Correspondence

Temperature Stable Crystal Oscillator

John R. Vig, *Fellow, IEEE*, and Raymond L. Filler, *Member, IEEE*

***Abstract*—A crystal oscillator is proposed which can exhibit a frequency versus temperature stability comparable to that of the best atomic frequency standards.**

I. Introduction

Atomic frequency standards possess superior stability relative to crystal oscillators in the areas of frequency versus temperature (f versus T), frequency versus static acceleration (but not vibration), and aging. The purpose of this correspondence is to suggest that, using existing technologies, it ought to be possible to produce crystal oscillators which exhibit a frequency versus temperature stability comparable to that of the best atomic frequency standards.

The f versus T stability of an oven controlled crystal oscillator (OCXO) depends on: the static and dynamic f versus T characteristics of the resonator and the sustaining circuit, the difference between the oven set point and the point where the static f versus T characteristic has zero slope (i.e., the oven offset from turnover), the oven's temperature excursions from the set point (i.e., the oven "cycling" range), and the rate of change of temperature during the oven's temperature excursions [1]. The best OCXO's commercially available today exhibit f versus T stabilities of $\sim 10^{-10}$ over a temperature range of, e.g., -40°C to +75°C. The dynamic f versus T stability can dominate the static f versus T stability when the resonator is not thermal transient compensated (i.e., when it is not an SC-cut). For maximum stability, a thermal transient compensated resonator must be used. Many so-called SC-cut resonators exhibit a finite thermal transient effect. However, in the vicinity of the "true" thermal transient compensated cut, small changes in the angles of cut can produce either positive or negative thermal transient effects. The thermal transient effect is exactly zero at one set of angles of cut in the vicinity of $\theta = 34°$ and $\phi = 22°$. The exact values of the "true" SC-cut angles vary with resonator configuration. The OCXO's dynamic f versus T performance can also be influenced by factors such as transient effects in the oven control and sustaining circuit components [1]–[3].

II. Temperature-Stable OCXO

In [1] and in a recent paper on the fundamental limits to crystal oscillator stability [4], it was shown that, with proper care, extremely high f versus T stabilities ought to be achievable. Tables similar to Tables I and II were used to illustrate the possibilities. The static f versus T characteristic assumed in Table I is for an SC-cut resonator the turnover point T_{TP} of which is 10 K from the inflection point T_i [1]. The assumed f versus T characteristic for Table I is not the best f versus T that can be achieved. Fig. 1 shows the f versus T for the optimum resonator, i.e., for one where the turnover temperatures coincide with the inflection temperature [5], [6]. Such a resonator is not easy to make. However, with careful X-ray orientation and angle correction [7], recontouring [6], design and fabrication, it is possible to achieve close to such a f versus T characteristic. (The f versus T characteristic in Fig. 1 is of a resonator produced by recontouring.) The frequency offsets in Table I become much smaller for such a resonator, as can be seen in Table II. (A cubic f versus T was assumed in drawing the data for Fig. 1, and in calculating Tables I and II.)

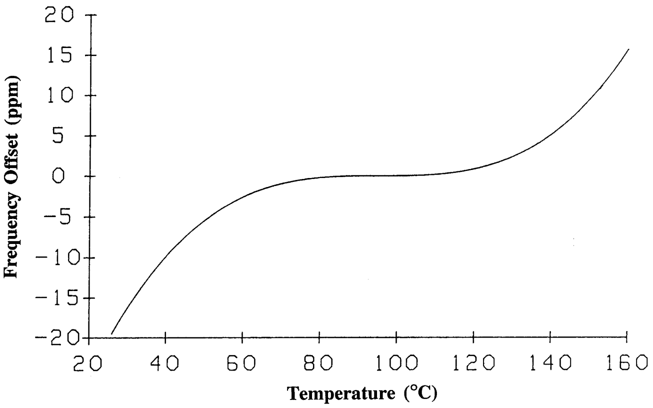

Fig. 1. Frequency versus temperature of an SC-cut resonator with zero f versus T slope at the inflection temperature [5], [6].

TABLE I
Frequency Offsets due to Thermal Cycling as a Function of the Offset of the Oven Set Point from the Resonator Turnover Point for $T_i - T_{\mathrm{TP}} = 10°\mathrm{K}$

for T_i - T_{TP} = 10°K		Oven Cycling Range (mK)			
		100	**10**	**1**	**0.1**
Oven Offset (mK)	**1000**	4×10^{-10}	4×10^{-11}	4×10^{-12}	4×10^{-13}
	100	6×10^{-11}	4×10^{-12}	4×10^{-13}	4×10^{-14}
	10	2×10^{-11}	6×10^{-13}	4×10^{-14}	4×10^{-15}
	1	2×10^{-11}	2×10^{-13}	6×10^{-15}	4×10^{-16}

How accurately one can set the oven temperature to the optimum set point depends primarily on the hysteresis of the resonator and of the thermometer. Secondary factors are the noise of the resonator, thermometer and amplifier [4]. If, for example, the normalized beat frequency between three times the fundamental mode frequency minus the third overtone frequency is used as the thermometer [8], then the slope of this frequency is about 10^{-4}/K, and the hysteresis of such SC-cut resonators (over a much wider temperature than is necessary for setting the oven to turnover) is about 10^{-8}. Therefore, in principle, the temperature can be set to within about 10^{-4} K of the optimum set point.

The stability of an oven depends on the temperature changes in the oven's environment and on the thermal design of the oven. Excellent oven stability can be obtained, even with a single oven, if the oven

Manuscript received August 2, 1994; revised October 10, 1994; accepted October 23, 1994.

The authors are with the Frequency Control and Timing Branch, U.S. Army Research Laboratory, AMSRL-PS-ED, Fort Monmouth, NJ 07703-5601 USA.

IEEE Log Number 9410106.

TABLE II
FREQUENCY OFFSETS DUE TO THERMAL CYCLING AS A FUNCTION OF THE OFFSET OF THE OVEN SET POINT FROM THE RESONATOR TURNOVER POINT FOR $T_i - T_{TP} = 0°K$

for T_i - T_{TP} = 0°K		Oven Cycling Range (mK)			
		100	10	1	0.1
Oven Offset (mK)	1000	2×10^{-11}	2×10^{-12}	2×10^{-13}	2×10^{-14}
	100	4×10^{-13}	2×10^{-14}	2×10^{-15}	2×10^{-16}
	10	8×10^{-14}	4×10^{-16}	2×10^{-17}	2×10^{-18}
	1	6×10^{-14}	8×10^{-17}	4×10^{-19}	2×10^{-20}

TABLE III
TYPICAL FREQUENCY VERSUS TEMPERATURE STABILITIES OF COMMERCIALLY AVAILABLE ATOMIC STANDARDS

Atomic standard type	f vs. T stability	Temperature range (°C)
Small rubidium	3×10^{-10}	-55 to +65
Militarized cesium	2×10^{-11}	-28 to +65
Commercial cesium	1×10^{-13}	0 to +50

is designed properly [9], [10]. A thermal gain of 10^5 can be achieved with a single oven [4], [9]; e.g., if the environment changes by 100 K, the inside temperature of the oven changes by only 1 mK. According to Table II, if the oven is stable to 1 mK, then, as long as the oven offset is no worse than about 0.5 K, the OCXO's instability due to temperature fluctuations will be less than its short term instability, $\sigma_y(\tau)$. Of course the sustaining circuit, output amplifier and oven control circuits must also be carefully designed and temperature controlled in order to insure that the stabilities shown in Tables I and II can be realized. Careful attention must also be paid to other design aspects; e.g., the oscillator would need to be hermetically sealed in a rigid enclosure in order to minimize pressure and humidity effects [4].

Table III shows typical f versus T stabilities of the major types of commercially available atomic frequency standards. It is clear from Tables II and III that f versus T stabilities comparable to those of the atomic standards ought to be achievable with a properly made OCXO.

If such an OCXO also has an aging rate of, for example, 4×10^{-11} per day, which the best available OCXO's can achieve after extended operation [11], then the OCXO can maintain, for periods up to about two weeks, a frequency accuracy equal to or better than the accuracy of a miniature rubidium standard. Of course there are tradeoffs; e.g., retrace effects (parts in 10^{10} even in the best of OCXO's) would require the OCXO to remain powered continuously, or to be recalibrated after turn-on, in order to maintain the high accuracy, and OCXO's require a much longer stabilization time in order to achieve parts in 10^{11} per day aging rates. On the other hand, commercially available OCXO's typically have better reliability and short term stability, lower cost, longer life, smaller size and power requirements, and can operate over a wider temperature range than commercially available atomic standards.

A possible difficulty with achieving the temperature stable OCXO is as follows. The above discussion assumes that the f versus T characteristic near the turnover temperature is smooth, and can be represented by a cubic polynomial. These assumptions seem to be correct in most measurements, however, most measurements of f versus T are made with resolution of parts in 10^9 or coarser. This is especially true for other than SC-cut resonators for which the thermal transient effect would make higher resolution measurements virtually impossible. There is some preliminary information [12], [13] which indicates that when the f versus T characteristic of SC-cut resonators and oscillators are examined with high resolution, fine structure is revealed, i.e., the f versus T is not smooth. It has also been found that a cubic polynomial representation of f versus T is insufficient over a wide temperature range; much higher order polynomials or segmented polynomials or splines are needed in order to obtain a good fit to the data [8], [13]. Should fine structure in the f versus T be a universal phenomenon, then the difficulty of setting the oven temperature to a zero temperature coefficient point would be greatly increased and the frequency offsets in Tables I and II would also increase. Another difficulty to be overcome is the acceleration sensitivity of the oscillator. Although the fundamental limit to the acceleration sensitivity is zero [4], the best currently available oscillators possess acceleration sensitivities of 10^{-10} per g, so, until the acceleration sensitivity is greatly reduced, either the attitude of the oscillator will need to be controlled, or acceleration compensation will need to be used in order to be able to take advantage of the proposed temperature stability. Otherwise, attitude changes as small as $\sim 10^{-2}$ radians would cause frequency changes of $\sim 10^{-12}$.

III. POSSIBLE APPLICATIONS

The temperature stable OCXO proposed would be especially useful in applications where a recalibration capability (e.g., with the aid of a GPS receiver) is frequently but not necessarily continuously available, e.g., in mobile applications where the user returns to a base station at the end of a day (or mission) and where the base station has a calibration facility which can automatically recalibrate the OCXO—e.g., at the same time as the batteries are being recharged. Such an OCXO plus recalibration system may be preferable in some situations to an OCXO which is continuously locked to GPS [14].

Another application is in GPS receivers where rapid reacquisition of the GPS signal is desired after a loss of lock (e.g., among tall buildings or under heavy foliage). The proposed oscillator could maintain a 100 ns accuracy for periods of at least an hour after a loss of lock, provided that the aging rate is less than 6×10^{-11} per hour (i.e., 1.4×10^{-9} per day). The proposed oscillator could maintain a 100 μs accuracy for more than two days after a loss of lock, provided that the aging rate is less than 1×10^{-9} per day.

ACKNOWLEDGMENT

This correspondence is a "spin-off" from the collaborations reported in [1] and [4]. The authors acknowledge that without the discussions with Arthur Ballato and Fred Walls which led to those papers, this correspondence would probably not have been written.

REFERENCES

[1] A. Ballato and J. R. Vig, "Static and dynamic frequency-temperature behavior of singly and doubly rotated oven controlled quartz resonators," in *Proc. 32nd Annu. Symp. Freq. Cont.*, 1978, pp. 180–188.
[2] J. A. Kusters, "The SC-cut crystal—An overview," in *Proc. IEEE Ultrason. Symp.*, 1981, pp. 402–409.
[3] E. P. EerNisse and J. A. Kusters, "Orientation dependence of 'True' SC-cuts," in *Proc. 44th Annu. Symp. Freq. Cont.*, 1990, pp. 185–192.
[4] J. R. Vig and F. L. Walls, "Fundamental limits on the frequency instabilities of quartz crystal oscillators," in *Proc. 1994 IEEE Int. Freq. Cont. Symp.*, 1994, pp. 506–523.
[5] J. R. Vig, "Quartz crystal resonators & oscillators—For frequency control and timing applications—A tutorial," R&D Technical Report SLCET-TR-88-1 (Rev. 7.0) (AD-A284995), Aug. 1994.
[6] J. R. Vig, W. Washington and R. L. Filler, "Adjusting the frequency versus temperature characteristics of SC-cut resonators by contouring," in *Proc. 35th Annu. Symp. Freq. Cont.*, 1981, pp. 104–109.
[7] C. A. Adams, D. C. Bradley, and J. A. Kusters, "X-ray technology—A review," in *Proc. 41st Annu. Symp. Freq. Cont.*, 1987, pp. 104–109.

[8] R. L. Filler and J. Vig, "Resonators for the microcomputer-compensated crystal oscillator," in *Proc. 43rd Annu. Symp. Freq. Cont*., 1989, pp. 8–15.
[9] F. L. Walls, "Analysis of high performance compensated thermal enclosures," in *Proc. 41st Annu. Symp. Freq. Cont*., 1987, pp. 439–443.
[10] R. Brendel *et al*., "Improved OCXO's oven using active thermal insulation," *IEEE Trans. Ultrason., Ferroelect., Freq. Cont*., vol. 41, pp. 269–274, 1994.
[11] R. L. Filler and J. R. Vig, "Long term aging of oscillators," *IEEE Trans. Ultrason., Ferroelect., Freq. Cont*., vol. 40, 1993, pp. 387–394.
[12] M. Bloch, private communication, Sept. 1994.
[13] R. L. Filler, "Frequency-temperature considerations for digital temperature compensation," in *Proc. 45th Ann. Symp. Freq. Cont*., 1991, pp. 398–404.
[14] J. A. Kusters *et al*., "A no-drift and less than 1×10^{-13} long term stability quartz oscillator using a GPS S/A filter," in *Proc. 1994 IEEE Int. Freq. Cont. Symp*., 1994, pp. 572–577.