Analysis of Aging of Piezoelectric Crystal Resonators

Andi Asiz, Weiping Zhang, and Yunping Xi

***Abstract*—Aging of piezoelectric (quartz crystal) resonator has been identified as one of the most important quality control problems of quartz crystal products. Aging is defined as frequency change with time. Aging in quartz resonators can be due to several sources: mass transfer due to contamination inside the resonator enclosure, stress-strain in the resonator blank, quartz defect, etc. In this study, the stress-strain effect, which has been believed as a dominant factor contributing to aging, is studied. The stress-strain effect is caused mainly by the long-term viscoelastic properties of bonding adhesive that attach quartz crystal plate to the ceramic base package. With the available accelerating testing method under elevated temperatures, the stress-strain induced aging in the quartz crystal resonators can be investigated. Because of the miniaturized size of the resonator, a digital image analysis method called image intensity matching technique (IIMT) is applied to obtain deformation patterns in the quartz blank due to thermal load. Our preliminary results showed that the unsymmetric thermal deformations may be a dominant contributing factor to aging. For simulation purposes, finite-element analysis is used to investigate the deformation patterns (i.e., stress-strain distributions) and corresponding natural frequency shift in the piezoelectric resonators. The viscoelastic behavior of mounting adhesives is incorporated into the analysis to show the dominant effect of long-term behavior of stress-strain developed in the crystal resonators. Also, some geometrical aspects—such as uneven mounting supports due to distances, volumes and heights of the adhesives—are simulated in the model.**

I. Introduction

Piezoelectric (quartz crystal) resonators have been used for frequency control and timing applications in many electronic products. As one of the widely used electronic material products, there has been a strong demand for highly stable and precise frequency control for the resonators. One of the major problems of the frequency stability over a long-term period is aging, which exhibits as a change in resonant frequency with time. Although aging problems probably never can be eliminated completely in piezoelectric resonators, understanding mechanisms that cause aging and isolating the dominant mechanism(s) are important steps that can be taken to minimize aging.

One of the mechanisms that can have significant impact on the aging of resonators is the stress-strain effect. This effect can have significant influence on piezoelectric resonators of AT-cut type, which is due to the fact that the AT-cut resonator is often designed for temperature compensation and not for stress compensation. In this study, the aging of AT-cut resonators due to stresses developed at mounting adhesive (stress relaxation) is analyzed using the finite-element method (FEM). In addition, the coupled effect of geometric imperfections of the mounting adhesive and the stress relaxation on the aging behavior is studied. The numerical analyses provide useful information for design and fabrication of the device in order to minimize the aging due to stress relaxation at the adhesive and the geometric imperfections of the mounting adhesive.

In the first part of the paper, aging mechanisms and high-frequency modes of piezoelectric resonators are briefly introduced. Then, experimental studies on the deformation behavior of resonator under thermal load and the experimental characterization of the viscoelastic behavior of the adhesives are described. The experimental results are used as qualitative information for modeling the aging of resonators due to stress relaxation at the mounting adhesive. Then, finite-element analysis is applied to evaluate natural frequency changes with time in the resonator due to the stress-strain effect and geometric imperfections of the mounting adhesive.

II. Aging of Piezoelectric Crystal Resonators

Aging of quartz crystal is generally defined as any change in the crystal unit as a function of time [1]. In most resonator device applications, aging can shift the frequency out of operating range, causing channel interference. Aging of the device is one of the critical customer specifications. The quantity of aging is expressed as total normalized frequency change over a specified time period. Aging specifications usually refer to a certain operating temperature, noting whether the device is in a proper operation mode during a specific time range. In commercial applications, 1 part per million (or 1 ppm) per year at 25°C for resonators and 5 ppm per year for oscillators are usually used for specifications [2]. Aging can be positive or negative as shown by the typical (computer simulated) aging graph on Fig. 1, where Y_1 (positive aging) is the logarithmic function of the frequency shift, and Y_2 (negative aging) is the same function but with different coefficients. The sum of Y_1 and Y_2 curves shows a reversal, which indicates the presence of at least two aging mechanisms.

The mechanisms that can cause aging in quartz crystal resonators and oscillators are very complicated. The pri-

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A. Asiz and Y. Xi are with the Department of Civil, Environmental, and Architectural Engineering, University of Colorado, Boulder, Colorado, 80309 (e-mail: yunpin.xi@colorado.edu).

W. Zhang is with CTS Wireless Components, Schaumburg, IL.

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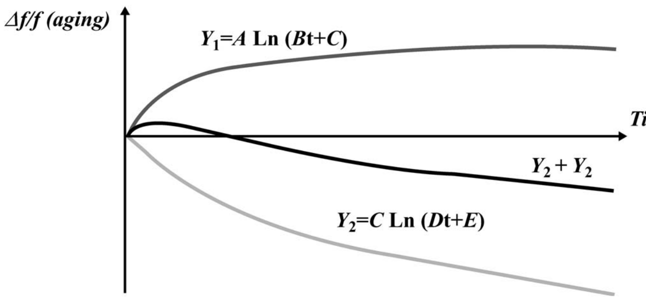

Fig. 1. Typical aging behavior.

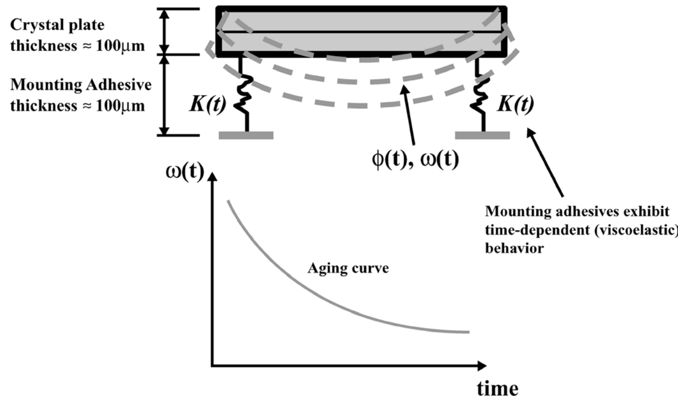

Fig. 2. Aging model.

mary aging mechanisms are: stress relief in the resonators, bonding effects, electrode effects, surface contamination due to adsorption or desorption, and other changes in the resonator packages.

A. Stress-Strain Effect

The resonant frequency of a quartz crystal unit usually is dependent on mechanical strains imposed on the crystal blank. Consequently, any change in the static stress imposed on the blank results in a change in the resonant frequency. Mechanical stresses are imposed upon the AT-cut quartz plate by the mounting structure and bonding material, both of which, in general, have different coefficients of thermal expansion (CTE) from the CTE of quartz. This leads to the so-called stress-induced frequency shift, in which stresses change with time (stress relaxation), so does the frequency. Bonding materials, such as silver-filled epoxies and polyimides have volumetric changes upon curing. This results in further stress changes with time. Unless great care is exercised in mounting the blank, the supporting adhesive may exert different loads on the blank, such as an in-plane tensile force, an in-plane compressive force, or a bending moment, and most probably combinations of the three. The frequency of the blank depends, to a certain extent, on the strains resulting from these applied stresses, which vary with time due to viscoelastic feature of the adhesive.

B. Surface Contamination

Surface contamination is one of the important aging mechanisms. The sensitivity of the frequency of a crystal device to this type of mechanism can be understood by notifying that a single atomic layer of contaminant on the surface of a 20-MHz AT-cut blank is equivalent to a frequency increase of some 100 Hz, or about 5 ppm [1]. In order to achieve low-aging, crystal units must be fabricated and hermetically sealed in ultraclean, ultrahigh vacuum environments, and into packages that are capable of maintaining the clean environment for a long period of time. There are other factors such as: oscillator circuit aging, diffusion effects, and quartz outgassing and defects. Pressure change in the enclosure also can cause aging. A comprehensive review of these effects on aging can be seen in Vig and Meeker [1].

C. Dominant Mechanism(s) and Modeling of Aging

Several studies have been devoted to investigate experimentally the dominant aging mechanisms. Gehrke and Klawitter [3] conducted accelerated aging tests. Their results showed that, for AT-cut resonators, the major cause of aging was dominated first by stress relief, followed by contaminants adhering to the crystal. They also showed that, as a function of temperature, the negative, long-term aging was mainly caused by the type of conductive epoxy used and the subsequent curing cycle.

The material properties of conductive epoxies (adhesives) are highly time-and-temperature dependent. The stress or strain relief in the quartz crystal blank cannot be accurately determined without a theoretical model that takes into account these dependencies. To this end, viscoelastic and thermoelastic models have been used widely for modeling creep and stress relaxation for many polymeric materials. A similar approach will be applied in this study to characterize the behavior of the conductive epoxy (adhesive) under elevated temperatures and time-dependent temperature profiles.

Fig. 2 shows a simplified aging model of crystal resonators. The model consists of a beam representing a crystal plate and two springs representing the mounting structure of the resonator. The springs have mechanical properties as a function of time. Any change in the mechanical properties of springs leads to a change in natural frequency of the beam (crystal plate). The plot of the natural frequency with time is shown in Fig. 2. Note that the figure shows only the flexural mode of the beam. In practice, higher modes such as thickness shear of crystal plate need to be considered in the analysis.

III. Experimental Study

There were two parts in the experimental study. The first part was focused on the deformation analysis of crystal resonators under uniform thermal load. In order to accelerate the aging of resonators, elevated temperatures were applied to resonators. Actual deformations of the

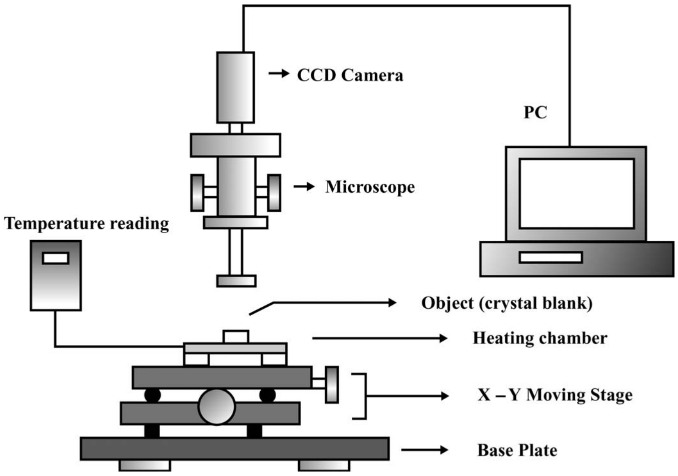

Fig. 3. Experimental image analysis setup.

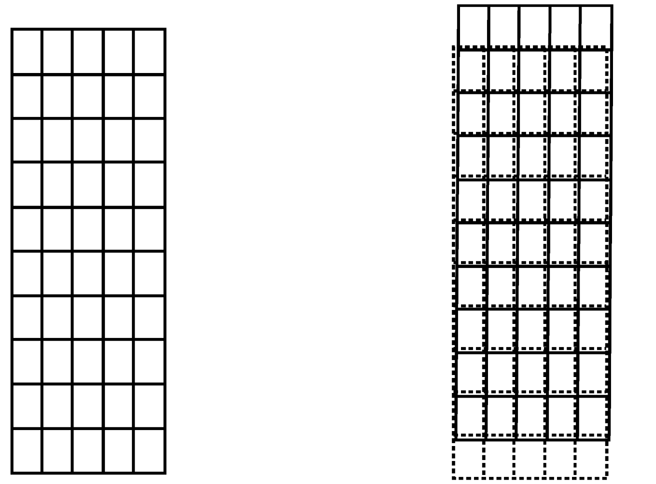

Fig. 4. Deformed shape of resonator under uniform thermal load.

crystal plate under the elevated temperature were observed, which provide information for the strain variation in the plate induced by the stress relaxation from the mounting structure. The second part was a creep test for characterizing the long-term behavior of adhesives. This is very important because the time-dependent stress variation is directly related to the viscoelastic behavior of the adhesive.

The deformation in crystal plate was studied by using an experimental setup shown in Fig. 3. There are three main parts of the setup: an image capturing equipment (CCD camera, optical microscope with 50 to 200X magnification, and a computer image card), temperature platform (with temperature control and microdisplacement control), and a computer for postprocessing the obtained images. The resonator used in this study is rectangular AT-cut resonator with length 4.39 mm, width 1.82 mm, and average thickness 0.1 mm. The electrode covers about 70% of the top and bottom surface of the crystal plate. An image analysis technique called image intensity matching technique (IIMT) [4] was used in the study. Two images are taken for the deformation analysis. A reference (initial) image is taken prior to the occurrence of any deformation, and a deformed image is taken after the deformation. In the present study, because we are studying the deformation of the crystal plate under elevated temperature, the reference image was taken at room temperature (25°C) and the deformed image was taken at 100°C. All displacements measured are absolute values (without referring to a point) and in pixel scale. By comparing the two images using IIMT, the surface deformation in the crystal plate can be evaluated. It should be mentioned that the image analysis can be used at different temperatures so that the variation of surface deformation associated with a specific temperature profile can be evaluated.

As reported in the literature [5], [6], the coefficients of thermal expansion of quartz crystal are $7.5 \times 10^{-6}/°C$ in x-direction (width) and $13.7 \times 10^{-6}/°C$ in z-direction (length). Therefore, the elongation in the length direction should be about two times larger than that in the width direction. The typical experimental result shown in Fig. 4 indicates that the v displacements in the length direction have the average value about six times larger than that of u displacements in the width direction. Note that the length of the blank is almost three times larger than width.

One important observation from Fig. 4 is that the deformation pattern is unsymmetrical about the y axis (the length direction). This may be due to the uneven heights in the two mounting points, for example, the volumes of the two adhesives applied are not controlled properly during the fabrication process. In fact, the resonators used in the present study were manufactured by manual process, not only the volume of the adhesive but also the location of the mounting points are not precisely controlled. It is important to note that the changes in the mounting structure may result in significant variations in the frequency of the resonator. The unsymmetric deformation and its effect on the frequency variation will be studied in detail by the finite-element analysis in the following sections.

The long-term behavior of the conductive adhesive has been a major issue in the manufacturing of surface-mount microelectronic devices. The information in the literature on time-dependent behavior of conductive adhesive, especially on polymer-type, is scarce. Therefore, there is a need to characterize the mounting adhesive as a viscoelastic material. The viscoelastic material exhibits phenomena such as creep, relaxation, and strain recovery. Because the creep test is the easiest one to conduct, the creep behavior was investigated first, then the viscoelastic parameters such as relaxation modulus and relaxation time can be determined based on the creep test data. Creep properties of the silicone adhesive can be determined by measuring the deformation of prismatic specimens under constant compressive load over time. The main consideration in the creep test is to obtain the compliance or relaxation function of the adhesive, which is the creep deformation under a unit stress. The compliance or relaxation function is important information for characterizing the aging behavior of resonators.

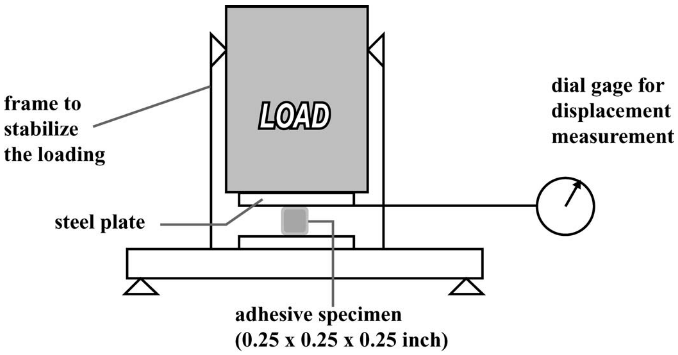

Fig. 5. Experimental setup for creep test of adhesive.

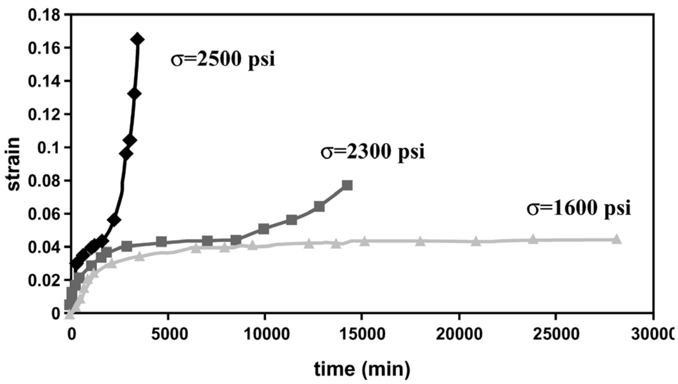

Fig. 6. Creep response of silicone adhesive in term of displacement versus time.

The experimental setup for the creep test of adhesive can be seen in Fig. 5. The creep tests were conducted at constant stress levels of 1600, 2000, and 2300 psi. The creep response at many stress levels of the adhesive material can be seen in Fig. 6. Creep rupture is the excessive deformation over time under the applied constant load, which indicates that the applied loading level is too high, much higher than the linear viscoelastic range of the material. A lower stress level then must be applied. In this study, we found that 1600 psi is a proper loading level corresponding to linear viscoelastic response of the adhesive. Therefore, the creep response under a stress level of 1600 psi is used. The relaxation function at this stress level is determined based on the creep test data, which then are used as inputs in the finite-element analysis and is presented in Fig. 7.

IV. Finite-Element Method

The FEM is used in the present study for analyzing aging of piezoelectric crystal resonators. There are two parts in the finite-element analysis: one is the numerical analysis for the natural frequency of the crystal plate, and the other is the viscoelastic analysis of the time-dependent properties of the mounting conductive adhesive. Combination of the two parts gives the time-dependent frequency variation of resonators due to time-dependent behaviors of conductive adhesive.

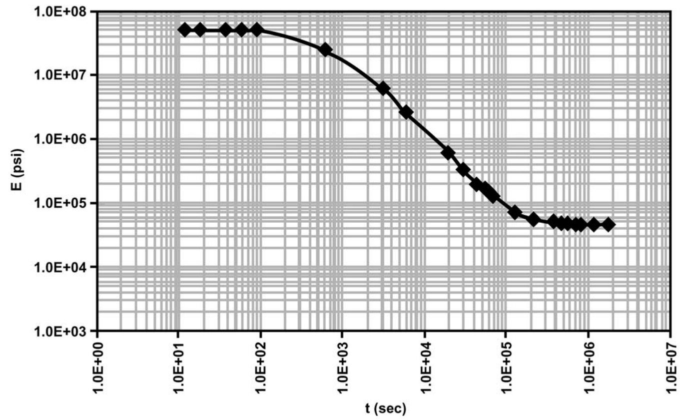

Fig. 7. Elastic modulus of adhesive versus time.

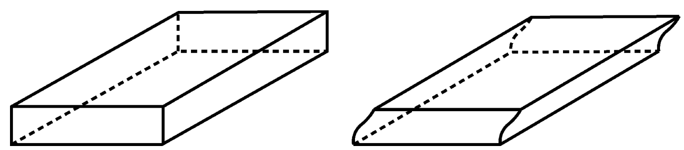

Fig. 8. Fundamental thickness shear mode.

A. Finite-Element Method for Piezoelectric Analysis

The piezoelectric effect is the coupling of mechanical stress and electrical field in a material (i.e., an electric field causes material to strain, and vice versa). The variables used in the finite-element formulation are the displacements and electric potential. The finite-element formulation for piezoelectric resonators mostly leads to eigenvalue or modal-frequency analysis [7]–[9], i.e.:

$$[K - \omega^2 M]u = 0, \quad (1)$$

where K is the stiffness of a piezoelectric resonator, M is the mass of the resonator, ω^2 is the eigenvalue or natural frequency (ω) of the resonator (which will be computed), and u is the corresponding eigenvector or mode shape.

The motion of a quartz plate is determined almost solely by its dimensions and the particular type of wave generated or the frequency applied, and very little upon the driving system if the coupling to the driving system is not strong. Basically, there are three type of motions: flexural, extensional, and shear. Among these three types of motion, the high-frequency shear (thickness shear) mode is the most important mode in high-frequency applications. Fig. 8 shows the thickness shear mode of an AT-cut resonator.

B. Finite-Element Method for Viscoelastic Analysis

As previously mentioned, the mounting supports of crystal blank are composed of conductive epoxy or silicone gel adhesive. The material properties of these adhesives are highly time-and-temperature dependent. Viscoelastic or thermoviscoelastic models can be applied to the mounting adhesive to characterize the time-dependent behavior at elevated temperatures. The finite element formulation for viscoelasticity leads to the following material formulation [10], [11]:

$$Ku(t) + \int_0^t H(t-\tau)u(t)d\tau = F(t), \tag{2}$$

where t is the time, K is the (instantaneous) stiffness of the resonator, F is the external force, and H is the material history, which generally can be expressed as:

$$H(t-\tau) = \sum_{m=1}^{M} C_m \exp\left[-\alpha_m(t-\tau)\right], \tag{3}$$

(3) is well-known as the generalized Maxwell model for viscoelastic solid materials. This model will be used in the finite element model for aging simulation.

V. Aging Analysis

There are two main parts for the aging analysis using the finite-element method. The first part is a thermoviscoelastic analysis to obtain time-dependent responses of the resonator induced by the applied temperature variation and viscoelastic mounting points. The second part is an eigenvalue analysis for the frequency variation induced by the time-dependent responses of the resonator obtained in the first part.

In the first part, only the mounting adhesive is considered to be time dependent, i.e., viscoelastic. The crystal plate is assumed as an anisotropic elastic material, independent of time. A thermoviscoelastic analysis then is carried out for the crystal plate with two mounting points. A uniform temperature variation (from 25 to 100°C) was applied on the plate, and because of the different CTE for the plate and the mounting adhesive, thermal stresses occur in the plate as well as in the mounting adhesive. Due to viscoelastic property of the adhesive, the thermal stress gradually relaxes. The time-dependent responses of the crystal plate—such as displacements, strains, and stresses—can be obtained in this part.

In the second part, the frequency shift that leads to aging is computed using the perturbation integral of Tiersten [12]. The eigenvalue analysis, which is the main input in this step—in addition to the stresses, strains, and displacement fields—is conducted to determine the frequency shift of the resonator. The commercially available finite-element analysis program ABAQUS© (ABAQUS Inc., Pawtucket, RI) [13] was used to determine the displacements, strains, and stresses in the resonator. A subroutine then was developed to evaluate the frequency shift as a function of time.

A. Materials and Geometry

The crystal plate in the present study is an AT-cut quartz that has 25 independent constants, i.e., 13 independent elastic constants, 8 independent piezoelectric constants, and 4 independent dielectric constants [6], [14]. The numerical values and matrix (array) of those constants are as follows:

Fig. 9. AT-cut crystal resonator.

- The elastic-constants ($\times 10^9$ N/m^2) are:
  $c_{11} = 86.74$, $c_{22} = 129.77$, $c_{33} = 102.83$,
  $c_{12} = -8.25$, $c_{13} = 27.15$, $c_{14} = -3.66$,
  $c_{23} = -7.42$, $c_{24} = 5.7$, $c_{34} = 9.92$,
  $c_{44} = 38.62$, $c_{55} = 68.81$, $c_{66} = 29.01$, $c_{56} = 2.53$.
- The piezoelectric constants (Coulomb/m^2) are:
  $e_{11} = 0.171$, $e_{12} = -0.152$,
  $e_{13} = -0.0187$, $e_{14} = 0.067$,
  $e_{25} = 0.108$, $e_{26} = -0.095$,
  $e_{35} = -0.0761$, $e_{36} = 0.067$.
- The dielectric constants ($\times 10^{-12}$ Coulomb/Volt-m) are:
  $d_{11} = 39.21$, $d_{22} = 39.82$, $d_{33} = 40.42$, $d_{23} = 0.86$.
- The (orthotropic) coefficients of thermal expansion are [6], [15]:
  $\alpha_{11} = 7.50\times10^{-6}$/°C, $\alpha_{22} = 0$, $\alpha_{33} = 13.70\times10^{-6}$/°C.
- The mass density (kg/M^3) = 2649.

The type of crystal resonator used for the aging study is a 16.4 MHz fundamental-thickness, shear mode device (Fig. 9). The crystal plate is mounted on a ceramic base using the adhesive silicon gel. The three-dimensional model of the crystal blank, including adhesive mounting points, was constructed without incorporating the ceramic base (ceramic packaging) for simplicity. However, the ceramic substrate plays an important role in developing thermal stresses caused by the mismatch of the coefficients of thermal expansion between the adhesive points and the ceramic substrate. In this study, the ceramic base was modeled as a rigid substrate. Hence, the model incorporating the adhesive dots and crystal plate is a simplified model for analyzing the vibration of the crystal resonator. Furthermore, the connection behavior between the adhesive points and ceramic base is modeled as fixed connections.

The vibrating plate is a rectangle plate with a length of 4.39 mm and a width of 1.82 mm, and an average thickness of 0.09 mm. The finite-element meshes of the quartz crystal blank are shown in Fig. 10. The crystal plate and adhesive supports are discretized using eight-node- and six-node-quadratic isoparametric elements. Four layers of elements through the thickness direction were used for computing the thickness shear mode. The total number of nodes and elements are 4168 and 3010, respectively.

The crystal blank has two adhesive bumps as its supporting points and as the connections to the electrical de-

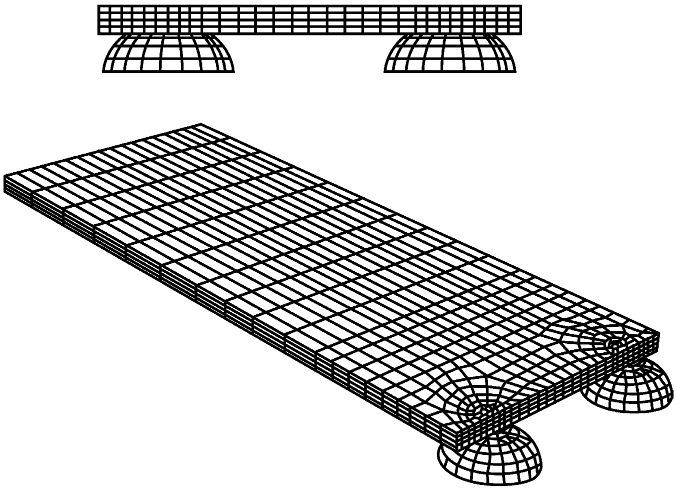

Fig. 10. Finite-element mesh of quartz crystal resonator.

vice. These bumps have base diameters of about 0.5 mm, top diameters of about 0.3 mm, and heights of about 0.15 mm. The eight-node-isoparametric element was used to model the two adhesive bumps. The material used for the mounting structure was a conductive adhesive of silver-filled silicone type from Emerson and Cuming, Inc. (Billerica, MA) [16] with instantaneous elastic modulus $E = 1.31 \times 10^{11}$ N/m^2, Poisson's ratio $v = 0.36$, and isotropic coefficient of thermal expansion (isotropic) = $30 \times 10^{-6}/°$C. The viscoelastic behavior of the mounting material (from the creep test) is shown in Fig. 7, in terms of the change of elastic modulus with time.

In order to use the data of the creep test as inputs in the finite-element analysis, in which the generalized Maxwell model is used, the viscoelastic parameters of the generalized Maxwell model needs to be determined first. In practical case, (2) can be written as:

$$E(t) = E_\infty + \sum_{i=1}^{M} E_i \exp\left(-\frac{t}{\tau_i}\right), \tag{4}$$

where M is the total number of Maxwell units used in the model. $M = 8$ was used in the present study. Then, by using a curve-fitting technique, the parameters in (3), such as the relaxation time τ_i and the relaxation modulus E_i, can be determined for each Maxwell unit. Table I shows the eight pairs of parameters for the eight Maxwell units used for the mounting adhesive materials.

B. Frequency Aging Computation

Frequency changes or shifts of a resonator may arise from the effects of geometric and material nonlinearities. Changes in the geometry can be characterized by a nonlinear, strain-displacement relation or known as the Green-Lagrange strain tensor. The shape of resonator changes slightly under prescribed loadings, and such a small change alters its stiffness and frequency slightly. The effect of material nonlinearity results from the nonlinear stress-strain relation of the materials, which can be characterized by a third-order elastic constant.

TABLE I
The Numerical Value of Ei of Maxwell-Prony Series.

i	τ_i (second)	E_i (psi)
1	1E+01	7.4E+07
2	1E+02	7.2E+07
3	1E+03	7.0E+07
4	1E+04	6.9E+07
5	1E+05	1.3E+07
6	1E+06	8.4E+05
7	1E+07	5.4E+05
8	1E+08	5.0E+05

The frequency shift Δ that leads to aging of the μ^{th} eigenmode at the frequency w_μ and the perturbed (nearby) frequency w can be computed using the perturbation equation derived by Tiersten [12], i.e.,

$$\Delta = \omega_\mu - \omega = \frac{H_\mu}{2\omega_\mu}, \tag{5}$$

where

$$H_\mu = -\int_\Omega K^n_{L,\gamma} g^\mu_{\gamma,L} d\Omega, \tag{6}$$

$$g^\mu_j = \frac{\hat{u}_j}{N}, \tag{7}$$

$$N = \rho \int_\Omega \hat{u}j\hat{u}j d\Omega, \tag{8}$$

are the perturbation integral of Tiersten [12], the normalized mode shape, and the normalization constant, respectively. K is the nonlinear component of Piola-Kirchoff stress tensor. The perturbation integral is derived from the unperturbed eigensolution of linear piezoelectric equation and nearby perturbed states, assuming the orthogonality of eigensolution [14]. This formulation incorporates the distortion of mode shape with respect of the stress distributed throughout the resonator.

By using the normalized mode shape in which:

$$K^n_{L\gamma} = \hat{c}_{L\gamma M\alpha} g^\mu_{\alpha,M}. \tag{9}$$

Then, the perturbation integral in (6) can be written as:

$$H_\mu = -\int_\Omega \hat{c}_{L\gamma M\alpha} g^\mu_{\alpha,M} g^\mu_{\gamma,L} d\Omega, \tag{10}$$

where the elastic constant:

$$\begin{aligned}\hat{c}_{L\gamma M\alpha} = T_{LM}\delta_{\gamma\alpha} + c_{L\gamma M\alpha KN}E_{KN} \\ + c_{L\gamma KM}w_{\alpha' K} + c_{LKM\alpha}w_{\gamma' K}.\end{aligned} \tag{11}$$

The stress tensor T_{LM}, strain tensor E_{KN}, and displacement field w_j are retrieved from the finite-element output.

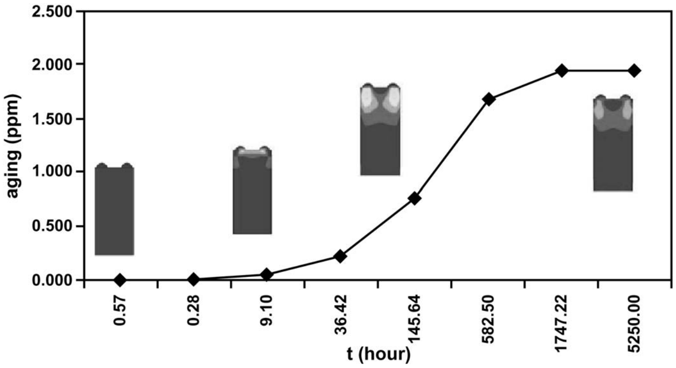

Fig. 11. Frequency aging and Mises stress history for idealized model of resonator.

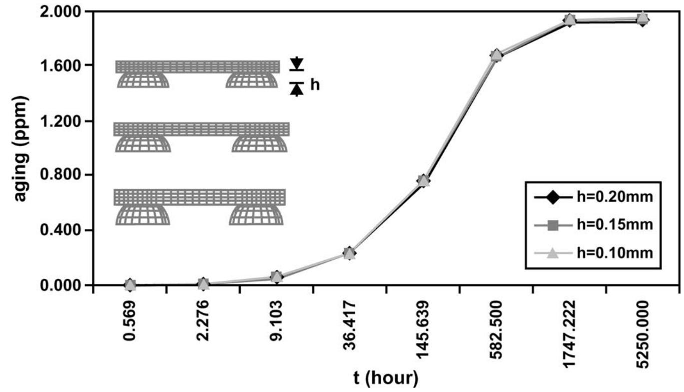

Fig. 12. Aging for volume (height) adhesive mounting variations.

The second order elastic constant c is presented in the previous section, and the third order elastic constant c can be found by the method described in [6]. As shown in (9), the electric variables are neglected. This is a reasonable approximation, especially for a quartz material with weak electromechanical couplings.

The perturbation integral then is evaluated as a sum over the total number of elements in the finite-element analysis comprising the active region of resonator mode (electrode region), i.e.:

$$H_{\mu} = -\sum_{n=1}^{NEL} \int_{\Omega_m} \hat{c}_{L\gamma M\alpha} g^{\mu}_{\alpha,M} g^{\mu}_{\gamma,L} d\Omega_n, \tag{12}$$

where Ω_n is the volumetric domain of the n^{th} element. The integral in (12) is performed numerically by using single quadrature points located at the centroid of elements in the finite element model of the resonator [15].

After retrieving displacements, strain and stress on the crystal blank at every time step, the eigen-frequencies analysis can be conducted. For practical purposes, the mesh used in this analysis did not include the adhesive material. Note that the quartz crystal plate is modeled as time-independent (nonviscoelastic material). As stated in (1), the natural frequency depends on the mass and stiffness of the crystal plate. Because the mass is assumed as a constant, the variation of stiffness with time is due to solely prescribed boundary conditions that are imposed on the crystal resonator plate, resulting in the changes of natural frequency (i.e., aging).

The results on the eigen-frequency analysis in term of normalized aging, defined as the frequency change divided by initial frequency, are plotted in Fig. 11. It shows the aging for the resonator under the uniform thermal load $T = 100°C$. One can see that the aging at 5.23×10^3 hours (219 days) is about 2.0 ppm, which is less than the total aging obtained from the experimental studies using network analyzer [2], [3]. This is due to the fact that only one aging mechanism is incorporated in this computational analysis. The computational results also indicate the time range where the primary aging occurs. In this study, the primary frequency change occurs at the elapsed time of 2 million seconds (23 days), which is in the same range as the primary relaxation time of the adhesive (see the creep test data in Fig. 7).

C. Geometric Variations (Imperfections) of the Mounting Points

Many crystal resonators are fabricated with some geometric variations (imperfections), which can cause changing in resonant frequency. In fact, as our analysis showed, the geometric variations of mounting adhesive play a critical role on aging behavior of resonators, which means that good quality control in the manufacturing process of the resonators is very important. In the present study, three types of geometric variations of mounting adhesive were analyzed, namely, adhesive volume, skewness (uneven mounting height), and distance variations between the two mounting points. The agings due to the three geometric variations then were compared with the idealized model shown in Fig. 11.

For the variation of adhesive volume, three types of geometry were modeled using the finite-element method. To simplify the geometric modeling, the adhesive volume was represented by the height of the adhesive as shown in Fig. 11. Note that the diameter of the adhesive was kept constant. The adhesive with a height of 0.20 mm was assumed as the reference volume (height) of the resonator. As shown on Fig. 12, the variation of adhesive volume does not have a significant effect on aging. The corresponding variation of aging is about 0.03 ppm among the three models.

For the variation of the skewness (uneven height), the models shown in Fig. 13 were analyzed. The reference model has 0° of skewness as shown in Fig. 13. As shown on Fig. 13, the total difference of aging is about 0.33 ppm between zero and 3° skewnesses. The aging difference between 1.5° and 3° skewnesses is about 0.11 ppm.

For the variation of the distance between the mounting points, three different distances were modeled: 1.52, 1.22, and 0.80 mm. The 1.22 mm was considered as the reference distance. As shown on Fig. 14, uneven mounting height has a significant effect on the aging. The aging shifts

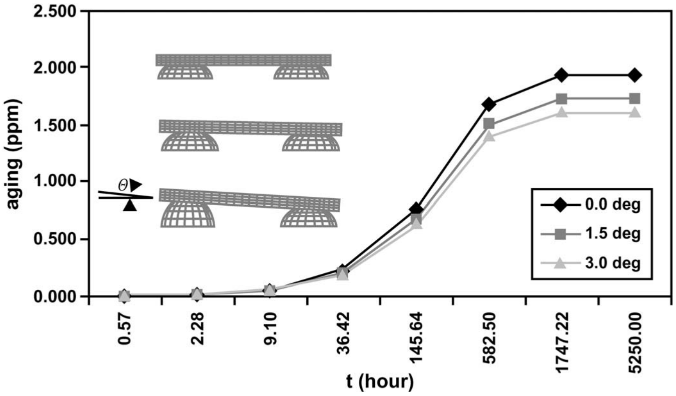

Fig. 13. Aging for uneven mounting variations.

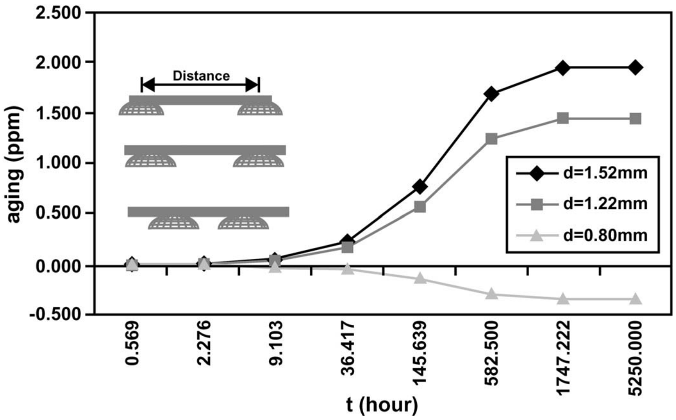

Fig. 14. Aging for distance adhesive mounting variations.

from positive to negative, if the distance between mounting points is very close. As shown in Fig. 14, the distance 0.80 mm between two mounting points has negative aging of −0.34 ppm, and the distances 1.22 and 1.52 mm have positive aging with 1.94 and 1.44 ppm, respectively.

VI. Conclusions

The FEM for aging simulation of piezoelectric resonators is described. The aging is considered due to stress relaxation of mounting points, which are made by viscoelastic materials with strong time-dependent properties. Therefore, the numerical analysis encompasses piezoelectric analysis, frequency analysis, and thermoviscoelastic analysis of the resonator. The resonator used in this study was AT-cut type, which is very sensitive to the stress-strain developed at the mounting adhesive.

Because of the miniaturized size of the resonator, a digital image analysis method, IIMT, is applied to obtain deformation patterns in the quartz blank due to thermal load. The image analysis results showed that the thermal deformation is unsymmetric, which may be due to imperfections of the mounting points; and, in turn, the imperfection of the mounting points may be an important aging mechanism. The viscoelastic properties of the mounting adhesive were obtained by a creep test, based on which the relaxation behaviors of the adhesive were characterized and used as input in the numerical analysis.

Numerical results showed that the aging due to the effect of stress relaxation (or so-called stress-strain) is very significant, and the primary aging occurs in the same time interval as the primary relaxation time of the adhesive.

Some geometric imperfections in the adhesive were analyzed in the simulation. The results have shown that distance variations between the mounting points have significant impacts on aging. In these cases, aging can shift from positive to negative for relatively small variations in the distance between the mounting points. Therefore, controlling this factor is one of the critical steps that should be taken during the fabrication process.

The magnitude of the aging obtained from this study is smaller than that from experimental results. This may be due to the fact that only one aging mechanism was included in this analysis. In reality other aging mechanisms—such as surface contamination, quartz defect, circuitry aging, etc.—are involved in the aging process. Ongoing research has been performed by authors focusing the aging due to mechanisms other than the stress-strain effect.

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Andi Asiz received his doctoral degree in structural mechanics from the University of Colorado, Boulder in 2002. He then was employed as a research associate at the same university.

Currently, he is a Research Fellow in the University of New Brunswick, Fredericton, New Brunswick, Canada working on the interdisciplinary research of biofiber based composites. His research interests include durability mechanics of materials and structures, structural and material health monitoring, and finite-element analysis.

Weiping Zhang received his doctoral degree in theoretical and applied mechanics from Northwestern University, Evanston, IL, in 1995.

His technical interest is in modeling, design, and development of frequency generation and management products.

Yunping Xi received his doctoral degree in structural engineering from Northwestern University, Evanston, IL, in 1991. He was an assistant professor at Drexel University, Philadelphia, PA. Currently, he is an associate professor at the University of Colorado, Boulder.

His research interests include experimental study and numerical modeling of long-term properties of various materials, and health monitoring and simulation of long-term performance of structures and devices.