EXTENSION OF THE FREQUENCY AGING MODEL OF CRYSTAL RESONATORS AND OSCILLATORS BY THE ARRHENIUS FACTOR

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The aging of quartz crystal resonators has been a key requirement of the product development and broad applications in signal generation and processing of many mission and life critical functions. Among many aging models for the analysis of long-term behavior of quartz crystal resonators, the Arrhenius model is widely accepted for most materials in engineering applications and physical process including quartz crystal resonators. A series of testing were conducted in different industrial laboratories in Japan and Germany to collect essential aging data of quartz crystal resonators and oscillators with the consideration of time, temperature, and frequency changes. The measurement data is merged and analyzed to extract different parameters of aging models for evaluation and validation. Finally, after careful examinations of parameters from different aging models, it is suggested that the Arrhenius model with modification is to be considered for the aging standard and further analysis are made with selected parameters.

Keywords: Quartz; Crystal; Resonator; Aging; Arrhenius

1. INTRODUCTION

The aging of quartz crystal resonators and oscillators has been subjected to extensive studies for many critical issues in applications such as accuracy, reliability, maintenance, and manufacturing improvement, to name a few. Similar to many other mechanical components, the temporal effect in service is related to many factors like thermal process, loading, surface condition, contamination, fatigue, and many others leading to the total failure under combined effects. Studies have been done to have thorough and detailed understanding of each and every factor mentioned above for a better estimation of the long term behavior in benefiting to applications. However, it is almost impossible to distinguish the effect of each factor from the total result and then combine them for the overall performance. Besides, many effects like the surface condition are hard to analyze quantatively in terms of time through a simple model. To provide solutions for better estimation of aging related effects, we need a simple mathematical model for key parameters like the frequency change with time to demonstrate from observations and simple measurements. With the major effects and parameters considered, other parameters with less significant effects can be incorporated into other non-specific parameters to establish an empirical model. Clearly, this approach will be able to satisfy application needs with mathematical relations readily available for some identical process and product types. This approach is represented by the aging analysis of quartz crystal resonators with the Arrhenius equation, which considers the time as the primary factor and other effects are taken care of through parameters related to specific products based on measurements [1-4]. This approach has been successful in providing better estimation of aging effect of quartz crystal resonators and results have been widely used in industry as the standard procedure for device characterization [5-11].

In this paper, we continue the effort initiated by the IEC/TC-49 on the general model of aging of quartz crystal resonators and oscillators through measurements and comparisons [2]. In the earlier paper, it is confirmed that the Arrhenius model has a better representation of measurement data by this group with measurements from typical products made by NDK of Japan and ECEC and TXC (Ningbo) of China by industrial laboratories in Japan and Germany [2]. Other empirical aging models, such as the Mattuschka and others exhibited agreeable but less consistent trend, can be used in occasions with reasonably good prediction of device properties for certain applications. To be precise, we have to adopt a more accurate aging model based on common standard and widely accepted data. It is hoped that such a model will be used in the device characterization for the aging property. This is the continuation of earlier work by adopting a different function for the acceleration factor. Specifically, the logarithmic function with modification is used for the time effect. The current results show a better improvement of the aging curves from our measurements with samples, thus providing better model for the parameters and behavior.

2. TYPICAL AGING MODELS

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There are many factors affecting the aging of typical quartz crystal resonators such as material surface, impurity, stress, oxidation, and structural change, to name a few. However, such effects have not been studied quantatively so far with known results. As for the aging, major factors are to be considered including time, temperature, acceleration factors, and frequency shift in a phenomenological model. Among many models for the relationship with acceleration factor, time, and temperatures with the frequency shift, the simplest one we choose is

$$\frac{dy}{dt} = -\alpha e^{\frac{y}{\beta}} \tag{1}$$

where the frequency shift is defined as $\Delta f = yf$, and t, α, and β are time and two parameters to be determined. In terms of frequency shift, we have

$$\frac{\Delta f}{f} = \alpha \ln(1 + \beta t). \tag{2}$$

From our experience, this aging model in conjunction with Arrhenius model will give better description of the long term aging of quartz crystal resonators [2].

There are other approaches to describe the aging effect of quartz crystal resonators through the general variation of material properties such as the exponential decaying of diffusion [3], slow increase [4, 5], and the power law process also for diffusion process [4]. In this paper, we adopted the modified logarithmic model for the aging and it is proven to be a slightly better model.

3. TEMPERATURE EFFECT ON AGING

The effect of temperature on the frequency shift is important because the accelerated measurement is possible with the relations. The acceleration factor is given by the Arrhenius equation in the form of

$$AF = e^{-\frac{E_a}{kT}}, \tag{3}$$

where $AF, E_a, k,$ and T are the acceleration factor, activation energy, Boltzmann constants (=$1.3806488 \times 10^{-23}$J/K), and temperature, respectively. Efforts have been made on the estimation of activation energy E_a for specific materials and products. As part of our research on the aging of quartz crystal resonators and oscillators [2], it is proven that the even for the quartz crystal resonators crafted for this study, there is no way to obtain a reliable and unique value for the relationship. It implies that the activation energy, however important, is clearly affected by many factors in the design and manufacturing process by individual makers. There is no way to obtain a universal value of activation energy with even the same materials from different sources, and even more unlikely with the consideration of different process. For this reason, we should not expect to have specific values for products we want to evaluate because it is not realistic. However, the extensive research conducted so far can safely predict that the general patterns are consistent, and values of major parameters like the activation energy are dependent on specific makers, products, and all difference related to the same type of product. The acceleration test is also acceptable and can be carried out for the evaluation of product.

In this analysis, we use the following model [2]

$$y = Ae^{-\frac{E_a}{kT}} \ln(1 + Bt), \tag{4}$$

where A and B are parameters to be determined for the frequency dependence on temperature and time.

Through a modification with reference time T_0, we can also have

$$y = A\ln\left\{1 + B\exp\left[-\frac{E_a}{k}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right] t\right\}, \tag{5}$$

which is actually

$$y = A\ln\left[1 + B\exp\left(-\frac{E_a}{kT}\right) t\right], \tag{6}$$

we now can use this one and the earlier model in (4) for the determination of parameters with measurement data for comparison and evaluation of models. Of course, it should be pointed out that the parameters in (4) and (6) are different even they appear in the same name and positions. Actually, a lot of factors have been hidden with constants in (4) and (6).

4. RESULTS AND DISCUSSION

The analysis of measurement data has been discussed in our earlier paper [2]. Now with the new relation shown in (6), we can examine the parameters and models for comparison.

As for the accuracy of models, we use the correlation coefficients from the two models, which are the logarithmic model in (4) and the current model in (6). Through regression analysis of the measurement data of each type of samples, we have the correlation coefficients in Table 1. It is clear that the current model is slightly better than the earlier model based on logarithmic model.

Table 1. Correlation coefficients from two aging models

Sample	QCR1	TCXO2 520	TCXO3 225	SPXO2 520	SPXO3 225
Eqn (4)	0.9920	0.9611	0.8769	0.9406	0.9620
Eqn (6)	0.9976	0.9728	0.9011	0.9656	0.9896

Now we turn to the estimation of activation energy E_a with the two models. As in earlier analysis, the activation energy is not a constant and changes wildly with product samples. Comparing with results from logarithmic model, the variation range is even bigger, but still within the usual range of such values. Now it is clear that we have to identify a reliable and acceptable model for the analysis and parameters extracted with the same model will be helpful in the comparison of products. The definition of activation energy or even other parameters with the same origin can be altered by aging models on the time. Since the precise model of aging cannot be determined from so many candidates, an industrial standard will help to reach a common objective to use the unified model and parameters for comparison and eventually the definition of product standards.

Table 2. Activation energy of sample products based on different aging models

Sample	QCR1	TCXO2 520	TCXO3 225	SPXO2 520	SPXO3 225
Eqn (4)	0.3781	0.4194	0.524	0.197	0.221
Eqn (6)	0.6195	0.632	0.781	0.371	0.542

Finally, we turn to the long term variation of activation energy with time to verify earlier trends from the same data. By regression analysis, we have the activation energy with time for all samples plotted in Fig. 1. Note that the correlation factors less than 0.9 have been deleted to improve the reliability of extracted parameters. Basically these curves will show the smoothness of activation energy with time. Again, they are different for different samples.

A systematic comparison of parameters extracted with the same set of measurement data found that they are close by not the same. It shows that the aging model can affect these parameters and necessary procedure and experiences should be taken into consideration for the selection of an aging model for industrial applications. The general trend is close with these parameters and more analysis of data should be used for the choice of an aging model.

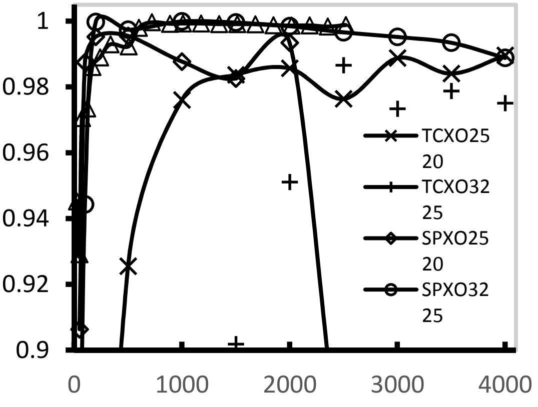

Fig. 1 Correlation coefficients of five samples versus time based on the current aging model

5. CONCLUSIONS

By extending our earlier analysis of measurement data of quartz crystal resonators and oscillators, we performed the analysis and parameter extraction with the current algorithm shown in (6) based on the aging with Arrhenius model. It is shown that the frequency shift with time has been improved, so as the estimation of activation energy. There is a clear sign that the value of activation energy based on the current algorithm is better and it may be the most competitive candidate for the industrial standard on the aging and parameters. The measurement data and analysis are the essential elements for the evaluation of aging models which are needed in the industry for unified evaluation and specification standard. Our efforts so far are on the right track for better understanding of the models and measurement methods. Now we shall turn to the two competitive algorithms and making decisions about the adoption within the framework of the IEC standards. Then, it is natural to examine the algorithms further with more measurements and parameter evaluations to support the selection and increase the acceptance in product recommendation.

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