Aging of Dual Mode Resonator for Microcomputer Compensated Crystal Oscillator

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Abstract— A Microcomputer Compensated Crystal Oscillator (MCXO) utilizes the dual c-mode excitation (fundamental mode and 3rd overtone (OT)) of an SC-cut resonator for self-temperature sensing and compensation. The long-term stability of the MCXO depends primarily on the aging of the dual mode resonator. When two modes age differently in time, the aging MCXO's output frequency curve would shift with a tilt over its operating temperature range.

In this paper, we report the aging of the dual modes of the 20 MHz 3rd OT SC-cut MCXO resonators. The resonators were measured over the –55°C ~ +85°C temperature range with the self-temperature sensing technique utilized for the MCXO. The measured aging of the two modes ranges from 0.083 ppb to 0.386 ppb per day. The fundamental mode shows more aging than the OT. Observing the different aging of the two modes is not surprising since the mode shape effect and stress relief would be different between the two modes. The different aging rates exacerbate the long-term aging in the MCXO by increasing the offset more than the worse aging rate of the two.

I. INTRODUCTION

A Microcomputer Compensated Crystal Oscillator (MCXO) utilizes the dual c-mode excitation (fundamental mode and 3rd overtone (OT)) of an SC-cut resonator for self-temperature sensing and compensation. The long-term stability of the MCXO depends primarily on the aging of the dual mode resonator. The presumption that the two modes may age differently in time has been of concern since the aging difference affects the long-term stability of the MCXO [1]. It was reported that the output frequency curve of an aging MCXO tilts over the operating temperature range and the aging difference between the two modes was speculated as the cause [2]. The measurement of the aging of the MCXO frequency output is found elsewhere [3], but that of the two modes, *i.e.* the primary source of the aging of the output, has not been reported yet.

Several years ago, we reported the hysteresis measurement of some 20 MHz 3rd OT SC-cut MCXO resonators, packaged in TO-5 metal cans [4]. In this paper, we present the aging of the same resonators. The aging data were analyzed with the same self-temperature sensing technique utilized for the MCXO. A prediction of long-term aging of the resonators is also presented.

II. MEASUREMENT METHODOLOGY

A design of a 20 MHz 3rd OT SC-cut resonator has been found to provide well-behaved characteristics for the fundamental mode and 3rd OT c-mode frequency vs. temperature for a –55°C to +85°C operating temperature range [4]. The resonator uses a 6.4 mm diameter blank that is plano-convex, with a 9.0 or 9.5 diopter contour. The electrodes are 3.3 mm in diameter, Cr-Au, with tabs along the X-axis. A four-point mounted crystal is packaged in an HC-35/U (TO-5).

Measuring the aging of a resonator frequency is not as straightforward as measuring an oven controlled crystal oscillator (OCXO) or a temperature compensated crystal oscillator (TCXO), whose frequency output is temperature-compensated, since, not only does the resonator frequency change with respect to temperature, but the temperature-frequency fluctuations are also greater than the aging. Rather than attempting to measure the aging at a fixed temperature, we measure it at the turning point of the frequency-temperature (F-T) curve of each mode. We utilize the self-temperature sensing of an MCXO, *i.e.* using the beat frequency rather than temperature to take advantage of its much higher resolution.

Initially, five resonators were measured in π-networks and three resonators were measured in dual-mode oscillators (DMXO) as shown in Fig. 1. Employing the π-network was to eliminate the aging associated with oscillator circuits. Simultaneous measurement of the dual modes is the key of self-temperature sensing to eliminate the temperature fluctuation error. With the π-network, however, it was only possible to sequentially measure the two modes, resulting in greater noise than aging. Thus, the π-network measurement data were discarded. The DMXO allows simultaneous measurements of the two modes by triggering the two counters simultaneously. Therefore, the data analyzed in this paper are from the DMXO measurements.

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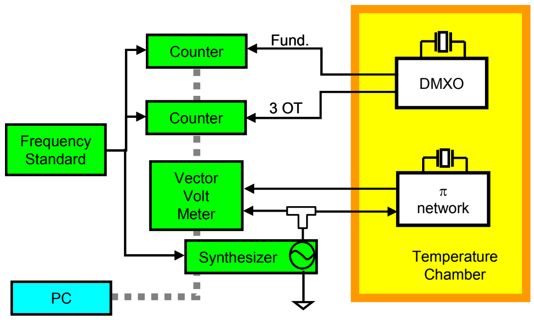

Figure 1. Measurement setup.

The measurements started at –55 °C after a 40 minute period of stabilization. The temperature was increased to +85 °C and then decreased back to –55 °C in increments of 4 °C, making a temperature cycle. At each target temperature, the resonators were soaked for 30 to 50 minutes to achieve a quasi-static temperature condition. The frequencies were measured 10 times at each target temperature to obtain an average value.

Fig. 2(a) shows typical F-T curves of the fundamental mode f_1 and the 3rd OT f_3 and the beat frequency, defined by $f_\beta = 3 \cdot f_1 - f_3$. The beat frequency shows an almost linear coefficient of –33.9 Hz/°C and this monotonic slope in temperature is essential to make self-temperature sensing possible. Fig. 2(b) shows the mode frequencies as a function of f_β instead of temperature T. All the frequencies are referenced to the corresponding ones at the starting temperature of the cycle, –55 °C, so that $f_\beta = 0$ at $T = -55$ °C. The turning points of f_1 and f_3 occur at $\Delta f_\beta \cong -780$ Hz ($T \cong -27$ °C) and $\Delta f_\beta \cong -2170$ Hz ($T \cong 17$ °C), respectively.

Since the frequencies were measured at discrete temperature points with 4 °C intervals, there are gaps between the frequency data. To fill the gaps, the frequency data were interpolated with curve-fittings and the maximum values are obtained for the turning points. To analyze the data, we can adopt the noise analysis found in Filler and Vig's paper [1] since the frequency changes due to aging can be regarded as noise. To describe the analysis here, some of the equations in the paper are reproduced.

Each mode frequency can be approximated with polynomials in f_β

$$f_1(T) \sim F_1(f_\beta) = \Sigma C_{1j}(f_\beta)^j \qquad (1)$$

$$f_3(T) \sim F_3(f_\beta) = \Sigma C_{3j}(f_\beta)^j \qquad (2)$$

where the C represents the coefficients of the polynomials and the subscript 1 and 3 represent the fundamental mode and 3rd OT, respectively. Similarly, aging frequencies f_1' and

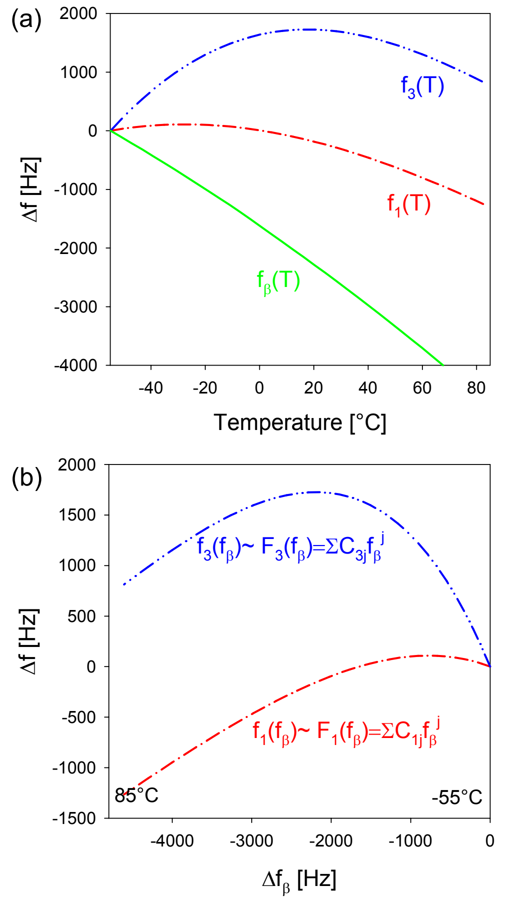

Figure 2. Fundamental and 3rd OT frequency curves as a function of (a) temperature, (b) beat frequency.

f_3' perturbed by aging, δf_1 and δf_3, respectively, are expressed as

$$f_1'(T) = f_1(T) + \delta f_1(T) \sim F_1'(f_\beta') = \Sigma C_{1j}'(f_\beta')^j \qquad (3)$$

$$f_3'(T) = f_3(T) + \delta f_3(T) \sim F_3'(f_\beta') = \Sigma C_{3j}'(f_\beta')^j\,. \qquad (4)$$

Note that the aging data are approximated with their own polynomials with the coefficients C', which are different from the previous C. The prime sign is used to signify the aging.

Close-up views near the turning points of the f_1 and f_3 of initial and aging data of a resonator are shown along with the polynomial interpolations in Figs. 3(a) and 3(b). The initial data was measured after ~3 years had passed from the fabrication of the resonator. The aging data were measured after ~5.5 years passed from the initial measurement. The agings at the turning points are 87 ppb and 122 ppb for δf_{10} and δf_{30}, respectively. (Because of the tilt discussed later, the f_β at the turning point of the initial f_1 is not necessarily the same as the f_β' of the aging f_1', and ditto to 3rd OT.) During the time span, the whole measurement setup was disintegrated then reassembled; thus, there could be

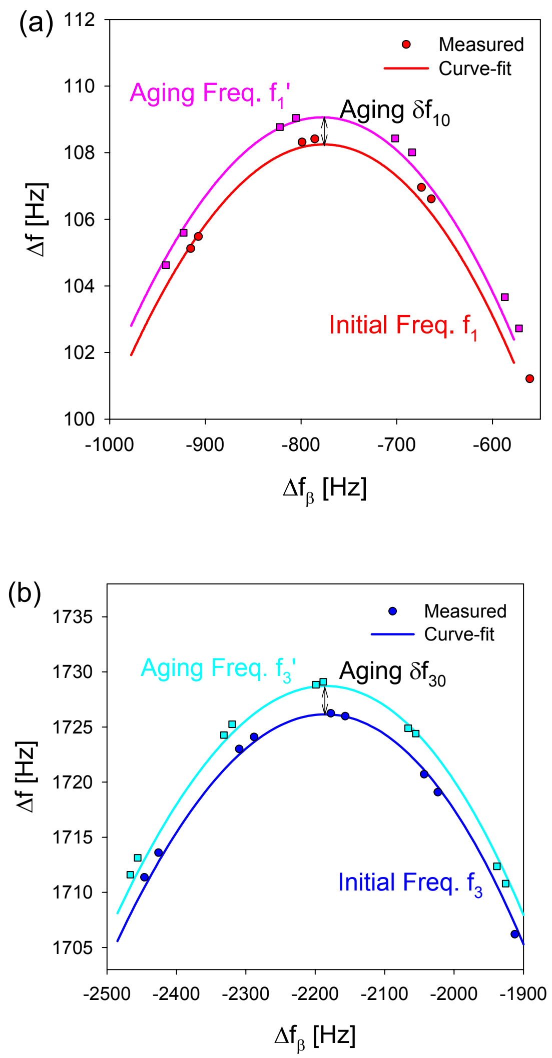

Figure 3. Aging at turning points: (a) fundamental mode, (b) 3rd OT.

measurement errors associated with this disruption. Nevertheless, the data are good enough to describe the analysis.

If the two data are plotted in a same graph in order to see the aging over the full range of f_β, they appear as identical curves since the difference between the two is less than a fraction of 1 % in comparison to the whole scale. To expose the minute difference, the commonly-used residuals are defined by the difference between actual data and curve fitting as follows,

$$R_1(f_\beta) = f_1(f_\beta) - F_1(f_\beta)\,. \tag{5}$$

Applying the F_1 of the initial data to the aging data instead of the F_1' reveals the aging over the full range of f_β, as follows

$$R_1'(f_\beta') = f_1'(f_\beta') - F_1(f_\beta')\,. \tag{6}$$

This operation would be analogous to an aging MCXO in which temperature is resolved by applying pre-determined polynomials to aging frequencies. (The two modes are measured with two counters here whereas a true MCXO has one counter using a mode as the time-base of the counter and the other mode as the counter input. The variation of the time-base frequency between the two methods is negligibly small [3].) The residuals of the initial and aging f_1 data calculated using Eqs. (5) and (6) are shown in Fig. 4. The residual errors incidentally appear as waveforms because suboptimal polynomials were used. With better polynomials such as multi-segmented polynomials, the residual error would be minimized [1]. However, since it is intended to find the "baseline" shift due to aging rather than the optimal polynomials, non-segmented 4th order polynomials were used for simplicity. The "baseline" is the line with zero residual errors from hypothetical polynomials providing perfect curve-fitting. One can see that the baseline of the aging f_1 is shifted up by ~130 ppb with a slight tilt from that of the initial f_1. Note that the residuals of the f_3 are identical with those of the f_1, as explained in [1]. Therefore, showing the residuals of the f_3 is unnecessary.

Due to the tilt, obtaining the aging of each mode at the other f_β points than the turning points would include errors. Thus, it is assumed that the aging is uniform over temperature, so that the aging obtained at the turning point may be uniformly added (or subtracted) to the initial data across the entire temperature or f_β range as follows:

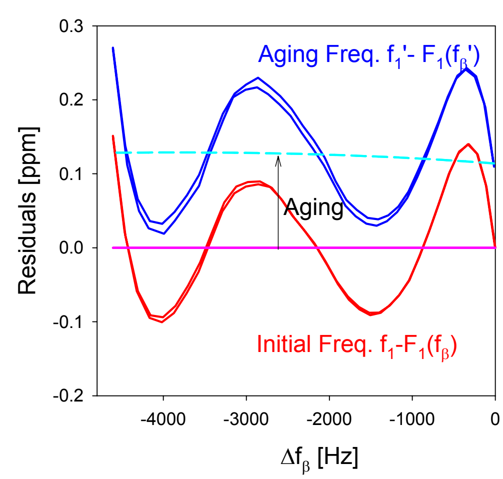

Figure 4. Frequency residuals of initial frequency and aging frequency. The baseline shifts up due to aging.

$$f_{1a}^{'}(f_\beta) = f_1(f_\beta) + \delta f_{10} \quad (7)$$

$$f_{3a}^{'}(f_\beta) = f_3(f_\beta) + \delta f_{30} \quad (8)$$

$$f_{\beta a}^{'} = 3\cdot\left[f_1(f_\beta) + \delta f_{10}\right] - \left[f_3(f_\beta) + \delta f_{30}\right]. \quad (9)$$

To substantiate the validity of this assumption, the $f_{\beta a}'$ of the initial data shown in Fig. 4 is calculated using Eq. (9). Then, the residuals are calculated using Eq. (6) to be compared with the residuals of the measured aging f_β'. The results are shown in Fig. 5. The calculated residuals match very well with the measured ones, implying that the assumption is acceptable.

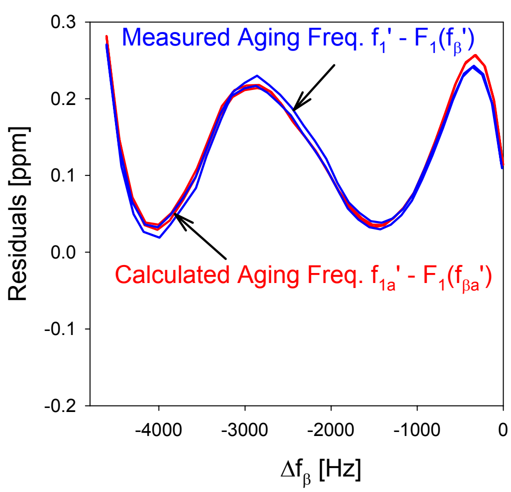

Figure 5. Comparison of the residuals of measured aging and the calculated residuals using initial data.

III. Results And Discussion

Concerning possible measurement errors in the aforementioned long-term aging data, the resonators in DMXOs were consecutively measured for about 110 days with 15 day intervals without disturbing the set-up. During the rest period between the temperature cycle measurements, the DMXOs were left at room temperature and the power supplied to the DMXOs was maintained on. The results are shown in Fig. 6. Fitting the data to linear aging curves yields the aging rates per day as shown in Table I. The OTs show lower aging rates than the fundamental modes.

Observing the different aging between the two modes is not surprising, considering the mode shapes of the two modes are different. The energy trapping in the fundamental mode spreads out more than in the OT, i.e., more tail of the energy profile in the fundamental mode falls on the quartz surface than in the OT. Two main sources of aging are due to changes of mass loading by contaminating molecules and stress relief over time [5]. Adsorption and desorption of contaminating molecules would not be the same on quartz and gold surfaces due to the difference in the binding energy of the molecules onto the surface. Since this mass loading is weighted by the mode shapes, it would affect the fundamental mode and OT differently. It is more obvious that the stress changing over time would affect the two modes differently due to the non-uniformity in the stress distribution at the interfaces of crystal, electrodes, and mounts.

The baseline shift can be calculated using the error equation $E(f_\beta)$ found in [1]:

$$E(f_\beta) = 3\frac{\delta f_3}{f_3}\frac{dF_1(f_\beta)}{df_\beta} - \frac{\delta f_1}{f_1}\frac{dF_3(f_\beta)}{df_\beta}. \quad (10)$$

Assuming the linear aging rates remain the same, the long-term predictions for the baseline shifts of the three resonators are shown in Fig. 7. After 15 years, the resonator No. 1 would change by 0.63 ppm and 0.45 ppm for f_1 and f_3, respectively, and because of the tilt, the baseline would have the maximum offset of 0.8 ppm at –55 °C. The resonator No. 3 would change by 2.11 ppm and 0.59 ppm for f_1 and f_3, respectively, and the baseline would have the maximum offset of 3.5 ppm at –55 °C. The tilt caused by the different aging rates inflicts more offset in the baseline than the worse aging rate. Furthermore, the more difference causes the more offset.

If both f_1 and f_3 have the same aging rate as $\delta f_1/f_1$, the baseline would shift by $\delta f_1/f_1$ without tilt (*i.e.* a constant in terms of f_β) as evidenced by,

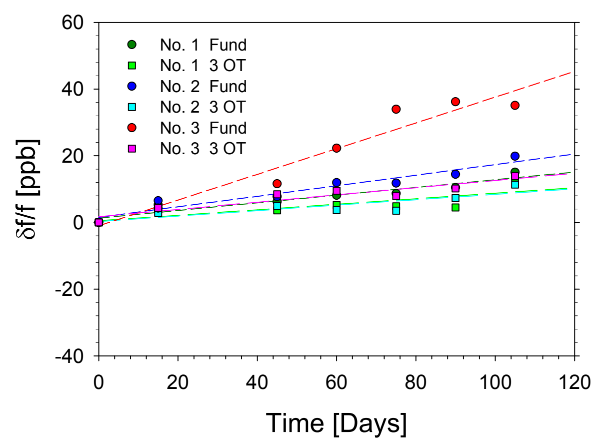

Figure 6. Measured aging rates and linear curve-fits.

TABLE I. Aging rates per day of dual modes and the ratios.

Resonator	δf_1	δf_3	$\delta f_1/\delta f_3$
No. 1	0.115 ppb	0.083 ppb	1.4
No. 2	0.158 ppb	0.082 ppb	1.9
No. 3	0.386 ppb	0.108 ppb	3.6

$$E(f_\beta)=\left(3\frac{dF_1(f_\beta)}{df_\beta}-\frac{dF_3(f_\beta)}{df_\beta}\right)\frac{\delta f_1}{f_1}=\frac{\delta f_1}{f_1} \tag{11}$$

since

$$3\frac{dF_1(f_\beta)}{df_\beta}-\frac{dF_3(f_\beta)}{df_\beta}=1 \tag{12}$$

as shown in [1]. However, as discussed above, the aging rates are expected to be different. The efforts for reducing the aging offset in an MCXO resonator aim for producing a dual mode resonator with low aging for the both modes.

IV. Conclusion

The aging rate of the fundamental mode of a dual mode SC-cut resonator for an MCXO is not the same as that of the 3rd OT. The aging rates are different between the two modes because the mode shape effects on mass loading of the contaminating molecules and stress relief are affecting the two modes differently. The different aging rates cause an offset with a tilt in the MCXO frequency output over the operating temperature range. The tilt exacerbates the long-term aging in the MCXO by inflicting more offset than the worse aging rate.

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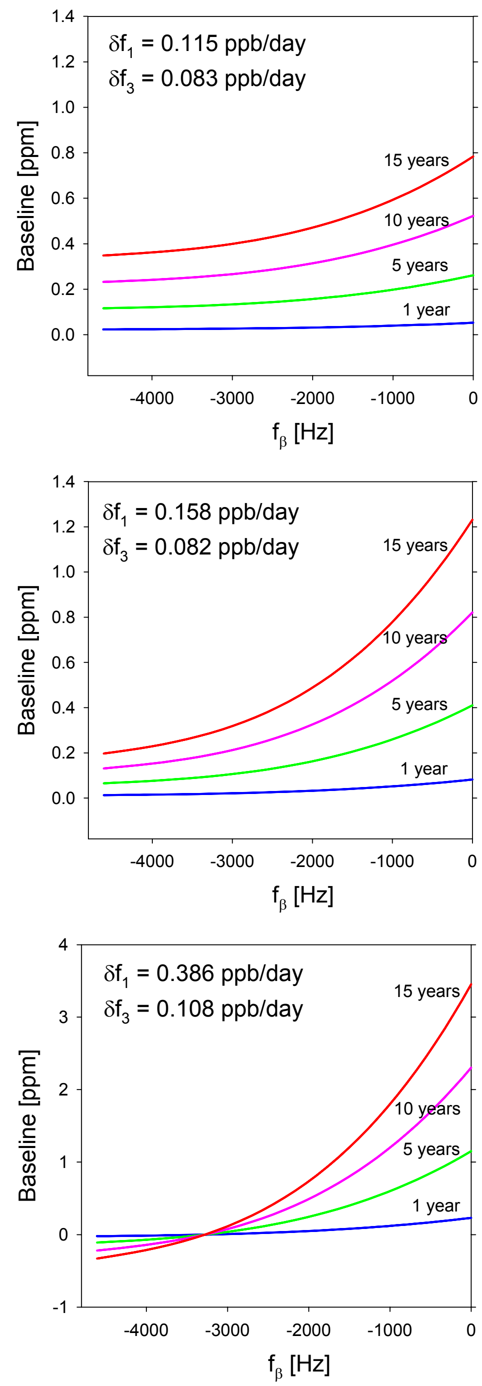

Figure 7. Predicted long-term aging of the baseline shifts for the measured aging rates shown in Table I.