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THE INFLUENCE OF PRESSURE AND HUMIDITY ON THE MEDIUM AND LONG-TERM FREQUENCY STABILITY OF QUARTZ OSCILLATORS

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Summary

The medium-and long-term frequency stability of most quartz-crystal-controlled oscillators is degraded by various environmental effects. The most important of these are acceleration, temperature, load change, humidity and possibly pressure. In this paper we show data which indicate that the medium-and long-term frequency stability of some oscillators can be improved by controlling the moisture and pressure around the oscillator. Measurements on four different quartz-crystal-controlled oscillators of three different designs yielded improvements of 2 to 5 in frequency stability for measurement times of 1 to 11 days. The frequency stability of one oscillator, with very low drift, improved to $3 \pm 1 \times 10^{-13}$ for measurement times from 0.03 s to 21 days. Supplemental experiments indicate that the probable cause for these improvements is the stabilization of frequency changes due to moisture that corresponds to a fractional change in frequency of about 10^{-9} for a 100% change in the relative humidity at room temperature. If these improvements can be routinely obtained in other precision quartz-crystal-controlled oscillators, then they may become useful for some applications generally thought to require atomic standards.

Introduction

Most precision, quartz-crystal-controlled oscillators exhibit a flicker-of-frequency floor which is approximately given by the phenomenological equation $\sigma_y(\tau) = 2.8 \times 10^{-7}/Q$ for measurement times of order Q/ν. Here, $\sigma_y(\tau)$ is the fractional frequency stability, ν is the oscillation frequency, and Q is the unloaded quality factor of the resonator [1-7]. For times much longer than Q/ν, the frequency stability generally is degraded by various environmental effects. The predominant processes in the long term appear to be random-walk-frequency modulation and frequency drift. The most important systematic effects are acceleration, temperature, load change, moisture (humidity) and possibly pressure. Some oscillators may also show a sensitivity to magnetic field probably caused by the electronics. The level of flicker frequency modulation appears to be very closely tied to the inverse of the fourth power of the unloaded quality factor, Q^{-4}. Gagnepain has shown that the predominant contribution to the flicker level is acoustic scattering losses [6].

In this paper we show experimentally that when the obvious environmental effects such as acceleration, temperature, pressure, moisture, and load changes are controlled, the frequency stability (of at least one crystal controlled oscillator) is constant within a factor of 2 for measurement times from 0.03 s to at least 1.8×10^6 s (21 days). The random walk process normally observed in quartz-crystal-controlled oscillators appears to be eliminated, and only flicker and frequency drift are apparent in the long term. This indicates that the observed flicker-frequency spectrum is not just a superposition of several noise processes over a narrow range of times, but rather represents a fundamental noise process within the oscillator (quite likely due to the quartz resonator) which extends over 7 orders of magnitude in Fourier frequency or averaging time. If such performance can be duplicated in other oscillators, then the areas in which quartz-crystal-controlled oscillators can be used may potentially be expanded.

Measurements on three other oscillators also show improvements of a factor of 2 to 5 in performance when the humidity and pressure are held approximately constant. These oscillators do not, however, maintain the exceptionally high level of performance demonstrated by the first oscillator. Several experiments show that the most probable cause for these improvements is the stabilization of moisture induced changes in frequency which at room temperature can approach a few parts in 10^9.

Measurements of Medium-and Long-Term Frequency Stability

We have recently made measurements on the medium-and long-term frequency stability of several bulk-wave, quartz-resonator-controlled oscillators. Oscillators #1 and #2 use a traditional fifth-overtone, 5 MHz, AT-cut resonator. These oscillators are of different design and from different manufacturers. Oscillators #3 and #4 use a fifth-overtone, 5 MHz, AT-cut resonator of the BVA design [8]. All are precision oscillators exhibiting very good frequency stability for measurement times from 0.03 s to 100 s. For these tests the changes in acceleration, vibration, and load impedance were minimized. The initial tests were performed in a room with a temperature of about 24 ± 1°C.

Figures 1 and 2 show the response of oscillators #1 and #3 to a step change in relative humidity from about 20% to 100% created by loosely enclosing them in aluminum foil with a wet sponge. The magnitude of the observed change in frequency is enormous for oscillators with a flicker frequency level of approximately 3×10^{-13}. The time constant in both cases was several days. The excess moisture was then removed and the oscillators run for several days. The frequency of the oscillators was then recorded while they were rotated about five of the six faces. These data are shown in figures 3 and 4. The steady state levels are primarily due to the acceleration sensitivity. It is interesting to see that for oscillator #1 there is a transient change in frequency of order 1 part in 10^{10} shortly after the oscillator is rotated. Quite likely this transient effect is due to a change in the convection cell within the oven, which changes the thermal gradients. The changes in frequency for the five different orientations of oscillator #3 were about four times smaller due to a lower acceleration sensitivity. The thermal transients are not noticeable except when the oven is tipped up on end. Measuring the frequency transients under rotation appears to be a simple test to determine the relative importance of thermal gradients in oscillators. The data of figures 3 and 4 show that the orientation (averaged over the measurement time) of oscillator #1 needs to be stable to 10^{-4} radians and the orientation of oscillator #3 needs to be stable to 5 x 10^{-4} radians in order not to compromise frequency stability measurements at a level of 3 x 10^{-13}.

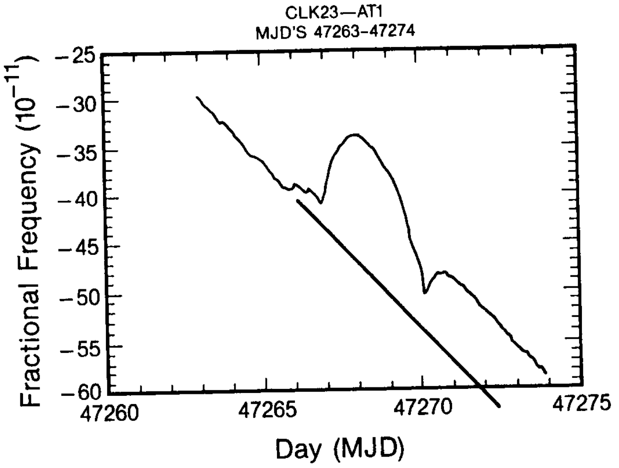

Figure 1. Fractional frequency offset from the NBS time scale of oscillator #1 for a change in relative humidity from approximately 20% to 100% at a nominal temperature of 24°C. This oscillator used a fifth-overtone, 5 MHz, AT-cut resonator of traditional design .

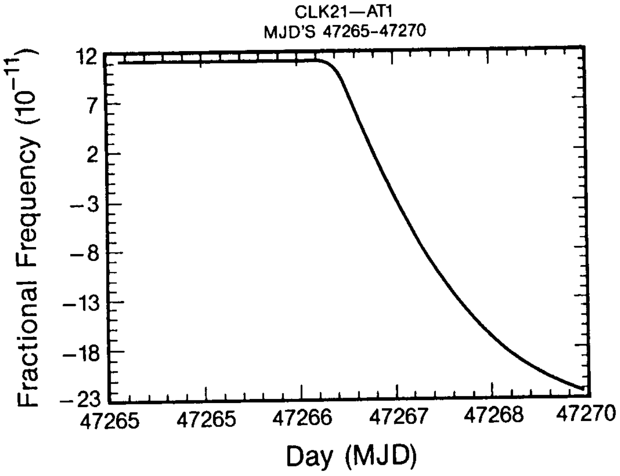

Figure 2. Fractional frequency offset from the NBS time scale of oscillator #3 for a change of relative humidity from approximately 20% to 100% at a nominal temperature of 24°C, with the frequency drift removed. This oscillator used a fifth-overtone, MHz, AT cut resonator of the BVA design [8].

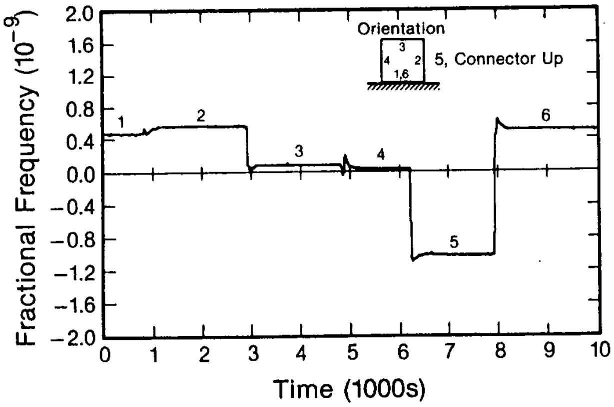

Figure 3. Fractional frequency offset from the NBS time scale of oscillator #1 for 6 different orientations. The last orientation is the same as the first. Note the frequency transient after each rotation.

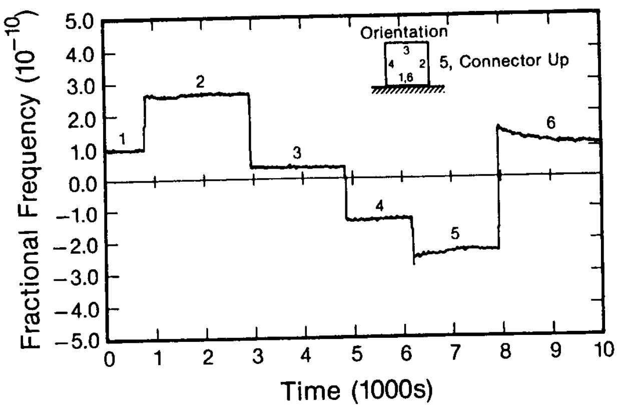

Figure 4. Fractional frequency offset from the NBS time scale of oscillator #3 for 6 different orientations. The last orientation is the same as the first.

Curve A of figure 5 shows the frequency stability of oscillator #1 (with a traditional fifth-overtone, 5 MHz resonator) under conditions of nominally constant power supply voltage, constant load, constant average acceleration, and a temperature of 24 ± 1°C. The humidity and atmospheric pressure were not controlled. Curve B of figure 5 shows the performance of the same oscillator under similar conditions except that the unit was sealed inside a sturdy metal container to hold the moisture and pressure approximately constant. The noise in curve A is predominantly random-walk frequency modulation, while that of curve B tends to be more like flicker-frequency modulation in the long term.

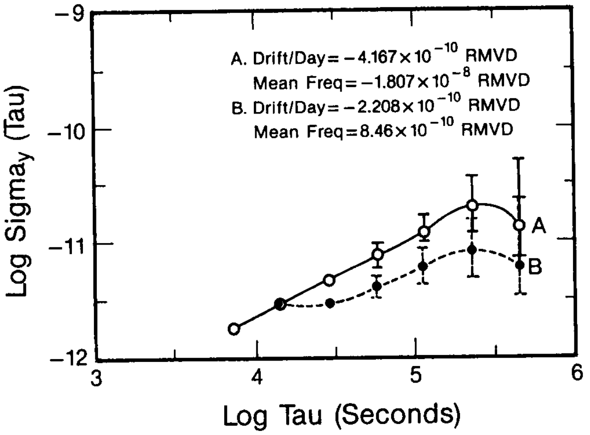

Figure 5. Curve A shows the fractional frequency stability, $\sigma_y(\tau)$, of oscillator #1 as a function of measurement time at a temperature of 24 ± 1°C and normal laboratory humidity and pressure. A second difference has been removed as an estimate of frequency drift. Curve B shows the same clock with the moisture and pressure around the oscillator stabilized and all other conditions similar to curve A. This oscillator used a traditional fifth-overtone, 5 MHz, AT cut resonator.

Curve A of figure 6 shows the performance of oscillator #2 (also with a traditional fifth-overtone AT cut resonator) exposed to room pressure and humidity, while curve B shows the same oscillator with the moisture and pressure held approximately constant. Oscillator #2 also shows some indication of improved performance when the moisture is held constant.

Curve A of figure 7 shows the performance of oscillator #3 (with a fifth-overtone, 5 MHz, AT-cut resonator of the BVA design) exposed to room humidity and pressure, while curve B shows the same oscillator after holding the moisture and pressure approximately constant. The noise in curve A is predominantly random-walk-frequency modulation while that of curve B is more like flicker-frequency modulation in the long term.

Curve A of figure 8 shows the performance of oscillator #4 (with a fifth-overtone, 5 MHz AT cut resonator of the BVA design) exposed to room humidity and pressure, while curve B shows the performance of the same oscillator when the moisture and pressure are held approximately constant. The temperature stability was improved to approximately ± 0.1°C for curve B. Degrading the temperature stability to ± 1°C degrades the frequency stability approximately 50%. We have also included the short-term-stability performance for a measurement bandwidth of 100 Hz.

The 90% error bars on the medium-and-long term data have been calculated for flicker noise. The change in frequency of approximately 1×10^{-11} between curves A and B appears to be due a change in the load impedance from changing the cable length. This is a typical sensitivity to load changes for precision quartz-crystal-controlled oscillators.

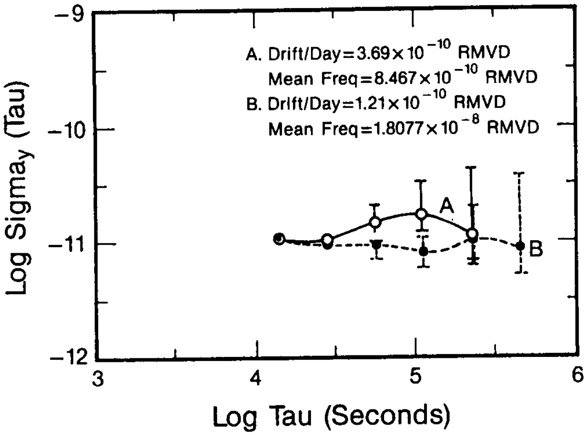

Figure 6. Curve A shows the fractional frequency stability, $\sigma_y(\tau)$, of oscillator #2 as a function of measurement time at a temperature of 24 ± 1°C and normal laboratory humidity and pressure. A second difference has been removed as an estimate of frequency drift. Curve B shows the same oscillator with the moisture and pressure around the oscillator stabilized and all other conditions similar to curve A. This oscillator used a traditional fifth-overtone, 5 MHz, AT cut resonator.

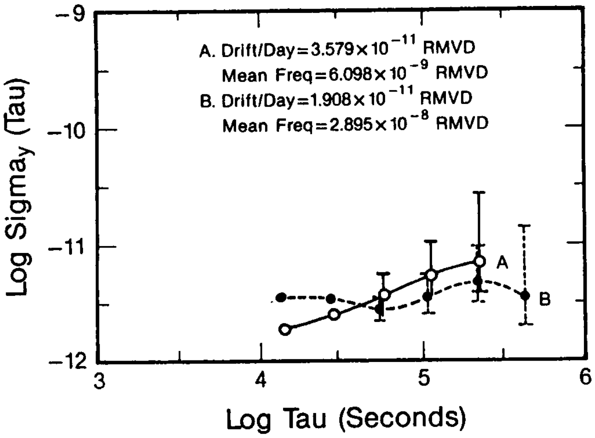

Figure 7. Curve A shows the fractional frequency stability, $\sigma_y(\tau)$, of oscillator #3 as a function of measurement time at a temperature of 24 ± 1°C and normal laboratory humidity and pressure. A second difference has been removed as an estimate of frequency drift. Curve B shows the same oscillator with the moisture and pressure around the oscillator stabilized and all other conditions similar to curve A. This oscillator used a fifth-overtone, 5 MHz, AT cut resonator of the BVA design.

Figure 9 shows the time residuals of oscillator #4 after the second difference was removed as an estimate to frequency drift.

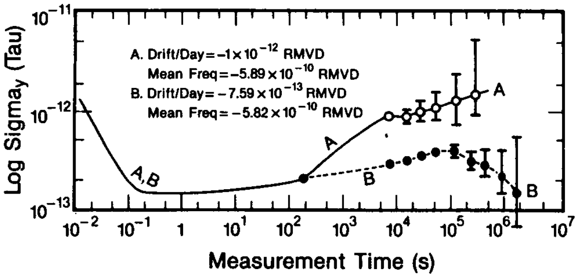

Figure 8. Curve A shows the fractional frequency stability, $\sigma_y(\tau)$, of oscillator #4 as a function of measurement time at a temperature of 24 ± 1°C and normal laboratory humidity and pressure. A second difference has been removed as an estimate of frequency drift. Curve B shows the same oscillator with the moisture and pressure around the oscillator stabilized and the temperature stabilized to approximately 0.1 C. This oscillator used a fifth-overtone, 5 MHz, AT cut resonator of the BVA design.

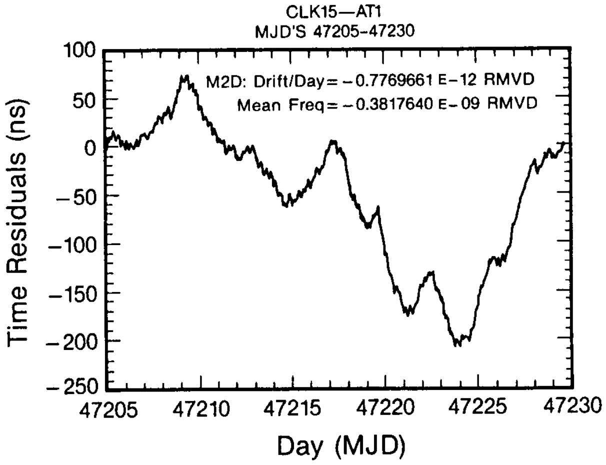

Figure 9. Time residuals of oscillator #4 after a 2nd difference was removed as an approximation to the frequency drift under the conditions of curve B of figure 8.

In all the oscillators examined, we achieved an improvement in the long-term performance by controlling the humidity and pressure. The random-walk-frequency-modulation component of the long-term-frequency stability is reduced. The data suggests that the most important effect is the changes in humidity. It is interesting to speculate on the difference between oscillators #3 and #4. The drift of oscillator #3 is about 2 x 10^{-11}/day. In order to observe a flicker level of 3 x 10^{-13} at 10^6 s, the drift level would have to be constant to 0.3%. Whereas the drift only needs to be stable to 6% to achieve the same flicker level in oscillator #4.

Conclusion

We have shown that the medium-term frequency stability of four different 5 MHz oscillators controlled by two different types of AT-cut resonators are sensitive to changes in atmospheric moisture and possibly pressure. Stabilizing the pressure and humidity, in addition to the normal parameters in an otherwise controlled laboratory setting, improves the frequency stability for measurement times in the region of hours to days. The mechanism by which fluctuations in moisture and possibly pressure transduce frequency changes are open to speculation. Perhaps the effect is due to changes in the thermal gradients or perhaps to changes in the dielectric constants or residual leakage between critical circuit elements. We also introduced a simple test to determine the relative importance of thermal gradients within air-enclosed ovens.

We have also shown that the frequency stability of one BVA-controlled oscillator was $\sigma_y(\tau)$ = 3 (± 1) x 10^{-13} for measurement times from 0.03 s to 21 days (measurement bandwidth of 100 Hz). These data and those on three other quartz-crystal-controlled oscillators indicate that the random-walk-frequency-modulation normally seen in the long-term-frequency stability data of quartz-crystal-controlled oscillators is not necessarily fundamental to the quartz, but is probably due to environmental influences. It also shows that the flicker-frequency modulation observed in quartz-crystal-controlled oscillators is not just a superposition of several noise processes over a narrow range of times, but rather represents a fundamental noise process within the oscillator. The flicker frequency level is most likely due to the quartz resonator. These data give an indication that quartz-crystal-controlled oscillators engineered to minimize the effects of changes in external parameters such as temperature, moisture, pressure, and load, may some day be used in areas which have traditionally been dominated by atomic frequency standards.

Acknowledgements

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