DIGITALLY CONTROLLED CRYSTAL OVEN

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ABSTRACT

Recent developments in integrated miniature semiconductor temperature sensors, low-cost micro-controllers, predictive finite-element thermal analysis and materials (conductive epoxies and insulating foams with well-characterized, repeatable properties) now enable the fabrication of low-cost, digitally programmed (temperature set-point and varactor diode bias) crystal ovens, greatly reducing capital equipment and labor. This paves the way for widespread deployment of high-stability oscillators.

1.0 INTRODUCTION

Various applications are served by frequency references of varying accuracy and stability as shown in Table 1. Ovenized crystal oscillators (OCXOs) have the potential to achieve the stability of low-end frequency standards at less than a tenth of their cost and with other attendant benefits: reduced steady-state power consumption and reduced warm-up time. Simultaneously, there are many widely proliferated applications, such as optical fiber communications, that demand low-cost, high-stability oscillators, either as back-up or replacements for frequency standards.

	Description	Stability/ accuracy	Price	Power	Warm-up time to rated operation	Applications
XO, VCXO	Crystal oscillator	10^{-4}-10^{-5}	<\$1	50mW	<10s	Watches, phones, TV, PC, toys
TCXO	Temperature compensated crystal oscillator	10^{-5}-10^{-6}	<\$10	50mW	<10s	Wireless, GPS
OCXO (AT-cut)	Ovenized Crystal oscillator	10^{-7}-10^{-9}	<\$200	600mW	<100s	Instruments, telecom, radar, satcom
Rubidium	Rb Frequency Standard	10^{-10}-10^{-12}	<\$5000	20W	<300s	SONET/ SDH, calibration, test, GPS base stations
Cesium	Cs Frequency standard	10^{-11}-10^{-12}	<\$50,000	30W	<2000s	SONET/ SDH, calibration, test

Table 1. *Attributes of widely-used frequency references*

Oven construction and controller architecture greatly influence manufacturing costs of high-stability OCXO's. A traditional method holds a crystal at a constant temperature (usually 10°C greater than the maximum anticipated ambient temperature) using a thermistor (a passive component whose resistance is inversely proportional to temperature), in an otherwise resistive bridge, and a heater driven by the operational amplifier output (Figure 1). The heater and thermistor are both attached to the same heat sink (hence thermally connected).

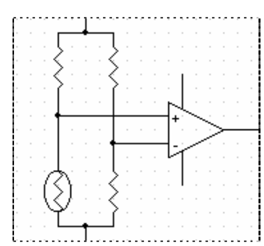

Figure 1. *Oven controller using a thermistor*

The oven's sensitivity to ambient temperature changes is reduced by the oven's thermal gain.

High oven gain, together with operation near the crystal turn-point (where its frequency's derivative with respect to temperature changes sign), may yield a 10 ppb oscillator stability (where the crystal would ordinarily exhibit 10 ppm variation over a desired temperature range). Disadvantages of conventional ovens are:

- Potentially mismatched oven set point (with respect to crystal turn point)
- Analog controllers require an internal voltage regulator, creating an uncontrolled hotspot
- Tuning varactor diode bias potentiometer (to set frequency) is time consuming. Mistuning due aging and shock may occur.
- Component aging effects PID controller performance

Our crystal oven, sans these disadvantages, uses:

- 8-pin SOIC low-cost micro-controller with internal EEPROM that retains:
  - Temperature set-point
  - Frequency tuning (digital potentiometer[1] changes varactor diode bias)
  - Temperature controller parameters
- Digital temperature sensor
- Digital PID controller with feed-forward to suppress oscillations around set-point
- Unregulated power for digital electronics/ heater, minimizing uncontrolled heat sources

2.0 PACKAGING, POWER CONSUMPTION AND TRANSIENT RESPONSE

The crystal is maintained at its turn temperature (75-90°C) inside an oven that consists of a cavity between the heat sink of a TO-220 or TO-252 power resistor and an electrically isolated copper pour of a printed circuit board. This cavity is filled with thermal epoxy (e.g. Dow-Corning STYCAST4954 with conductivity of 1.3 W/m·K). The temperature sensor (in the cavity) is intimately bonded to the heat spreader. The power resistor is connected to the supply voltage through a MOSFET switch. This entire assembly is then surrounded with an insulating potting compound (e.g., Dow-Corning SYLGARD184 with conductivity of 0.17 W/m·K) or foam insulation of appropriate thickness (to fit a standard crystal oscillator enclosure[2]) as shown in Figure 2.

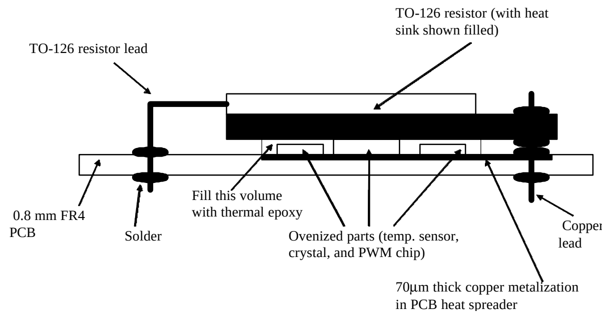

Figure 2. *Crystal oven section*

The required steady state power is estimated, using materials' geometry and conductivities as inputs, by a 3-D finite element analysis tool, (assuming perfect temperature control at the temperature sensor). For this example, the steady state power consumption is 2.5W, for oven and ambient temperatures of 363°K and 243°K respectively, assuming a 18.5×11×6 mm^3 enclosure, 18×10×0.8 mm^3 FR4 PCB (thermal conductivity of 0.273W/m·K) with an oven

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[1] Digital potentiometer wiper capacitance (typically 25pF) must be considered while designing the varactor network.

[2] Assuming purely conductive heat transfer, the relative dimensions of the oven (constructed using thermal conductors with high thermal capacity) and its blanket (constructed using thermal insulators with low thermal capacity) may be understood by considering the oven to be a homogenous sphere of radius r_1 and its blanket to be a concentric homogenous shell between radii r_1 and r_2. The heater is assumed to be negligibly thick shell sandwiched at radius r_1. The thermal capacity of the oven is proportional to r_1^3 while its thermal resistance to ambient is proportional to $(r_2-r_1)/r_1^2$; thus, the oven's thermal lag with respect to the ambient is proportional to $r_1 \cdot (r_2-r_1)$, which, for a fixed r_2, has a maximum at $r_1=0.5 \cdot r_2$.of $0.25 \cdot r_2^2$. Since the thermal capacitance seen by the heater is proportional to r_1^3 and the thermal resistance between the heater and the oven is proportional to $1/r_1^2$, the thermal lag of oven with respect to its heater is proportional to r_1. Oven controllability, the ratio of its thermal lags with respect to controlled parameters (heater duty cycle and supply voltage, the latter being "controlled" as its variations are, as shown in section 4, quickly compensated) and uncontrolled parameters (such as ambient temperature, barometric pressure, air flow and humidity) is proportional to (r_2-r_1), the insulating blanket's thickness, and must be greater than 1. The power consumed by the oven is proportional to $(q_h-q_a) \cdot r_1^2/(r_2-r_1)$ which is minimized for a given Δq, the temperature difference between the heater, at temperature q_h and the ambient, at temperature q_a, at a practically impossible $r_1=0$. With ideal control, $q_h=q_o$=constant, where q_o is the oven temperature.

volume of 14×9×2.5 mm^3, and four (V_{cc}, ground, crystal output and serial communication port) 8mm long, 1mm diameter copper (thermal conductivity of 385 W/m·K) pins. The oven's step response depends on the components' placement relative to the heater and by the materials' volumetric thermal conductance and capacitance.

3.0 SEMICONDUCTOR TEMPERATURE SENSOR WITH DIGITAL OUTPUT

All semiconductor temperature sensors make use of the relationship between a bipolar junction transistor's (BJT) base-emitter voltage to its collector current, $V_{BE}=(kq/q)\cdot\ln(I_c/I_s)$, with k being Boltzmann's constant, q the absolute temperature, q the electronic charge and I_s the current related to the geometry and temperature of the BJT, under the assumption that V_{BE}>200mV, where Early effects may be ignored. If N identical transistors share the current I_c equally, then the base-emitter voltage is $V_N=(kq/q)\cdot\ln(I_c/N^{x}I_s)$. The temperature dependence of I_s is eliminated by differencing the two voltages, i.e., $\Delta V_{BE}=(kq/q)\cdot\ln(N)$, providing a voltage output that is linear with respect to temperature. This voltage is amplified, digitized using a first-order sigma delta modulator and transmitted using popular two-wire protocols.

The repeatability of the temperature measurement is determined primarily by the amplifier's dc drift with respect to age (specified at a nominal temperature). The drift at the oven's operating temperature is calculated using the Arrhenius acceleration factor, $A_F=\exp[E_a/k(q_1^{-1}-q_2^{-1})]$, where k is Boltzmann's constant and E_a, the activation energy, is assumed to be 0.7eV in the ensuing calculation. A typical amplifier, drifting by 5mV over 1000 hours at 398°K, would yield a 0.47mV drift at 85°C. Thus drift-induced errors in 1000 hours of operation are of the order of 1 lsb (or 0.0625°C) at an oven temperature of 85°C (manufacturers' data sheets typically claim 0.2°C drift over 10,000 hours at 125°C).

4.0 DIGITAL PID CONTROLLED WITH TEMPERATURE AND SUPPLY-VOLTAGE COMPENSATION

A schematic of a heater, temperature sensor and proportional controller (in practice, derivative control is provided, i.e., the feedback constant K will be replaced by a first order FIR system) to illustrate the effect of heat spreader/ temperature sensor delay (while the ensuing discussion is for integer D, the analysis may easily be extended to the non-integer case) is shown in Figure 3.

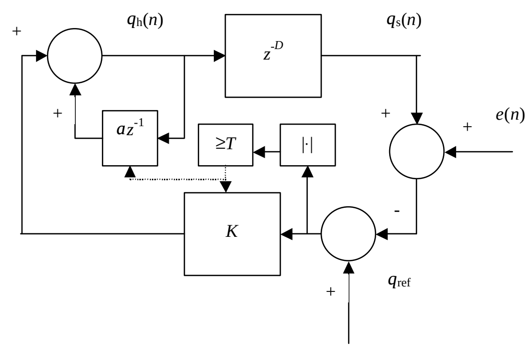

Figure 3. *Temperature controller without (a=1) and with temperature feed-forward (a<1)*

In Figure 3, at sample n, the heat spreader's temperature is $q_h(n)$, while the sensor's temperature is q_s and $e(n)$ is the observation noise (assumed white). It is simpler to consider q_s as a deviation from the reference temperature; i.e., $q_{ref}(n)=0$; thus, $\frac{q_s(z)}{e(z)} = \frac{-Kz^{-D}}{1-az^{-1}+Kz^{-D}}$, resulting in a high-order sensor spectrum (with at least one spectral peak). For most temperature sensors with digital output, the case-to-junction delay is of the order of the sampling period, $T=1/f_s$. Thus, D=2 or 3 and the spectrum is unimodal. The natural frequency for D=2 (when the roots are complex) is $f = \frac{1}{2p}\cos^{-1}\left(\frac{a}{2\sqrt{K}}\right) f_s$, $0\le K<1$, $|a|<2\sqrt{K}$. The natural frequency for D=3 (when two roots are complex and the third is real) is $f \approx \frac{1}{2p}\cos^{-1}\left(\frac{5K-\frac{a}{3}}{54K^2+\frac{2a-1}{9}-10K}\right) f_s$ (with exactitude for a=1). To flatten sensor spectrum, $a=1-b^{x}\mathrm{sgn}[e(n)]$ may be employed. Since the oven always heats from ambient, i.e., the sign of $e(n)$ is positive during convergence, a positive sign may be assumed always. To improve the step response, a=1 is used when the absolute error exceeds a threshold, and a combination of a<1 and an increased value of K is used otherwise.

To minimize overshoot, a derivative term, $K_d[q_s(n)-q_s(n-1)]$ is subtracted from the feedback (the integral term, that exacerbates sensor lag, is omitted as any droop may be adjusted in the set-point). In this case, the sensor temperature deviation from the set-point with respect to its quantization noise is obtained by replacing K by $K+K_d(1-z^{-1})$, i.e., $\frac{q_s(z)}{e(z)} = \frac{-[K+K_d(1-z^{-1})]z^{-D}}{1-az^{-1}+(K+K_d)z^{-D}+K_d z^{-D-1}}$. q_h is related by a proportionality constant (dependent on heater full-power, the set-point and the ambient temperature difference, the thermal properties of materials used, and oven dimensions), to the PWM[3] duty cycle, r ($0<r<1$).

The oven controller is an inexpensive 8-bit micro-controller (with 8-bit timer and 8-bit prescaler). With a 4MHz internal oscillator, corresponding to a maximum timer resolution of 256ms, the prescaler is set to 256. Every transition through zero of the timer interrupts the micro-controller. Conversion commands from the micro-controller to the temperature sensor are spaced apart by 1.245 (ΔT) seconds, i.e., every 19 interrupts. If the first interrupt interval is reserved (for turning the heater off, reading the temperature sensor, initiating a new conversion, PID controller[4], and communication with a personal computer using a serial protocol), the remaining 18 interrupt intervals are used to turn off the heater, to compensate for supply voltage changes and to poll the 8-bit timer to turn on the heater.

The oven temperature is sensitive to supply voltage variations within the oven convergence time. A superior alternative to supply voltage regulation, that avoids an uncontrolled hotspot in the oven's vicinity, is for the oven controller to compensate for supply voltage variations. The supply voltage, $V(n)$ is sampled every interrupt (i.e., every $\Delta T/19$ seconds), after an anti-aliasing filter suppresses high frequency components, and the PWM ratio, $r(n)$, is modified according to $r(n)= r(n-1)+r(n-1)\cdot[V^2(n-1)-V^2(n)]/V^2(n)$, with a suitable mid-step quantizer for $V^2(n-1)-V^2(n)$ and with the same clamp levels for $r(n)$ (the high clamp level applies when $V^2(n)$ is zero).

Assuming that the controller calculates the PWM duty cycle with 16-bit resolution, quantizer error feedback allows duty cycle resolution better than that provided by an 8-bit timer. At each interrupt, the 16-bit resolution duty cycle is added to the previous 8-bit quantizer error, the most significant 8 bits of which are used to determine the heater's off-to-on transition, while the least significant 8-bits form the new quantizer error. If T_1 denotes the off-to-on transition instant and r the duty cycle desired, T_1 may be calculated using $T_1=256(1-19r/18)$. The previous error, $e(n-1)$, is then added to $T_1(n)$ and quantized to 8 bits, i.e., $Q[e(n-1)+T_1(n)]$ (r is clamped in the oven so that $Q[e(n-1)+T_1(n)]$ always lies in the range 2-254). The quantizer error is the new value of $e(n)$.

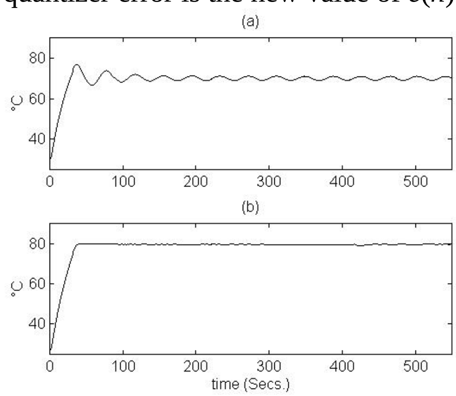

Figure 4. *(a) Continually cycling response at 70°C set-point with K=31 (b) Oven response: during the settling period, from 0-300 secs, the supply voltage is 5.25V; from 300-420 seconds, the supply voltage is 4.75V; while in the remaining time the supply is once again 5.25V*

Controller tuning, a variant of the Ziegler-Nichols method [2], sets $K_d=0$, $a=1$ and then increases the proportional gain, K, to a value K_u, where continuous cycling, with period P_u, around a desired temperature[5] occurs. K, K_d and a are set to $0.75K_u$, $4P_u/\Delta T$ and $1-(\Delta T/P_u)$ respectively. For the example oven, $K_u=31$, P_u=36 seconds (see Figure 4a); setting K=24, $K_d=128$ and $a=31/32$ yields a rise time and settling time (to the temperature sensor's resolution) of approximately 41 seconds and 93 seconds respectively. The

[3] The minimum time control law has the property that each control variable is either at its upper or lower bound (bang-bang control) [1]. Since this type of control results in excessive oscillation near the temperature set-point, PWM modulation (at a rate much faster than the oven's thermal time constant) is preferred. OCXO transient response, important during power-on of battery-powered applications, is only slightly reduced by a minimum time control law.

[4] $r(19\cdot n)=a\,r(19\cdot n-19)-K[q_s(19\cdot n)-q_{ref}]-K_d[q_s(19\cdot n)-q_s(19\cdot n-19)]$ where $a<1$ and $r(19\cdot n)$, has lower and upper clamp levels at 0.0074 and 0.940 respectively.

[5] This temperature is set somewhat lower than the elevated eventual set-point to avoid the potentially deleterious effects of overshoot during tuning.

absence of the integral term and the large K_d contribute to a droop of 0.28°C from the target (PID tuning) temperature of 70°C. The overshoot from the drooped temperature is 0.41°C.

Figure 4b shows the oven settling to a target temperature of 80°C, as well as the effect of supply voltage variations, as monitored by a PC. The droop and overshoot from the drooped temperature are 0.28°C and 0.34°C respectively.

5.0 CRYSTAL OVEN CALIBRATION AND MONITORING

The crystal's size and its manufacturing process largely determine its long-term (aging) stability, oven temperature having only a slight effect[6]. Since oscillator data is non-stationary, the modified *Allan deviation*, $\mathrm{mod}\,s_y(t)$, is used as a standard specification [3] for short-term stability:

$$\mathrm{mod}\, s_y(t) = \sqrt{\frac{1}{2(M-2n+1)} \sum_{i=1}^{M-2n+1} (\bar{y}_{i+1} - \bar{y}_i)^2}$$

where M is the number of points in the series, the data being equally spaced in time segments $t=nt_0$ (t_0 is the nominal time spacing between adjacent measurements), and averages are taken over a duration t. Random deviations of precision clocks and oscillators are often characterized by power law spectra $S_y(f)\sim f^a$, where f is the Fourier frequency and a is typically an integer. A useful integral expression that allows $\mathrm{mod}\,s_y^2(t)$ to be calculated from the spectrum is:

$$\mathrm{mod}\, s_y^2(t) = \frac{2}{n^4 p^2 t_0^2} \int_0^{f_h} \frac{S_y(f)\sin^6(ptf)}{f^2 \sin^2(pt_0 f)}\, df$$

where f_h is the measurement system's bandwidth.

The apparatus of Figure 5 allows crystal oven calibration and monitoring through:

- Selecting temperature (and monitoring settling close to the crystal's turn point)
- Adjustment of the temperature to obtain the desired phase noise spectrum
- Adjustment of varactor diode bias to obtain the desired frequency

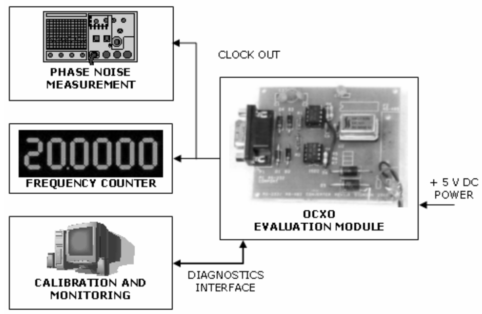

Figure 5. *Crystal oven tuning apparatus*

6.0 CONCLUSION

The construction of a low-cost crystal oven, that allows simple and automated calibration, is described. Summary features are:

- Optically isolated serial interface board for half-duplex communication to a PC
- Digital potentiometer for varactor diode bias
- Simple serial protocol that allows:
  - Setting and monitoring oven temperature
  - Tuning temperature controller parameters
  - Frequency tuning
- Interactive GUI to exercise serial protocol

Influence factors, such as crystal dimensions, its surface curvature and finish, its cut plane, the overtone mode selected and environmental conditions prevailing during hermetic sealing, on frequency stability is beyond this paper's scope.

References

[1] Bernard Friedland, *Advanced Control System Design*, Prentice Hall, 1996.

[2] Seborg, D.E., Edgar, T.F., and Mellichamp, D.A., *Process Dynamics and Control*, Wiley, New York, 1989.

[3] Allan, D.W., "Time and Frequency (Time-Domain) Characterization, Estimation, and Prediction of Precision Clocks and Oscillators," *IEEE Trans. On Ultrasonics, Ferroelectrics and Frequency Control*, vol. UFFC-34, No. 6, November 1987.

[6] The effect of a turn absolute temperature q_2, different from the nominal absolute q_1, on long term frequency drift is obtained via the Arrhenius acceleration factor, $A_F(q_1,q_2)=\exp[(E_a/k)\cdot(q_1^{-1}-q_2^{-1})]$, E_a being the activation energy (in *eV*) and *k*, Boltzmann's constant=0.000863.