Heating and thermostatic analysis of an oven-controlled quartz crystal oscillator

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ABSTRACT
An oven-controlled crystal oscillator (OCXO) uses thermostatic regulation to stabilize the output frequency by maintaining the temperature of the quartz crystal oscillator at a fixed level. The OCXO is heated by a chip which holds the temperature of the device at a working level of between 80 and 105 °C to stabilize the output frequency. In this study, finite element analysis was used to simulate heating of the OCXO element. The heating temperature vs. time change, when heat is transferred to the quartz crystal, and the quartz crystal thermostatic time variation vs. the quartz temperature distribution, were both investigated. The results were compared by simulation of the behavior of the quartz oscillator in a nitrogen and helium environment and also under vacuum.

1. Introduction
The high frequency stability of the quartz oscillator is well known and they are used in many scientific and technical applications including communications, navigation, electronic measuring equipment, etc. In the last few decades, the crystal oscillator is an indispensable device used in all physical laboratories, in electronics and engineering, and every other technical industry. The physical mechanism by which the quartz crystal oscillator operates is called the piezoelectric effect. The exponential growth of the communications industries has caused much serious attention to be paid to the frequency stability of these devices. The oscillation frequency of a quartz crystal is extremely sensitive to the environment. The slightest change in temperature, pressure, humidity, acceleration, etc. can cause the frequency to change. In 1988 and 1992, Walls et al. studied the effects of all such environmental changes on electronic oscillators of various kinds. It was found that pressure and humidity have a more serious effect on an open-type oscillator while quartz crystal oscillators are more sensitive to changes in temperature. [1–3]

As a response to the need to reduce the effect of temperature, both the OCXO and the temperature compensation type of crystal oscillator were developed. Although temperature compensation can improve frequency stability, devices of this type are subject to changes due to aging and some studies have been made with respect to a reduction in this effect. [4,5] On the other hand, the oven-controlled quartz crystal oscillator keeps the ambient temperature of the quartz crystal within a fixed temperature range and output frequency changes from temperature variation can be virtually eliminated.

However, keeping the temperature of the quartz crystal within a narrow range requires a differential series amplifier with a thermistor bridge and these things occupy space and also require input power. In this study, small physical size and low power were key points. [6,7] Amongst the many studies in this area, [8–13] some did consider low power and small size but the majority concentrated on temperature. [9–11] For these, a vacuum environment also became a choice to reduce heat loss. [12,13] However, filling with other gases can also lead to a reduction in heat transfer and is also worth investigation.

In this paper we used finite element analysis to compare simulations of the behavior of a quartz crystal oscillator with respect to temperature fluctuation when it was operated in vacuum, or in the presence of nitrogen or helium. We also simulated the steady state thermostatic power and observed conditions after heating was stopped within the working range, to determine power loss.

2. Finite element analysis
Although the thermostatic bath of the OCXO keeps the quartz crystal within a preset working temperature range the oscillator is enclosed and measurements can only be
made of the overall temperature of the OCXO, accurate reading of internal temperature of the quartz crystal is not possible. Finite element analysis can make simulations for different boundary parameter settings and COMSOL Multiphysics software was used to analyze heat conduction as well as changes in the behavior of the quartz crystal and simulate different heating element power. It can also accurately measure the temperature changes in the crystal and help in the selection of more suitable materials as well as determination of the thermostatic power involved in these temperature changes.

2.1. Model

The fundamental law governing all heat transfer is the first law of thermodynamics, commonly referred to as the principle of conservation of energy. However, internal energy is a rather inconvenient quantity to measure and use in simulations. Therefore, the basic law is usually rewritten in terms of temperature. The equation governing pure conductive heat transfer in a solid is [14]:

\[ \rho C_p \frac{dT}{dt} + \nabla \cdot (-k \nabla T) = Q \]  (1)

where \( \rho \) is the density; \( C_p \) is the specific heat capacity at constant pressure; \( T \) is absolute temperature; \( k \) is the thermal conductivity and \( Q \) contains heat sources other than viscous heating.

The model we use has the real dimensions of an oven-controlled quartz crystal oscillator as shown in Figure 1. Some unnecessary parts and assemblies not essential to function have been left out. This not only reduces the number of grids, but also increases the speed of simulation analysis. The parts included are the heating element, electric circuit board, copper foil, quartz oscillator and housing. The inside of quartz crystal housing is either under vacuum, or filled with nitrogen or helium to observe the effect on temperature (see Figure 2).

The present study discussed the time-dependent heat transfer modulus. All data analysis in the study was conducted by a server computer with an Intel CPU E5520 2.27 GHz (dual processor) and 144 GB of memory. According to detailed analysis results, the grid settings were able to produce favorable convergence results.

2.2. Boundary condition-highly conductive layer

Heat is transferred from the electric circuit board, which is made of FR4, to the quartz crystal. The thermal conductivity coefficient of the board material is 0.3 W/(m*K). According to Fourier’s law [15]:

\[ Q = -kA \frac{\Delta T}{\Delta x} \]  (2)

where \( A \) is the cross-sectional area and \( \Delta T/\Delta x \) is the temperature gradient. The thermal conductivity coefficient of the copper foil on the circuit board is 400 W/(m*K), which is greater than that of the board and simulation analysis was carried out on the heat transfer of the copper foil. The highly heat conductive thin copper foil was set as a boundary and this reduced the number and the density of the grids and also effectively reduced the time taken for simulation.

2.3. Boundary condition-heat convection in OCXO

Heating was done inside the housing by natural convection and was not affected by the external environment. The coefficient of natural heat convection is about 5–25 W/(m^2*K). Many factors affect heat convection such as, flow velocity, temperature, viscous force, etc. and need consideration. One of the most common boundary conditions when modeling heat transfer is convective cooling or heating whereby a fluid cools a surface by natural or forced convection. In this paper, modeling this process was adopted by a heat transfer coefficient on the convection-cooled surfaces. For most engineering purposes, the use of heat transfer coefficients is an accurate and numerically efficient modeling approach.[14]

This study then modeled convection cooling by specifying the heat flux on the boundaries that interface with the cooling fluid as being proportional to the...
temperature difference across a fictitious thermal boundary layer. The flux in terms of a heat transfer coefficient, $h$, is according to the equation [14]

$$-\mathbf{n} \cdot (-k \nabla T) = h(T_{\text{inf}} - T)$$

where $\mathbf{n}$ is the normal vector of the boundary and $T_{\text{inf}}$ is reference temperature.

3. Calculation results

In the Model section we mention that the uneven temperature distribution in the quartz crystal may affect frequency stability. It can be seen from the OCXO temperature distribution diagram that it is not possible to accurately determine the temperature of the quartz crystal. Therefore, a time vs. temperature curve was plotted using the mid ($T_1$) and end ($T_2$) temperatures of the crystal as shown in Figure 3, from which the temperature difference can be deduced. The heating power for the crystal was 1.485 W and the thermostatic power was 0.462 W.

3.1. Oscillator chamber under vacuum

A simulation of time vs. temperature change, as heat was transferred from the heating chip to the quartz crystal, was carried out. The crystal has to be heated to within the working temperature range and remain there (under thermostatic control) to ensure good output frequency stability. The heat durability of the heating element and the time taken to heat the crystal to working temperature need to be considered. Therefore, a simulation of the heating process was first carried out to observe the temperature changes in the heating element and quartz crystal, which made it possible to determine the time needed to change the thermostatic power.

From these heating simulations, it was found that when the heating element was heated continuously for 15 s, the crystal temperature rose to about 85 °C, which was within the working temperature range. The temperature of the heating element was about 120 °C (Figure 4). After reaching the working range, the thermostat maintained a constant working temperature for 30 s. As can be seen in Figure 5, the crystal temperature was about 80 °C at 20 s and the temperature of the heating element dropped to about 90 °C. The overall heat of the oven-controlled quartz oscillator was transferred via the copper foil. Figures 4 and 5 show that the heat was evenly distributed across the circuit board.

The time vs. temperature change diagram (Figure 6) of the heating element and quartz crystal shows the temperature of the crystal was about 85 °C at 15 s and dropped slowly to 80 °C over time. The mid and end temperatures of the crystal were also very close.
3.3. Oscillator chamber filled with helium

From Figure 8, it can be seen that time vs. temperature changes are not much different from those under vacuum. But during heating, the mid temperature of the quartz crystal is slightly higher.

Examination of Tables 3 and 4 shows that during the early heating stage, the mid temperature of the quartz crystal in helium is 1 °C higher than when under vacuum. The mid temperature of the crystal under vacuum is lower than the end temperature. However, the mid temperature of the quartz crystal in helium is the other way round. Despite the difference during the heating state, the temperature only differs by 0.01 °C under thermostatic control. A comparison of the tables shows that during the heating stage, the end temperature of the crystal under vacuum is 1 °C higher than when in helium. However, when it reaches working temperature, and is under thermostatic control, it is lower. Further observation of the

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Table 1. End temperature of a quartz crystal under vacuum and in nitrogen.

| Time (s) | Vacuum (°C) | Filled with nitrogen (°C) |
|---------|-------------|--------------------------|
| 5       | 44.77940    | 44.77905                 |
| 10      | 65.96534    | 65.96482                 |
| 15      | 83.42488    | 83.42427                 |
| 20      | 82.07607    | 82.07561                 |
| 25      | 80.86010    | 80.85972                 |
| 30      | 80.79569    | 80.79535                 |

Table 2. Mid temperature of a quartz crystal under vacuum and in nitrogen.

| Time (s) | Vacuum (°C) | Filled with nitrogen (°C) |
|---------|-------------|--------------------------|
| 5       | 44.26687    | 44.25884                 |
| 10      | 65.66457    | 65.65716                 |
| 15      | 83.25490    | 83.24809                 |
| 20      | 82.27876    | 82.27930                 |
| 25      | 81.00831    | 81.00817                 |
| 30      | 80.91654    | 80.91611                 |

Table 3. End temperature of a quartz crystal under vacuum and in helium.

| Time (s) | Vacuum (°C) | Filled with helium (°C) |
|---------|-------------|-------------------------|
| 5       | 44.77940    | 44.77826                |
| 10      | 65.96534    | 65.96505                |
| 15      | 83.42488    | 83.42493                |
| 20      | 82.07607    | 82.07692                |
| 25      | 80.86010    | 80.86056                |
| 30      | 80.79569    | 80.79600                |

Table 4. The mid temperature of a quartz crystal under vacuum and in helium.

| Time (s) | Vacuum (°C) | Filled with helium (°C) |
|---------|-------------|-------------------------|
| 5       | 44.26687    | 45.27302                |
| 10      | 65.66457    | 66.43637                |
| 15      | 83.25490    | 83.89147                |
| 20      | 82.27876    | 82.18035                |
| 25      | 81.00831    | 80.98513                |
| 30      | 80.91654    | 80.92703                |
3.4. Increased simulation times of 100 s

The thermostatically controlled temperature used for the 30 s simulations (sections 3.1–3.3.) was set to about 80 °C. To observe changes over a longer period, the simulation time was increased to 100 s and the working temperature range was set to 80–105 °C.

Examination of Figure 9, reveals that after 30 s the overall temperature tends to increase slowly and the crystal reached more than 105 °C after about 130 s. The temperature continued to rise up to 150 s and a decision was made to turn off the power and observe subsequent temperature changes over time. Figure 10 is a simulation in which the thermostatic power is turned off after 15 s. As can be seen in Figure 9 the overall temperature increases slowly over time and to investigate the power loss when the thermostatic control was turned off, another simulation of 200 s was carried out, see Figure 11. When the temperature was about to reach the upper limit of 105 °C, power input was turned off, and when it dropped to the lower limit of 80 °C, it was turned on again. The result was that it took 18 s for the temperature to drop to within the working temperature range of about 80 °C and after this it was necessary to turn the thermostatic control on again.

Since the temperature of OCXO would increase by adopting a power of 0.462 W, the finite element method can be used to find a suitable thermostatic power. Naturally, a reduction in power requirement was desirable but would result in a lower crystal temperature which might drop below the working range. This meant an increase in heating time would be necessary. Furthermore, this would also allow the use of a lower working temperature range. A new simulation was therefore carried out over 300 s,
However, the result shows that after 18 s, power input was again necessary. The simulations suggested that 25 s of power input was the most appropriate and the power needed was 0.245 W.

**Nomenclature**

| Symbol | Description |
|--------|-------------|
| ρ      | the density (kg/m³) |
| Cp     | the specific heat capacity at constant pressure (J/(kg K)) |
| T      | absolute temperature (K) |
| K      | the thermal conductivity (W/(m K)) |
| Q      | contains heat sources other than viscous heating (W/m³) |
| A      | cross-sectional area (m²) |
| ΔT/Δx  | temperature gradient (K/m) |
| h      | heat transfer coefficient (W/(m² K)) |
| T_inf  | reference temperature (K) |

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**References**

[1] Walls FL. The influence of pressure and humidity on the medium and Long term frequency stability of quartz oscillators. Frequency Control Symposium, Proceedings of the 42nd Annual Symposium on Frequency Control, pp. 279–283, NTIS Accession No. AD-A217725; 1988.

[2] Walls FL, Gagnepain JJ. Environmental sensitivities of quartz oscillators. IEEE Trans. Ultrason. Ferroelecetr. Freq. Control. 1992;39:241–249.

[3] Goryachev M, Galliou S, Imbaud J, Abbé P. Advances in development of quartz crystal oscillators at liquid helium temperatures. Cryogenics. 2013;57:104–112.
[4] Walter DG, Eugene SM. TCXO error due to aging adjustment. Symp. Freq. Control. 1980;34:504–508.
[5] Clark RL. Reducing TCXO error after aging adjustment. Symp. Freq. Control. 1985;39:166–170.
[6] Lim J, Choi K, Kim H, Jackson TN, Kenny D. Miniature oven controlled crystal oscillator (OCXO) on a CMOS chip. IEEE Int. Freq. Control Symp. Exposition. 2006;401–404.
[7] Lim J, Kim H, Jackson TN, Choi K, Kenny D. An ultra-compact and low-power oven-controlled crystal oscillator design for precision timing applications. IEEE Ultrason. Ferroelectr. Freq. Control Soc. 2010;57:1906–1914.
[8] Asamura, F, Oita, T, Obara, S Sakamoto, K. Temperature coefficients improvements of VHF oscillator circuit for OCXO. IEEE Int. Freq. Control Symp. 2007;230–233.
[9] Vorokhovsky YL, Drakhlis BG. High-stability quartz oscillators on internally-heated quartz resonators with AT and SC cuts. Symp. Freq. Control. 1991;45:447–451.
[10] Clark RL, Li J, Adler J. Improved aging results using thick-film hybrid packaging and evacuated miniature ovenized oscillators using such packaging. IEEE Int. Freq. Control Symp. 1999;420–424.
[11] Shi D, Li P, Li JP. The temperature characteristics research and improving methods of crystal oscillator. Wavelet Act. Media Technol. Inf. Process. 2013;198–200.
[12] Clark RL, Scalpi A. Design considerations of vacuum-sealed OCXO’s for high reliability applications. IEEE Int. Freq. Control Symp. 1996;481–483.
[13] Carron TL, Leost J. FEM thermal analysis of quartz oscillator with COMSOL. IEEE Int. Freq. Control Symp. 2009;482–486.
[14] COMSOL Multiphysics. User’s guide of heat transfer module. Comsol: Stockholm; 2009.
[15] Holman, JP. Heat transfer. 10th ed. New York, NY: McGraw-Hill Series in Mechanical Engineering; 2009.