CRYSTAL RESONATOR/OSCILLATOR TEST FACILITY and TEST RESULTS

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Introduction

The primary mission of the Frequency Control and Timing Branch of the U.S. Army Electronics Technology and Devices Laboratory (ETDL) is to advance the state of the art in quartz crystal resonators and oscillators in order to meet the requirements of military users. Secondary missions include consultative support to project managers and systems designers and the maintenance of the military specifications for quartz crystal resonators and crystal oscillators (i.e., MIL-C-3098[1] and MIL-O-55310.[2])

These activities require an intimate and practical knowledge of the state-of-the-art.

In the course of fulfilling the above missions and activities, comprehensive test facilities have been established at ETDL for quartz crystal resonators and oscillators. The purpose of this paper is to outline the capabilities of the laboratory, present the results of some investigations, and offer to DOD-sponsored users our assistance with the testing, selection, specification and development, when necessary, of crystal oscillators.

Crystal Resonator Test Facility

Computer controlled instruments such as impedance instruments and Pi network/vector voltmeter combinations are used to measure resonators' frequency and equivalent circuit parameters, i.e.,the motional resistance, motional capacitance, motional inductance, and shunt capacitance.[3,4]

For room temperature measurement of equivalent circuit parameters, the impedance instruments have been found to be convenient and accurate. All parameters can be measured as a function of drive current and various environmental stimuli such as radiation, shock, etc.

Frequency versus temperature (f-T) and resistance versus temperature (R-T) measurements are done with a multiposition pi network system. The pi networks are inexpensive thick film resistors deposited on ceramic substrates. The input and output are isolated by more than 100 dB by incorporating appropriate shielding between the network halves, then enclosing the whole assembly in an aluminum "minibox". Short circuit amplitude and phase data for each network are stored in the computer. A block diagram of the "temperature run" system is shown in Figure 1.

Each resonator to be measured is inserted into a pi network and the chamber is set to the lowest test temperature for a low temperature "soak". Temperature is then increased, stepwise, until the highest test temperature is reached. Frequency and pi-network input and output voltages are measured, after an appropriate stabilization time, prior to the next temperature step. This is called a "quasi static" temperature profile.

Figure 2 is a representation of the time-temperature profile used for these tests. For a single temperature run, only the first half of the cycle is used. For thermal repeatability and hysteresis measurements, reverse cycles are also used. The cycles are repeated when thorough hysteresis data is desired.

The data are stored and at the conclusion of a run the f-T and R-T data are plotted. Third- and fourth-order polynomials are fitted to the f-T data using a least squares technique. The third order polynomial is used to calculate upper and lower turning points, inflection temperature, and the frequency temperature slope at inflection. The fourth order curve is included for more accurate representation of the data, if needed. A typical temperature run plot is shown in Fig. 3.

If thermal hysteresis or thermal repeatability measurements are desired, the above process is modified. To measure thermal hysteresis, a technique has been evolved which allows self measurement of the resonator temperature via the excitation of two modes in the resonator.(5) This avoids the apparent hysteresis caused by thermal lag or thermal gradients between the temperature sensing probe and the resonator.

Thermal hysteresis as good as 5×10^{-9} has been measured. Figure 4 shows the results obtainable using the hysteresis test set. In the figure, the abscissa represents temperature and the ordinate represents the values of the residuals after a 6th order polynomial (fitted to the first f-T run) is subtracted from the data of the first run and from three subsequent runs. The hysteresis manifests itself as the spread of the residuals to a fitted polynomial curve. Deviation from the horizontal axis is indicative of the quality of the polynomial fit.

A parameter of increasing interest is the sensitivity of resonators to acceleration or vibration. The sensitivity is represented by Γ and is determined by measuring the "2g tipover" or vibration-induced sidebands.(6)

The "2g tipover" test is accomplished by incorporating the resonator in a stable OCXO and placing the oscillator into a fixture which has a horizontal axis of rotation. The operator rotates the oscillator, stepwise, through 360 degrees. At each step the frequency is measured and recorded. The frequency versus angle data is fitted to a sine curve. Next, the oscillator is rotated 90 degrees such that the axis which was initially horizontal is made vertical. Frequency is recorded and the oscillator is tipped 180 degrees. The frequency is again recorded. The three components of the acceleration sensitivity vector can then be determined and the sensitivity vector, $\vec{\Gamma}$, calculated.

A representative curve and calculated acceleration sensitivity are shown in Figure 5.

To determine whether there are vibration resonances in the resonator structure, the vibration-induced sidebands are measured as a function of vibration frequency, as follows. A test oscillator, containing the resonator under test, is completely filled with wax (potted), rigidly fastened to the shake table surface, and subjected to sine wave excitation over a range of 50 Hz to 2000 Hz. Oscillator output is mixed down to audio frequency and displayed on a spectrum analyzer. Vibration sideband amplitudes are measured and the components of Γ are calculated from the relation:

$$\gamma_i = \frac{2\,F_{vi}}{afo}\ 10^{\mathcal{L}/20}$$

where F_{vi} is vibration frequency in the i direction, a is acceleration, fo is the oscillator frequency, and L is the sideband amplitude in dBc. A representative L versus F_v curve is shown in Figure 6.

Aging, Allan Variance, and phase noise tests are generally performed with a specially designed test oscillator.[7] The test oscillator oven temperature is externally adjustable to facilitate setting to the turnover temperature. Resonator drive current is also externally adjustable. Some models of the test oscillator have ovens settable to below -60°C for low temperature aging and stability studies. The aging measurements are straightforward, data being automatically taken every workday. Periodically, the aging data are plotted and fitted to logarithmic, exponential, or combined log-exponential functions.

Allan Variance and phase noise measurements generally follow the procedures of NBS Monograph 140.[8] The oscillator under test is quadrature phase locked to a reference oscillator to suppress the carrier. Mixer output is displayed on a baseband spectrum analyzer which can be under computer control.

Oscillator Test Facility

Frequency versus temperature tests for complete oscillators are performed in a manner similar to the corresponding resonator test, according to the block diagram in Figure 7.

The apparatus can accomodate 150 oscillators. The power supply leads are isolated and filtered at each oscillator position to avoid crosstalk via the power supply leads. Each oscillator is terminated according to its specification, then matched to 50 ohms for a coaxial cable feed to the RF selector switch.

A temperature run starts with a two hour stabilization at 30°C. At this point, any required frequency adjustments are made. For example, TCXO may be adjusted to their marked calibration offset frequency, or offset by a predetermined amount to observe the trim effect. (The trim effect is the rotation of the resonator f-T characteristic caused by varying the load capacitor). After this initial interval, a temperature profile similar to Fig. 2 is followed, except that longer stabilization times are used to accomodate the thermal time constants of oscillators. Frequency is recorded every degree during the up- and down-cycles.

Upon completion of the temperature run, the chamber is again set to 30°C and a final frequency measurement is made after two hours. Figure 8 is a representative plot a TCXO f-T curve.

The two plotted curves depict the frequency versus temperature behavior in the temperature-increasing and temperature-decreasing directions. The left hand column of figures gives the maximum frequency and the minimum frequency measured during the temperature increasing half of the run. Also in the first column is the frequency at 30°C, taken "on the fly", and the slope of the f-T curve at 30°C. The center column gives similar figures for the temperature-decreasing half of the cycle.The right hand column gives the maximum and minimum frequencies recorded for the full cycle. These are used to compute stability according to the formula:

$$\frac{F_{max} - F_{min}}{2}$$

The "del F offset" figure is the frequency offset to which the oscillator must be adjusted (at 30°C) to center the maximum and minimum frequencies about the horizontal (nominal frequency) axis.

Thermal hysteresis can also be determined from the plotted data. This determination is made by measuring the separation of the two curves at each temperature. The maximum deviation is assigned as the hysteresis for the oscillator.

The trim effect is observed by offsetting the oscillator by means of the frequency adjust control as would be required to compensate for aging or other environmental effects. After each frequency adjustment the f-T run is repeated. Figure 9 is a plot of the trim effect for a TCXO.

Frequency aging measurements for oven controlled crystal oscillators (OCXO) are accomplished at laboratory room temperature, (oscillator oven energized, set to resonator upper turning point) and present no particular problem.

For TCXO's, the definition of aging is somewhat clouded: The effect of temperature on aging has not yet been determined; A "standard" TCXO aging temperature has not been defined, there is also the question of whether aging data taken at a constant temperature can be used to predict how an oscillator will age when it is subjected to variations in temperature.

Notwithstanding these issues, aging measurements are now made at 60°C for at least 30 days. The temperature chamber used for this test has been observed to be stable to ±0.05°C over a 30 day period.

Several additional tests which are soon to be implemented are: observation of hysteresis during repeating temperature cycling (twenty °C and one hundred °C swings); trim effect after repeated thermal cycling, hot soak, and cold soak; and aging at various temperatures and after repeated thermal cycling.

Allan Variance and phase noise testing are done as explained above for resonators.

Vibration testing, likewise, is similarly performed except that no potting is used. Peaks in the acceleration sensitivity curve, caused by resonating loose components, wires, or flexing circuit boards can, therefore, be seen. An example of an oscillator suffering this type of defect is seen in Figure 10.

Test Program Results

The results of a continuing oscillator testing program have been reported in detail elsewhere.[9,10]

Table I is a summary of the results to date of that TCXO testing program. From the table, it can be seen that the likelihood of finding TCXO that meet specifications diminishes as the specified stability improves.

Not included in the table are the latest measurements of the trim effect. The data are disappointing, showing that there are no TCXO in the 0.5 ppm stability class that can safely be designed into systems that have as little as five years expected life.

Conclusion

The Frequency Control and Timing Branch of the U.S. Army Electronics Technology and Devices Laboratory (Fort Monmouth, NJ) has established a comprehensive facility for the testing and characterization of quartz crystal resonators and oscillators.

The Branch is happy to offer to military users its assistance with the testing, selection, specification and development of crystal oscillators.

References

1. Military Specification; Crystal Units, Quartz, General Specification for, 1979

2. Military Specification: Oscillators, Crystal, General Specifications for, 1976

3. "Crystal Parameter Measurement Methods", Final report, contract Nr. DAAK-20-82-C-0390, 1983

4. Basic method for the measurement of resonance frequency and equivalent series resistance of quartz crystal units by zero phase technique in a pi network, Publication No. 444, Bureau Central de la Commision Electrotechnique Internationale, Geneva, Switzerland

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9. "Temperature Compensated Crystal Oscillator Survey and Test Results", V. Rosati, S. Schodowski, and R. Filler, Proc 37th Annual Frequency Control Symposium, IEEE Catalog No. 83CH1957-0, June 1983.

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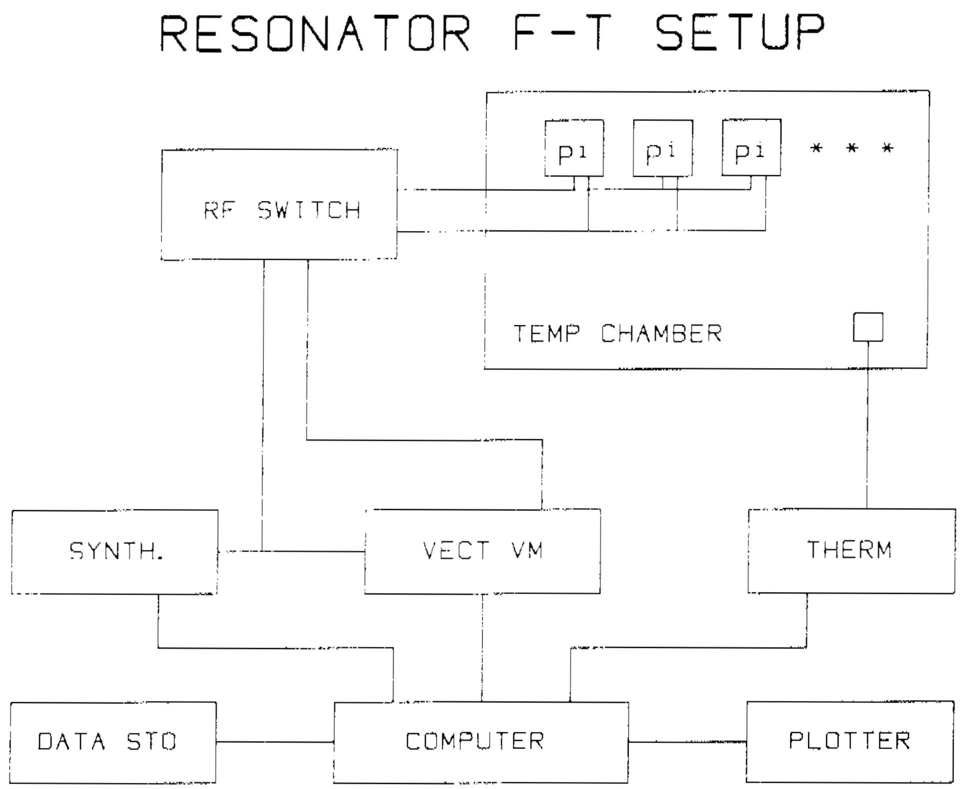

Fig. 1. Block diagram of resonator f-T apparatus.

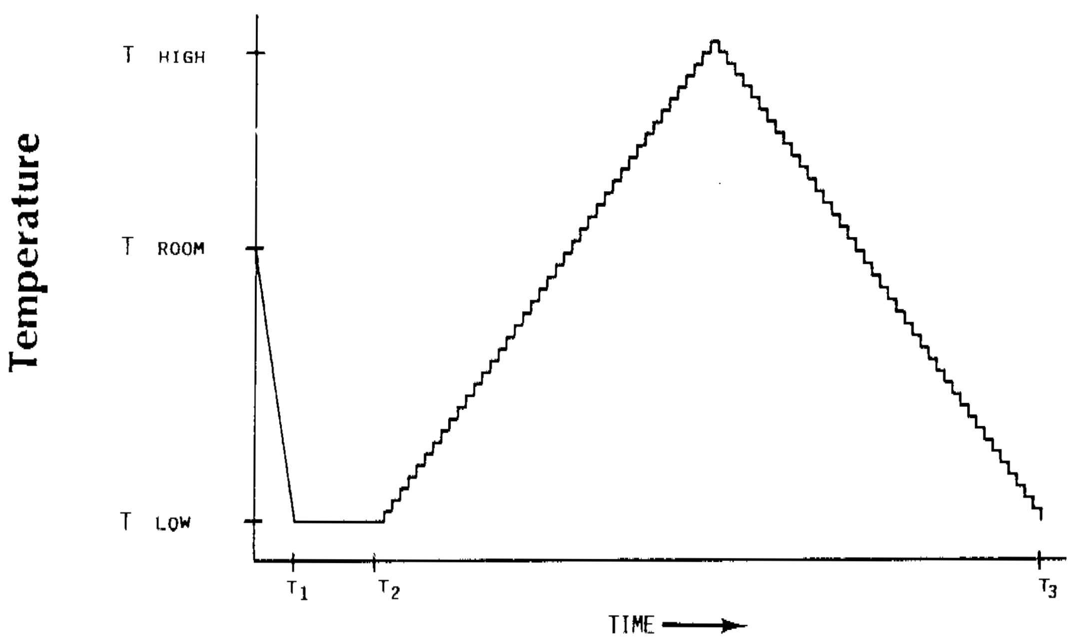

Fig. 2. Stepwise time/temperature profile.

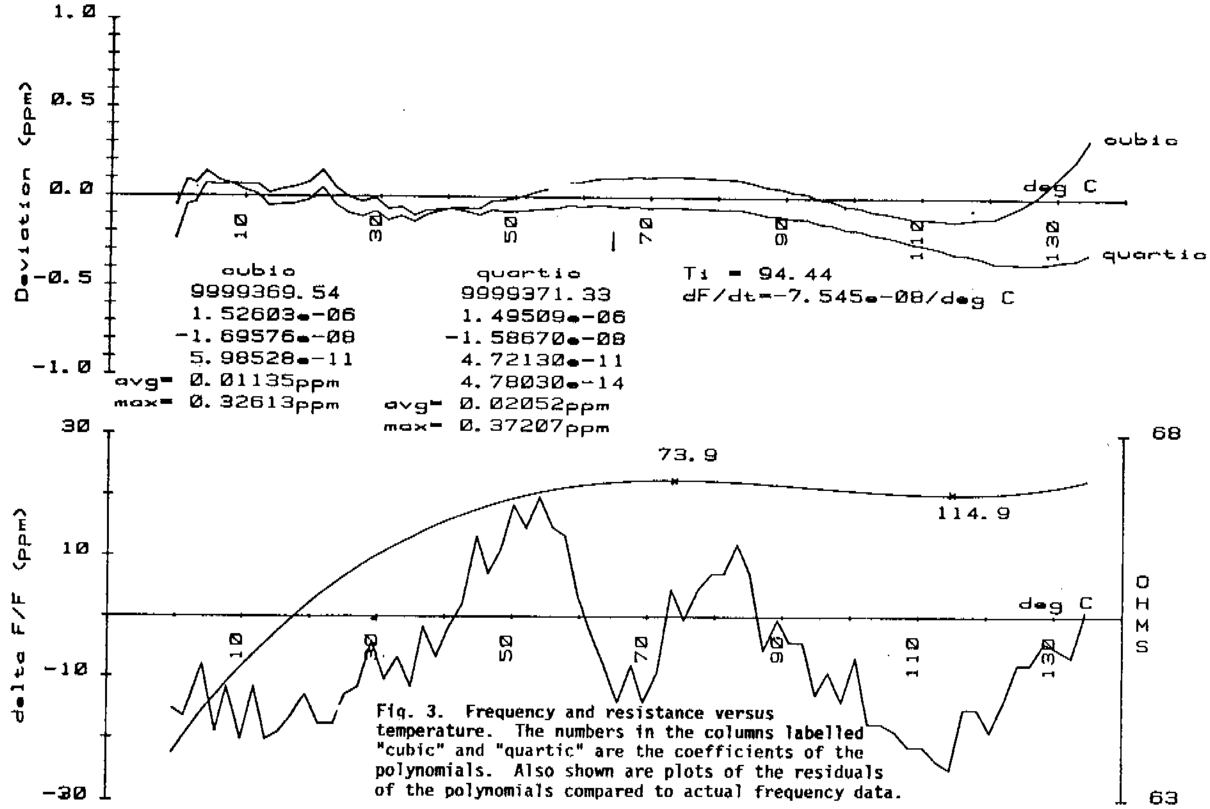

Fig. 3. Frequency and resistance versus temperature. The numbers in the columns labelled "cubic" and "quartic" are the coefficients of the polynomials. Also shown are plots of the residuals of the polynomials compared to actual frequency data.

RESONATOR THERMAL HYSTERESIS

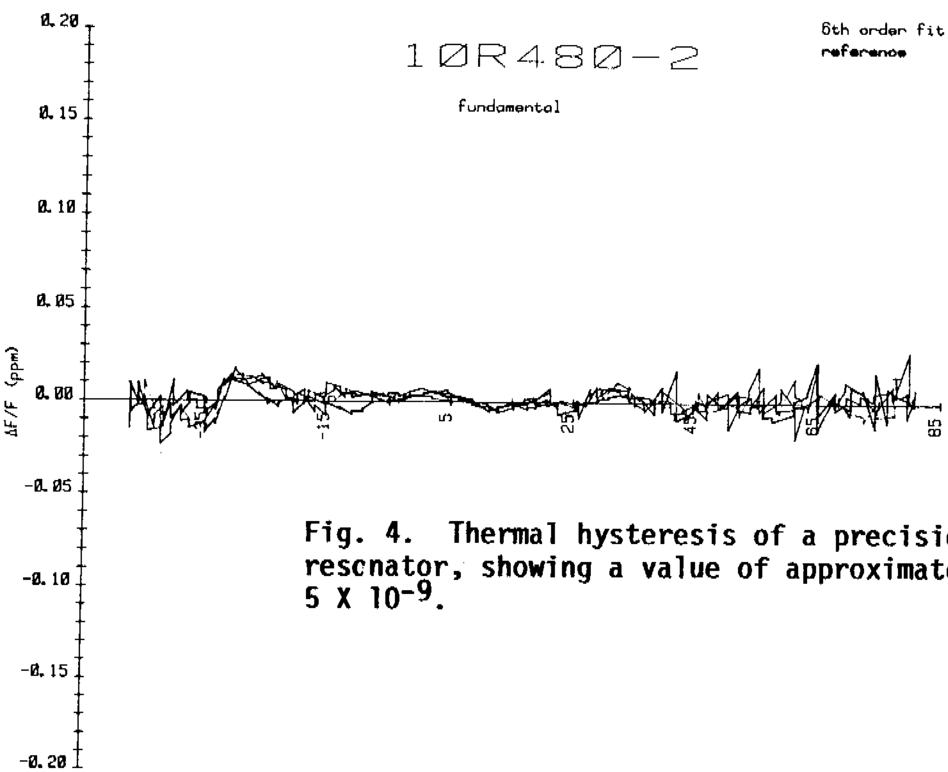

Fig. 4. Thermal hysteresis of a precision resonator, showing a value of approximately 5 X 10^{-9}.

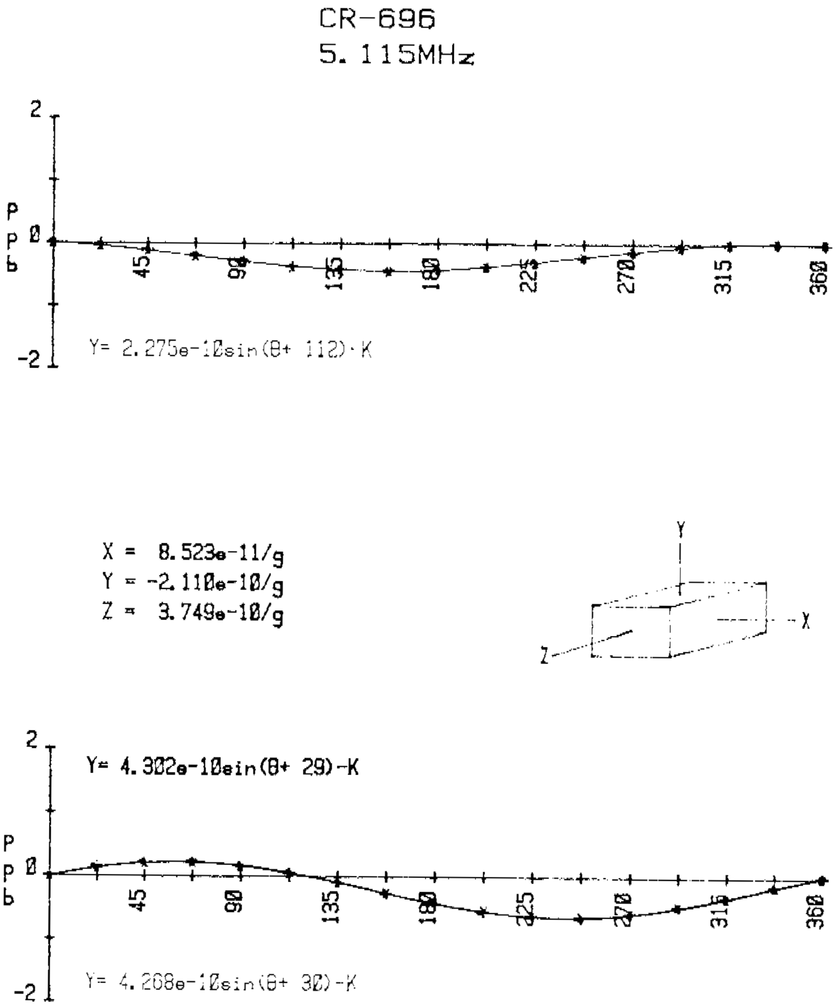

Fig. 5. "Two g tipover" results. The x, y, and z values are the components of the sensitivity vector, $\vec{\Gamma}$.

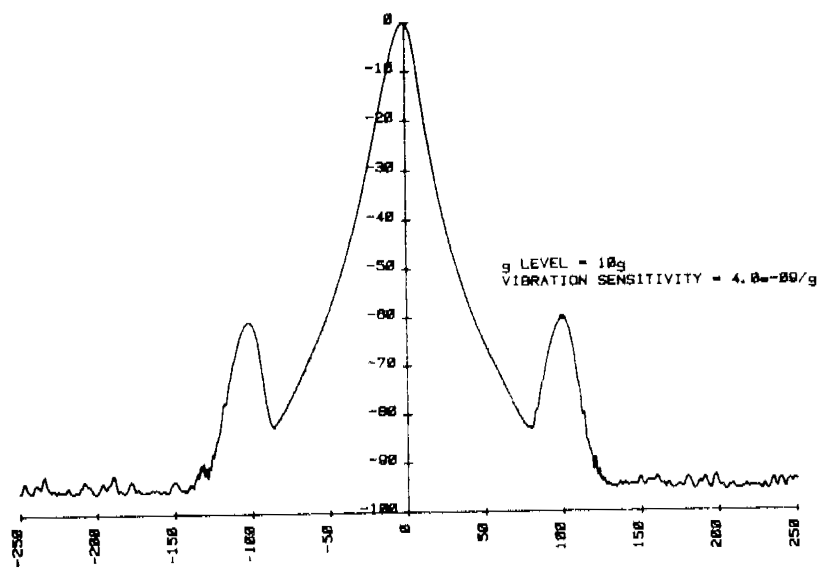

Fig. 6. Vibration-induced sidebands resulting from g acceleration at 100 Hz. The measured sensitivity of this resonator is 4 X 10^{-9}/g in the direction of vibration.

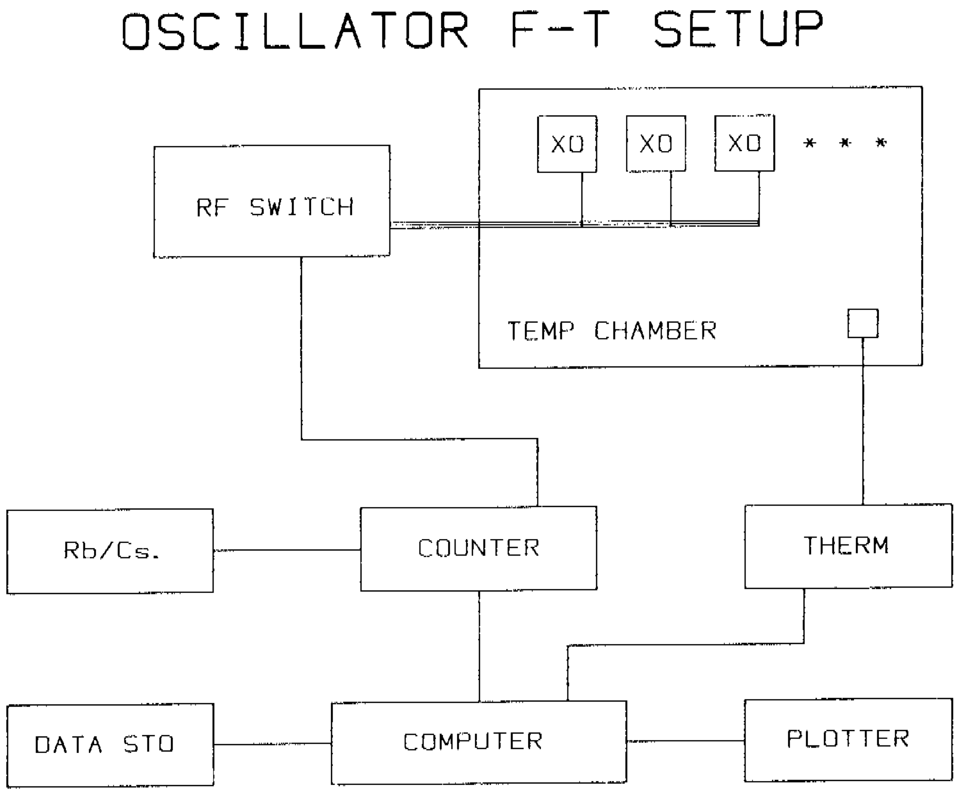

Fig. 7. Block diagram of oscillator f-T apparatus.

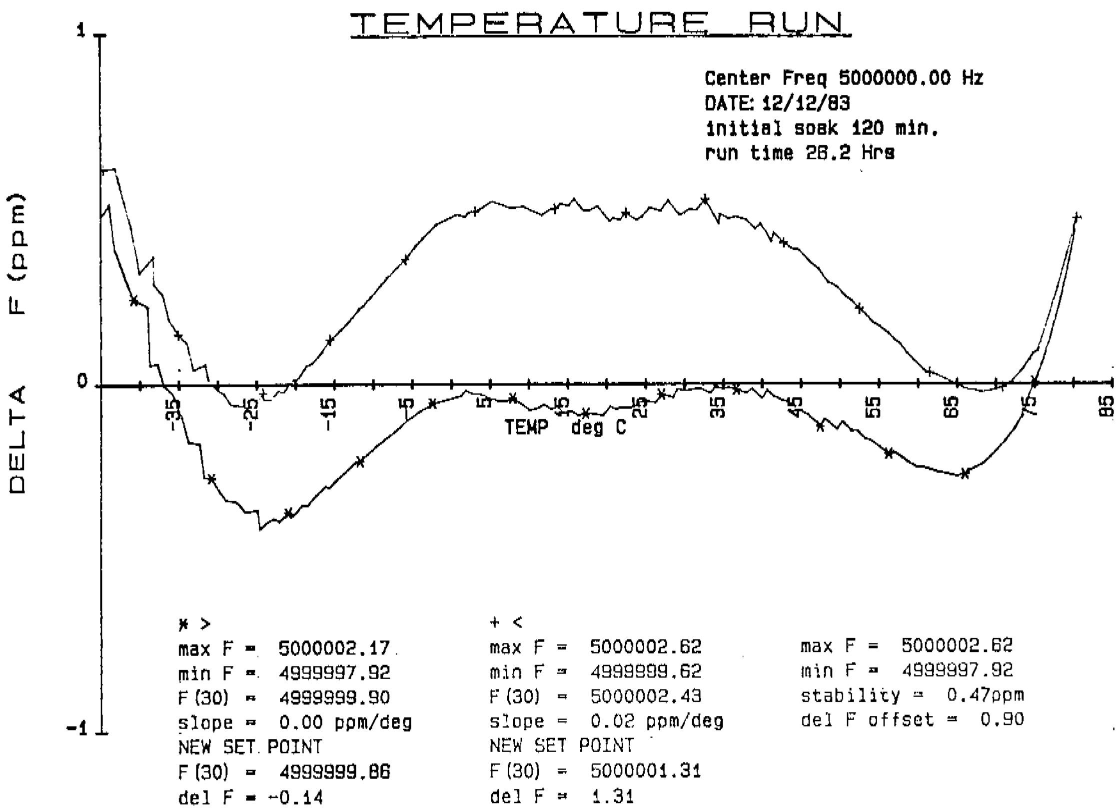

Fig. 8. Representative TCXO f-T curve. The thermal hysteresis of this oscillator is about 0.6 ppm.

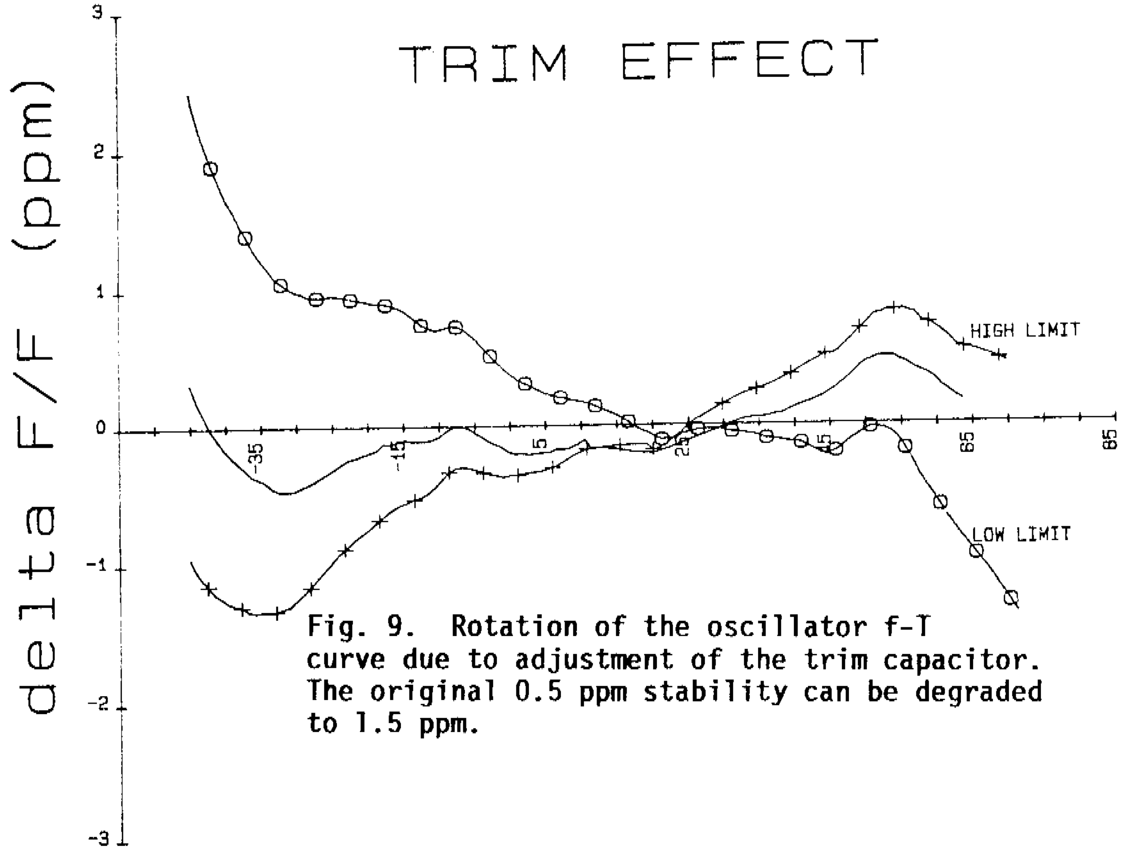

Fig. 9. Rotation of the oscillator f-T curve due to adjustment of the trim capacitor. The original 0.5 ppm stability can be degraded to 1.5 ppm.

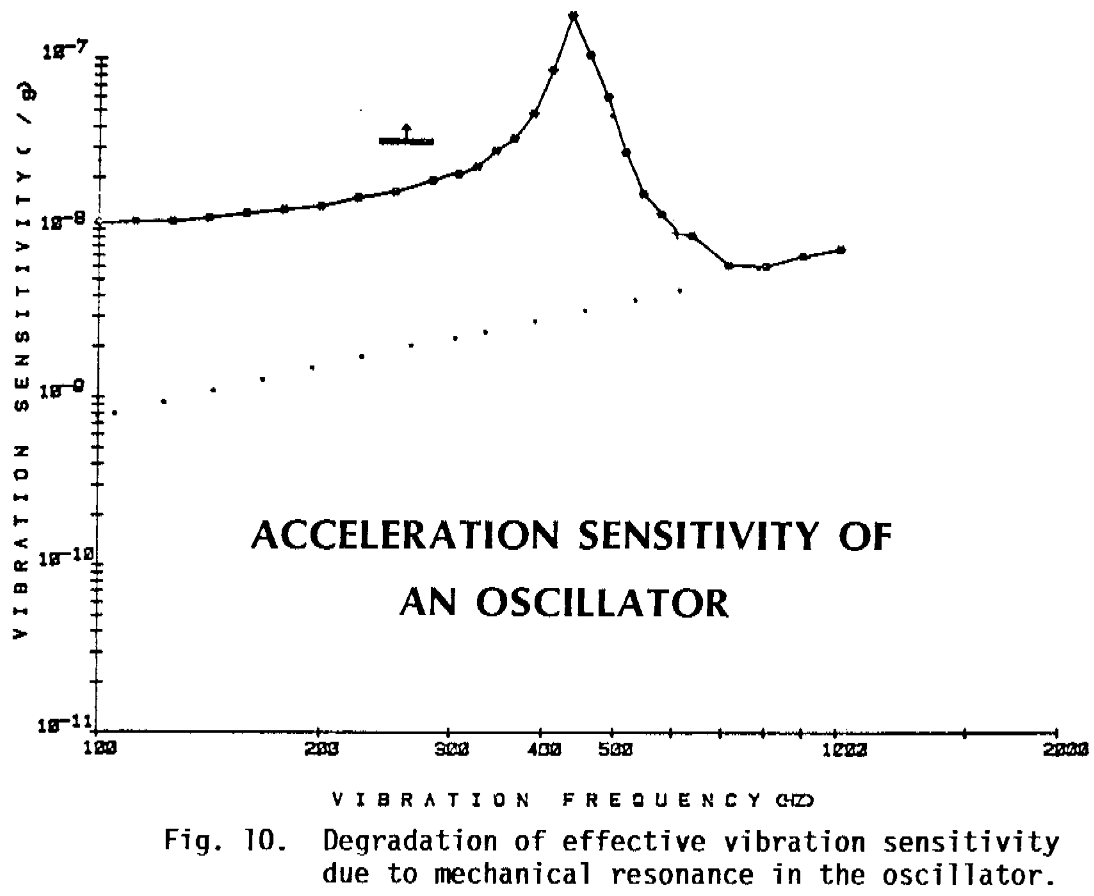

Fig. 10. Degradation of effective vibration sensitivity due to mechanical resonance in the oscillator.

SUMMARY OF ALL OSCILLATORS

Stability Claimed (ppm)	f-T Stability #Tested	f-T Stability #Failed	Aging/mo (ppm)
5	30	1	0.2
3	5	0	.25 (E)
2	5	0	.57
1	5	1	.18
0.6	5	5	.34
0.6	5	1	.5 (E)
0.5	5	3	.30
0.5	25	16	.36
0.5	5	2	---

E = erratic

Table I. Summary of the results of testing a group of 90 TCXO. Details of the study can be found in references 8 and 9.

QUESTIONS AND ANSWERS

A VOICE:

That blue slide on the summary, I can't understand that slide as saying that if you need stability or ageing of a half a part per million what you should do is order the cheapest and don't specify.

MR. ROSATI:

If you don't specify anything, I don't know what you would get.

DR. WINKLER:

Well, the conclusion is to spend the least amount of money on procurement and most of it on testing.

MR. ROSATI:

Absolutely. That is what we are trying to get across, that money spent up front in testing and guaranteeing that the oscillator will be good, delivers a good payoff in the logistic costs later on.