A SIMPLE METHOD OF SC RESONATORS DESIGN

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ABSTRACT

In the paper there is presented a method of SC-cut round, plano-convex resonators design with utilization of simple semi empirical equations. These equations were developed on the basis of experimental results of wide range frequency, curvature radius and plate diameter SC-cut resonators design and performance collected over a long time period. Presented equations make possible design of fundamental, third overtone and fifth overtone resonators. There is also presented an example of resonator parameters calculation and experimental results comparison.

1. INTRODUCTION

The SC cut resonators have been produced for over 20 years. Their design at the beginning was based on many experimental results and experience from AT resonators production. These resonators exhibit many advantages in comparison with AT resonators. But their technology and also design is more complicated. Many analytical design methods have been developed. A specially useful is the method of finite elements. But this method is very complicated and needs computers with large memory. Most of precise resonators are produced with vibrator as round plano-convex plate (fig.1).

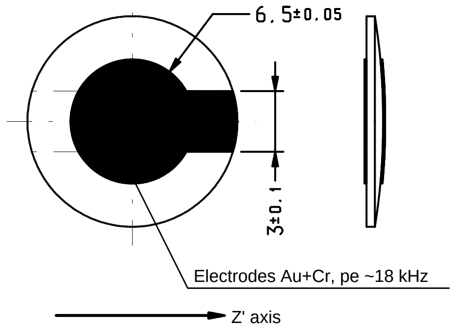

Fig.1. The example of SC resonator with 14 mm diameter vibrator design

In this case it is possible to use for resonator design simple approximate equations based on equations worked out for AT resonators –Ref.1. The SC cut resonators are produced mainly as precise resonators designed for high stability oven controlled quartz oscillators (OCXO). Resonators of this cut exhibit frequency versus temperature characteristic of the third order with inflection point temperature about 95°C and lower turnover point temperature depending on θ angle value. The turnover point temperature is a very important parameter of the resonator. At that point temperature induced changes of resonator frequency are lowest and it is this temperature that the resonator is working in an oscillator oven. This temperature depends not only on the θ angle value but also on quartz plate diameter and curvature radius. The parameters of the resonator electric equivalent circuit depend also on quartz plate dimensions and on electrodes diameter. It is possible to calculate optimum values of these parameters, using simple equations.

2. DESIGN PARAMETERS

2.1.The resonant frequency

Most of precise quartz resonators are designed with vibrating quartz element in the shape of plano-convex round plate. The most important resonator parameter is its resonant frequency.

The simplest equation expressing resonant frequency is:

$$f = \frac{N}{h} \qquad (1)$$

where: N - frequency constant [kHz*mm]

h - quartz plate thickness [mm]

N value is called a constant in reality it is not constant. Its value depends on quartz plate orientation, curvature radius R and diameter d. But over narrow frequency range and for a constant value of curvature radius it may be treated like a constant value for plate thickness calculation. On the basis of experimental results for different values of curvature radius and frequency the dependence of frequency constant on curvature radius was found to be:

$$N' = N + 280\frac{d_1}{R} \qquad (2)$$

where: $d_1 = 2\sqrt{2Rh - h^2}$

N - frequency constant of infinite plate depending on ϕ angle value (1800 for ϕ angle 22°10')

R - curvature radius

Comparing equations (1) and (2) it is easy to see that N' value depends on quartz plate thickness h. Its computation is possible by the method of successive approximations.

The nominal resonant frequency is the frequency measured at the temperature of resonator working in the oscillator. Usually for SC resonators it is the temperature of the lower turnover point of frequency - temperature characteristic. This temperature depends on quartz plate crystallographic orientation, diameter, thickness and curvature radius.

For quartz plate the frequency on temperature dependence can be expressed by equation:

$$f = f_0\left[1 + a\left(T - T_0\right) + b\left(T - T_0\right)^2 + c\left(T - T_0\right)^3 + ...\right] \qquad (3)$$

where: f_0 - resonant frequency at temperature T_0

a, b, c, ... - frequency vs. temperature coefficients of first, second, third .... order

For frequency vs. temperature characteristic calculation the first three coefficients are satisfactory. Usually the coefficient values describe third order curve with zero value of the first derivative at inflection point(T_I). T_I depends on ϕ angle and for SC resonators with ϕ equal to 22°10' it is about 95°C. The rate of change of coefficient "a" with θ angle of crystallographic orientation is expressed by equation:

$$\delta a / \delta\theta = -3{,}78 \times 10^{-8} \ / \ K^{*}`\theta. \qquad (4)$$

where : $`\theta$ – change of θ angle (in minutes)

A simple equation is useful for calculation of the lower turnover point of frequency vs. temperature characteristic dependence on curvature radius -Ref.2:

$$S_N = S_I + K(D_N - D_I) \qquad (5)$$

where: S_N - frequency vs. temperature characteristic slope at deflection point after curvature radius change

S_I - frequency vs. temperature characteristic slope for previous curvature radius

D_N - previous curvature radius in diopters

D_N - new curvature radius

K - empirical coefficient

for 5MHz fundamental resonator K = -21,6x10^{-8}/K

third overtone K = - 3,3x10^{-8}/K

fifth overtone K = - 8,5x10^{-8}/K

The lower turnover temperature can be expressed by equation:

$$T_L = T_I - \sqrt{\frac{S}{-1{,}959} \times 10^5} \qquad (6)$$

where : S - frequency vs. temperature characteristic slope at inflection point

T_I - temperature at inflection point

These equations are not exact but their accuracy is satisfactory for calculation of crystallographic orientation changes necessary to reach desired turnover temperature for different curvature radius. They do not give the value of θ angle but the possibility of crystallographic orientation changes calculation on the basis of the first samples of resonators turnover temperature measurement. These equations can be used if differences in θ angle do not exceed 3 minutes. If they are wider it is necessary to determine experimentally the K coefficient values for every frequency.

Sometimes resonant frequency is defined for additional series capacitance C_s. In this case the frequency shift can be calculated from equation –Ref.3:

$$\Delta f_{sc} = f_s \frac{C_1}{2\left(C_0 + C_s\right)} \qquad (7)$$

Where: C_1 - motional capacitance of resonator

C_0 - static capacitance of resonator

f_s - resonant frequency

<u>2.2. The quartz plate diameter</u>

The quartz plate diameter is the next important design parameter. It depends mainly on the type of enclosure. Of course that is not arbitrary. In quartz resonators technology quartz plates are placed many times in different kinds of equipment such as lapping masks, baskets for plates washing, or masks for electrodes deposition. In any case the plate diameter is an important parameter of this equipment. Every diameter change results in big costs of new equipment design and manufacture. For that reason each producer limits the quantity of the quartz plates diameters. For precise resonators the biggest diameter that fits in available enclosures is used. For example for TO - 3 (HC-40U) enclosures it is about 14 mm, for TO - 8 (HC-37U) enclosures it is about 10 mm. But quartz plate diameter depends not only on enclosure but also on quartz plate curvature radius. The plano-convex shape of quartz plate is used mainly to confine a vibration region to central part of the plate which results in Q value increase and makes the influence of mounting elements on resonator parameters smaller.

Concerning the technological process the curvature radius to plate diameter ratio should not be lower than 3.5. In plano-convex plate the vibration region is circular in shape. The highest vibration amplitude is in the center of plate and it decreases towards its perimeter. Approximately the vibrations are restricted to a round region called "active region" with diameter described by equation :

$$d_a^2 = 9{,}88\sqrt{\frac{Rh^3}{n^2}} \qquad (8)$$

2.3. The curvature radius

The optimal quartz plate curvature radius is that at which the diameter of the active region (d_a) is equal to the half of plate diameter (d_p). By transforming (8) and replacing d_a by $d_p/2$, the optimum value of curvature radius is expressed by:

$$R = \frac{{d_p}^4 n^2}{1560h^3} \qquad (9)$$

2.4. The electrode diameter

The next parameter is diameter of the electrode. Generally it has to be larger than the active region diameter, but sometimes it is necessary to design resonator with defined static capacitance. It can be calculated from equation:

$$C_0 = 0{,}035325\frac{d_e^2}{h}\ [\mathrm{pF}] \qquad (10)$$

This equation makes it possible to calculate electrode diameter for desired static capacitance and next to calculate curvature radius for restricting the active region to the area just under electrode.

2.5. The electrode thickness

The electrode thickness is also an important parameter. In precise resonators mainly the gold electrodes are deposited. The electrodes thickness optimum is presented in table 1.

Tab.1. Gold electrodes thickness

overtone	gold thickness [nm]
fundamental	100 - 150
third	75 - 100
fifth	60 -80

For the same electrodes thickness on both sides of the plate the frequency change caused by electrodes deposition can be calculated using equation –Ref.4:

$$\frac{\Delta f}{f} = -\frac{2\rho' \cdot h'}{\rho \cdot h} \qquad (11)$$

where: ρ' - electrode material density

h' - electrode thickness

ρ - quartz density

h - quartz plate thickness

2.5. The motional inductance

For resonator designer the equivalent circuit parameters are also of interest. The motional inductance can be expressed as

$$L_1 = \frac{900n^3}{f^3 d_a^2\left[1-\exp\left(-2\frac{d_e^2}{d_a^2}\right)\right]^2}[H] \qquad (12)$$

2.6. The motional capacitance

The motional capacitance can be calculated from equation:

$$f_r = \frac{1}{2\pi\sqrt{L_1 C_1}} \qquad (13)$$

3. RESONATOR DESIGN ALGORITHM

1. Input resonator parameters:
2. Choice of plate diameter
3. Frequency constant calculation for approximate value of curvature radius (eq.2)
4. Optimum of curvature radius calculation (eq.9)
5. Frequency constant and curvature radius calculation repetition
6. Active region diameter calculation (eq.8)
7. Choice of initial crystallographic orientation
8. Resonator with standard electrode manufacturing and its frequency vs. temperature characteristic measurement
9. Calculation of θ angle change (eq.4,5,6)
10. Electrode diameter choice (static capacitance calculation if necessary) (eq.10)
11. Motional inductance and capacitance calculation (eq.12 and 13)

4. EXAMPLE OF RESONATOR DESIGN

Input parameters:

- resonant frequency - 10 MHz
- nominal temperature - 75°C
- enclosure TO - 3 (HC - 40/U)
- overtone - 3

Plate diameter 14 mm

Initial curvature radius 1000 mm

Calculated: frequency constant N_1=1815.5 kHz x mm

N_3=5416,0 kHz x mm

plate thickness - 0,54160 mm

Curvature radius - 1394 mm

The lapping plates with curvature radius 750 mm,1000 mm and 2000 mm were used during resonators manufacturing.

Electrode diameter was calculated for curvature radius 1000 mm. For this curvature radius the active region diameter was 6,44 mm. Gold electrodes with diameter 6,5 mm and thickness 100 nm were used. With these electrodes 10 MHz third overtone resonators with curvature radii 750 mm, 1000 mm and 2000 mm were made. For crystallographic orientation determination resonators 8,192 MHz 3ov. with curvature radius 500 mm were used. These resonators with θ angle value of 34°04'30"±30" exhibited turnover temperature in the range of 73,9 - 82,3 °C

. For curvature radius 1000 mm and turnover temperature 75°C the θ angle change +1'01" was calculated. Resonators were made with θ angle value 34°05'30"±30" and 34°06'±30"(for R=2000 mm). Parameters of these resonators are presented in table 3.

5. CONCLUSIONS

The above presented method of SC plano - convex resonators design is very simple and easy to use. A practical computation program can be written by every engineer and successfully used. The precision of proposed method is satisfactory for resonator designer and makes it possible not only to calculate the quartz plate geometry but also crystallographic orientation changes and to predict parameters of equivalent circuit.

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Tab.3. Comparison of calculated and measured parameters of 10 MHz resonators.

Resonator	SC 10 MHz 3ov					
Curvature radius [mm]	750		1000		2000	
Parameters	calculated	measured	calculated	measured	calculated	measured
C_0[pF]	2,73453	2,7	2,73579	2,7	2,73817	2,6
C_1[fF]	0,30868	0,31	0,32839	0,33	0,35641	0,42
L_1[H]	0,82058	0,82	0,77134	0,77	0,71071	0,6
Q[10^6]	-	1,15	-	1,20	-	1,10
R[Ω]	-	45	-	40	-	39
h[mm]	0,54077	0,541	0,54052	0,541	0,54005	0,540
N[kHz*mm]	5418	5420	5416	5420	5411	5415
T_L[°C]	75	70 -75	75	70 - 72	75	70 - 80
θ[deg]	34°05'22"	34°05'30"	34°05'30"	34°05'30"	34°05'41"	34°06'00"