \right) \times \sqrt{\frac{s_{66}'}{s_{55}'}} \sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \left(1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \right) \right]$$

$$\times \sum_{n=1,3,5}^m \frac{1}{n^5} \cosh \left(\frac{n\pi}{2} \sqrt{\frac{s_{55}'}{s_{66}'}} \sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \frac{1}{\sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}}} \right) \times \tanh \left(\frac{n\pi}{2} \sqrt{\frac{s_{55}'}{s_{66}'}} \sqrt{1 - \frac{s_{56}'^2}{s_{55}' s_{66}'}} \frac{z_0}{y_0} \right) \right]. \quad (34)$$

In addition, when $s_{56}' = 0$, C_t reduces to

$$C_t = \frac{1}{3} \frac{1}{s_{55}'} (2y_0)^3 (2z_0) \left[1 - \frac{192}{\pi^5} \left(\frac{y_0}{z_0} \right) \sqrt{\frac{s_{66}'}{s_{55}'}} \times \sum_{n=1,3,5}^{\infty} \frac{1}{n^5} \tanh \left(\frac{n\pi}{2} \sqrt{\frac{s_{55}'}{s_{66}'}} \frac{z_0}{y_0} \right) \right], \quad (35)$$

this result agrees with those^{1,2,5,6)} derived from the first condition of $s_{56}' = 0$.

3. RESONATOR SHAPE AND EXCITATION ELECTRODES

Figure 3 shows resonator shape and dimensions of free-free bar-type vibrating in torsion which are used in the present experiments (a), and the sectional view of electrodes construction (b). The resonator has a dimension of $x_1 = 0.8$ mm, $x_2 = 1.66$ mm, $x_3 = 80$ μ m, $z_1 = 2z_0 + 2z_2 + 2z_3$, $z_2 = 200$ μ m, $z_3 = 100$ μ m and $2y_0 = 0.12$ mm, and are fabricated by a chemical etching process. The edges of arms of the beam are off perpendicular by the angle Θ . When the resonator has a cut angle of $\phi = 66^\circ$, $\theta = 0^\circ$ and $\Theta = 24^\circ$, an error for $\Theta = 24^\circ$ which is caused by masking accuracy and etching technology is within $\pm 40'$ according to measurement of X rays. The resonators are formed from a rotated Y-plate with a cut angle of ϕ and θ about the x - and y' -axes. In addition, the excitation electrodes are deposited on

Fig. 3 Shape and dimensions of torsional quartz crystal resonator of free-free bar-type (a) and its sectional view of electrodes construction (b).

obverse and reverse of the beam and the adjoining electrodes have different polarity.

4. RESULTS and DISCUSSION

The results obtained in the present analysis are compared with the measured values of torsional quartz crystal resonators of free-free bar-type. Namely, a relationship of a frequency constant versus a thickness-to-width ratio R_{yz} is shown. In the calculation the constants of the Ref. 7) are employed.

Figure 4 shows the relationship of a frequency constant ($f \cdot 2x_0$) to a thickness-to-width ratio R_{yz} of a quartz crystal resonator vibrating in torsion with a cut angle of $\phi = 66^\circ$ and $\theta = 0^\circ$, and an edge angle of $\Theta = 24^\circ$. The solid and broken lines are the calculated values when s_{56}' is taken and neglected, respectively, and circles are the measured ones. As is apparent from Fig. 4, the frequency constant ($f \cdot 2x_0$) analyzed taking s_{56}' into account becomes larger than that analyzed neglecting s_{56}' , particularly, in the range of $R_{yz} = 0.5$ to a crossing of $R_{yz} = 1.2$ approximately. The calculated values taking account of s_{56}' agree with the measured ones better than those neglecting s_{56}' . The frequency constant ($f \cdot 2x_0$) is approximately proportional to the aspect ratio R_{yz} when it is small. As is shown in Fig. 4, the frequency constant ($f \cdot 2x_0$) increases gradually according to increase of the aspect ratio R_{yz} . However, further increase of R_{yz} gives the maximum of the frequency constant in the vicinity of $R_{yz} = 0.9$, and then, an inclination to decrease gradually. For example, the frequency constant ($f \cdot 2x_0$) is 182.5 kHz·cm in the calculation and 181.2 kHz·cm in the experiments when a thickness-to-width ratio R_{yz} is 1.017. Since these values lie intermediately to those for flexural and length extensional mode resonators,

a miniature torsional quartz crystal resonator of 400 to 600 kHz can be realized when the resonator size is taken into account.

5. CONCLUSIONS

In this paper, an exact solution of torsional rigidity C_t for a resonator vibrating in torsion has been found. This theoretical result was applied to torsional quartz crystal resonators of free-free bar-type and the calculated values are compared with the measured ones.

First, the general strain-stress relation was transformed into a simple one from the conditions of resonator shape and dimensions, and from the equation of equilibrium the partial differential equation was derived with respect to the stress-function Ψ . In addition, the Ψ which satisfies the boundary conditions was derived and then, the torsional rigidity C_t was calculated.

Second, the relationship of a frequency constant ($f \cdot 2x_0$) versus a thickness-to-width ratio R_{yz} was clarified from the theoretically obtained equation, so that the calculated values were found to agree well with the measured ones, e.g., in the vicinity of the aspect ratio $R_{yz} = 1.0$.

For the coming subject the influence of the piezoelectric terms on resonant frequency will be clarified.

REFERENCES

- 1) H. Kawashima and M. Nakazato, "A new cut torsional quartz crystal resonator of tuning fork-type," Trans. IEICE (A) **J76-A**, No. 1, pp. 1-8, 1993 (in Japanese).
- 2) H. Kawashima and M. Nakazato, "TT-cut torsional quartz crystal resonators of free-free bar-type," Jpn. J. Appl. Phys. **33** Pt. 1, No. 5B, 2989-2993 (1994).
- 3) J. Hermann, "DT-cut torsional resonator," Proc. 31st Annu. Symp. Freq. Control, U.S.A., 55-61 (1977).
- 4) H. Kawashima and K. Sunaga, "A vibration analysis of torsional quartz crystal resonators taking account of lateral motion," Jpn. J. Appl. Phys. **34** Pt. 1, No. 5B, 3316-3319 (1995).
- 5) A. E. H. Love, *A Treatise on the Mathematical Theory of Elasticity*, 4th ed. (Cambridge University Press, Cambridge, England, 1952).
- 6) H. Kawashima, M. Nakazato, and Y. Shimizu, "Quartz temperature sensors of torsional vibration formed from doubly rotated plates," Jpn. J. Appl. Phys. **33**, Pt. 1, No. 5B, 3005-3009 (1994).
- 7) M. Aruga, "On the elastic constants of quartz and their temperature characteristics," Bull. Tokyo Inst. Tech. **A-2**, 88-182 (1956) (in Japanese).

Fig. 4 Relationship of frequency constant ($f \cdot 2x_0$) and thickness-to-width ratio R_{yz} .

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