Beveling AT-cut Quartz Resonator Design by an Efficient Numerical Method

S.Y. Pao(1), M.K. Chao(2), C.H. Chiu(2), C.S. Lam(2), and P.Z. Chang(1)

(1) Institute of Applied Mechanics, National Taiwan University, Taipei, Taiwan
(2) TXC Corporation, Ping Cheng City, Taoyuan County, Taiwan

***Abstract*—In recent years, the rapid progress of personal communication system pushes the size of circuit device to become smaller and smaller. For the miniaturization of quartz resonator, the role of an efficient and precision simulation tool is becoming more and more important. Based on Mindlin's 2-D model and Lee-Brebbia's [1] FEA method, Pao [2] et al. presented an efficient numerical method in calculating the electrical impedance of different modes of AT-cut quartz crystal resonator. This method considers not only the pure mechanical vibration but also the electrical response so we can identify different modes easily.**

To achieve good energy trapping, beveling process in low frequency and small size AT-cut quartz resonator is very important. It is very difficult to simulate that by general 3-D piezoelectric model because it is hard to mesh elements in the thickness direction with slight thickness variation. In this paper, we use the efficient numerical method we presented last year and the mass loading effect concepts to develop a program tool to simulate the characteristic of a beveling quartz plate. By this tool, we can easily obtain the electrical gain response and vibration mode shapes. At the same time, it can also predict the electrical response change with beveling. We present an actual quartz resonator design to show how we use this program tool to design the beveling process and how to suppress the dominating unwanted modes. The simulation result is consistent with that of the experimental data.

Keywords- AT-cut quartz resonator; electrrical impedance; finite element analysis; beveling blank; energy trapping

I. INTRODUCTION

Along with the mobile telecommunication process, the miniaturization of circuit components, including resonators and oscillators, is inevitable. As the size of quartz resonators becomes smaller and smaller, the mounting and electrode effects are much more important than that in the bigger size device in the past. If we do not control the bonding loss or if we reduce the electrode area too much, the electrical impedance will become very high, even more than 200 or 300 ohm, and the oscillator will be very hard to start. Beveling quartz plate with thinner thickness in the edge is the most common way to reduce the bonding loss. Unfortunately, beveling shape is hard to design because the relationship between impedance and surface contour is not as straight forward. Some commercial finite element analysis (FEA) software tools can do the simulation of piezoelectric resonators, but due to the high length/width to thickness aspect ratio of AT-cut strip plate, general purpose FEA software is not suitable for this specific problem [3]. Our work [2] in 2004 solved the AT-cut quartz crystal plate vibration mode and electrical impedance problems by an efficient numerical method based on Mindlin's 2-D model. Following this work, we continue to consider how to simulate the beveling effect for the AT-cut strip plate. We develop an efficient numerical tool to calculate the beveling effect for an actual oscillator design.

II. THE EFFICIENT NUMERICAL MEHTOD

According to Mindlin's two-dimensional model [4] and the FEA model presented by P.C.Y. Lee et al. [1], we developed the efficient numerical method for the AT-cut quartz resonator. The steps of this method are:

The equations of motion in matrix form of the quartz plate [2]:

$$\begin{bmatrix} M & 0 \\ 0 & 0 \end{bmatrix} \begin{Bmatrix} \ddot{U} \\ \ddot{V} \end{Bmatrix} + \begin{bmatrix} K & K_{uV} \\ K_{uV}^{\ T} & K_{VV} \end{bmatrix} \begin{Bmatrix} U \\ V \end{Bmatrix} = \begin{Bmatrix} F \\ Q \end{Bmatrix} \qquad (1)$$

we consider no external force first, so $\{F\}=0$; nodes of elements with electrodes (plated): $\{V\}=\text{constant}$; nodes of elements without electrodes (un-plated): $\{V\}=0$; $\{Q\}$ is the unknown to be solved.

Based on weak piezoelectric coupling, we solve the mechanical vibration and electrical potential separately. First we solve the pure mechanical vibration as an eigenproblem.

$$[M]\{\ddot{U}\}+[K]\{U\}=\{0\} \tag{2}$$

the harmonic eigenfunctions

$$\omega_f^2[M]\{U\}+[K]\{U\}=\{0\} \tag{3}$$

where ω_f is the angular frequency of the quartz plate. By solving (3), we can get the eigenmodes (without external force), $U_1, U_2, U_1, \cdots U_n$, and the eigenvalues, $\omega_{f1}, \omega_{f2}, \omega_{f3}, \cdots \omega_{fn}$. Up to now, we can get only natural frequencies and mode shapes in free vibration, but no electrical response. Many modes obtained by numerical calculation may not even exist physically. As we consider the electrical boundary further, we rearrange the $K_{uv}\cdot V$ terms to the right hand side of the elastic-piezoelectric equations of motion, and these terms become the forcing terms of the pure elastic equations of motion:

$$[K_{uV}]\{V(\omega)\}=\{F_e(\omega)\} \tag{4}$$

in (4), we consider the applied electrical potential V as sinusoidal $V(\omega)$; the subscript "e" in F means the applied force by electrical potential. Adding the forcing and damping term into the equations of motion:

$$\omega^2[M]\{U_{pie}\}+j\omega[\eta]\{U_{pie}\}+[K]\{U_{pie}\}=\{F_e(\omega)\} \tag{5}$$

the subscript "pie" means the displacement with piezoelectric effect. In this paper, we consider the damping is linearly proportion to frequency. Using the mode superposition method [5] to solve U_{pie}:

$$U_{pie}=\alpha_i U_i+\alpha_{i+1}U_{i+1}+\alpha_{i+2}U_{i+2}+\cdots+\alpha_k U_k \tag{6}$$

where $U_i, U_{i+1}, U_{i+2}, \cdots, U_k$ are the free vibration eigenmodes we choose to be superposed, and $\alpha_i, \alpha_{i+1}, \alpha_{i+2}, \cdots, \alpha_k$ are the weights.

We use the eigen-expansion method to decouple the ODEs (5) for the weight of each eigenmode. The elastic displacement field with electrical potential effect, U_{pie}, can then be calculated as the weighting sum of each eigenmode. The electrical charges on the quartz crystal resonator can be obtained from the elastic displacement and electrical potential field at each node point:

$$\begin{bmatrix} K_{uV}{}^T & K_{VV} \end{bmatrix}\begin{Bmatrix} U_{pie} \\ V \end{Bmatrix}=\{Q(\omega)\} \tag{7}$$

III. SIMULATION RESULTS

By this method, we develop a Matlab program to perform the finite element simulation. In this paper we present two design examples. One is that we use this tool to identify the dominating unwanted modes and redesign the electrode shape to shoot the temperature activity dip trouble. The other is that we use the tool to consider the beveling process.

A. Example I

In the first design of a 3.2*2.5 mm^2 (3225) package size 20MHz strip quartz resonator, the size of the quartz plate and electrode are 2.0*1.3mm^2 and 1.06*1.01mm^2. There is an activity trouble near $45^\circ C$ as shown in figure 1.

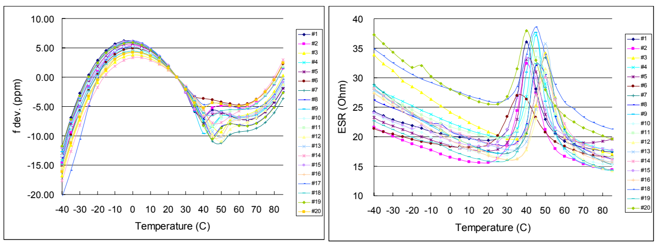


Fig 1. The activity dip of the 3225 strip quartz resonator.

As we use the FEA tool to analyze the unwanted modes close to the thickness shear mode, we find that the TS mode is coupled with flexure mode strongly, and there are also a flexure and a thickness twist (TT) mode near the TS mode as shown in figure 2.

By this mode shape information, we redesign the shapes/size of quartz plate and/or electrode to suppress the unwanted mode or to pull them away from the TS mode.

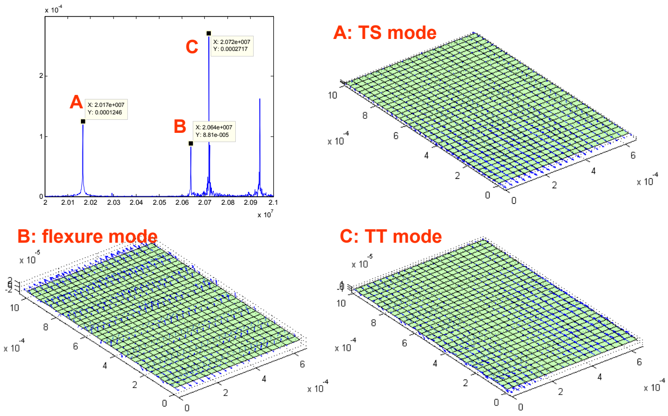


Fig 2. Modes identified by FEA simulation

As we change the electrode size to $1.2*0.8mm^2$, the flexure coupled to TS mode is weakened and the activity dip is suppressed as shown in figures 3 and 4.

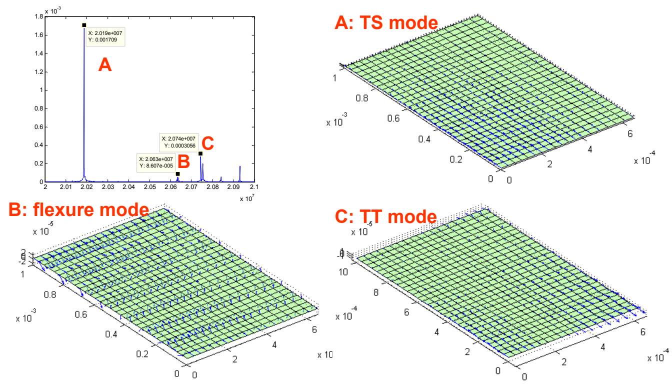


Fig 3. Electrical response and mode shapes simulated by the FEA tool (after redesign)

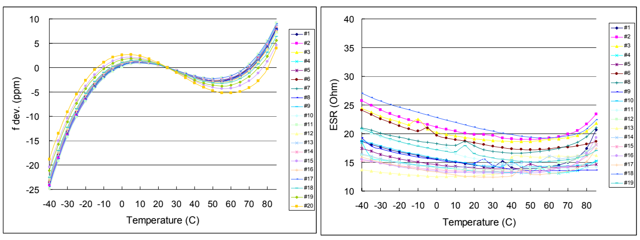
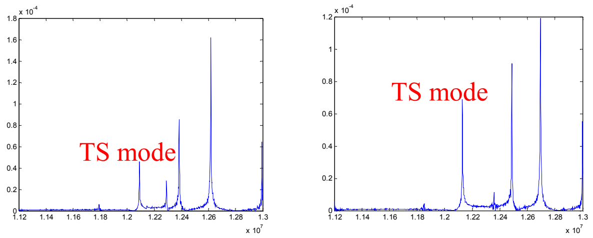


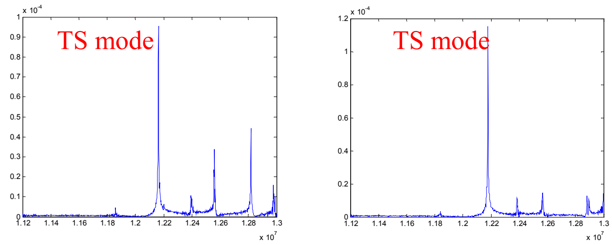
Fig 4. The experimental results of temperature characteristics after redesign.

B. Example II

In the second example, we use the FEA tool to simulate a 3225 12MHz strip quartz resonator.



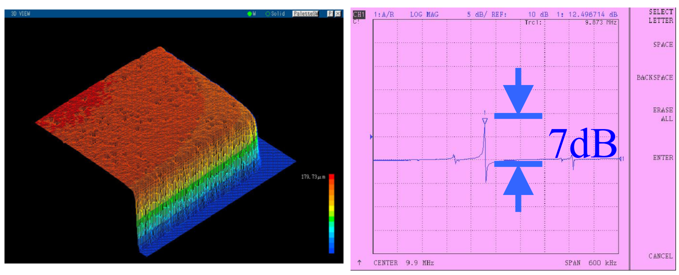
(a) No beveling (b) 8hrs beveling



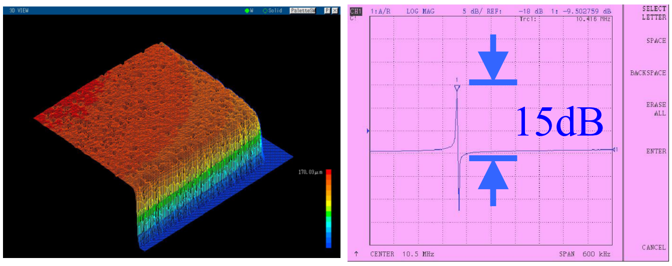
(c) 24hrs beveling (d) 30hrs beveling

Fig. 5. The FEA simulation results of the electrical response change as the beveling proceed. (the x-axis is frequency (Hz), and the y-axis is response).

As shown in figure 5, the unwanted modes are suppressed as the beveling proceeds. And because of the energy trapping effect, the response of TS mode is getting stronger compared to the other unwanted modes. This trend is consistent with the experimental results shown in figure 6.



(a) The shape of the strip quartz plate and its electrical response after 24hrs beveling.



(b) The shape of the strip quartz plate and its electrical response after 30hrs beveling.

Fig 6. The shape and electrical response of the beveling strip quartz plate (experimental results).

IV. CONCLUSION

Based on Mindlin 2-D elastic-piezoelectric model and weak piezoelectric coupling assumption, we develop an efficient numerical method in calculating the electrical impedance of different modes of AT-cut quartz crystal resonator. This method can simulate the electrical impedance behavior of the strip quartz chip very well, so it can be used to identify the unwanted mode shapes for the engineers to modify quartz plate and electrode shape to solve the activity dip problem. As we extend the function of this simulation program to design the beveling quartz blank, we can obtain results consistent with the experimental results very well. More effort is needed to enhance the simulation tool to be user-friendly, but now we already get some very useful information by this simulation tool. It is both precise and efficient for design engineers.

REFERENCES

[1] P.C.Y. Lee, C. Zee, and C.A. Brebbia, "Thickness-Shear, Thickness-Twist, and Flexural Vibration of Rectangular AT-Cut Quartz Plates with Patch Electrides," 1978 IEEE Tnt. Freq. Control. Symp, pp. 108-119.

[2] S.Y. Pao, M.K. Chao, C.S. Lam, and P.Z. Chang. "An Efficient Numerical Method in Calculation the Electrical Impedance Different Modes of AT-cut Quartz Crystal Resonator," 2004 IEEE UFFC Joint 50th Anniversary Conference, pp. 396-400.

[3] R. Lerch, "Simulation of Piezoelectric Device by Two- and Three-Dimensional Finite Elements," IEEE Trans. UFFC, Vol.. 37, No. 2, May 1990.

[4] R.D. Mindlin, "High Frequency Vibrations of Crystal Plates," Quarterly Appl. Math., vol. 19, pp. 51–61, 1961.

[5] A.K. Chopra, Dynamics of Structures, Prentice Hall, pp.434-439