Ultra-stable digitally controlled oven

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This paper describes design and characterization of a digitally controlled double oven system. This allows setting the turnover point of crystal oscillators automatically. Developed for metrological purposes of active phase noise measurements, this type of thermostat with a crystal oscillator is an ultra-stable digitally controlled oven crystal oscillator.

INTRODUCTION

The potential performance of an SC-cut resonator is difficult to attain because of their highly dynamic temperature coefficient. A performance in Allan deviation $\sigma_y(\tau)$ of order 10^{-14} can be achieved solely using double (multiple) ovens with extremely low thermal transients operating at turnover point (the oven offset tends to 0)[1-2].

High-stability quartz crystal oscillators are required in a number of different precision applications (ex: satellites and atomic fountain clocks). A short-term stability of parts in 10^{-14} [Allan deviation $\sigma_y(\tau)$] is sometimes required, for integration time τ of approximately 1–60 s, and often achieved by using 5 MHz or 10 MHz bulk acoustic-wave quartz crystal resonators. Quartz has very stable mechanical properties over time, but there are several factors that cause fluctuations in oscillator frequency. The main one is temperature: its deviations and gradients often cause frequency changes that are large compared to the slope of the static curve. The actual values depend on the resonator cut, overtone, frequency, diameter, and mounting technique[3].

The tuning process of a simple homemade oven when the operating temperature is set by means of a solder resistor. Thus, its requires a lot of time due to the complexity of this process (thermostat disassembling and soldering the resistor). Generally, during the determination of turnover temperature, few measured points are used and as a result the oven offset increases. So, the present work is devoted to developing a thermostat for metrological purposes of active phase noise measurements of ultra-stable quartz crystal in SC-cut[4]. It is referred to as a as a digital thermostat because all settings were conducted automatically.

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DIGITALLY CONTROLLED THERMOSTAT

The system of the digitally controlled double thermostat consists of 4 parts: computer with software program, control device, double thermostat and a frequency counter. These parts are connected among themselves as shown in Fig. 1 and represent the feed-back system.

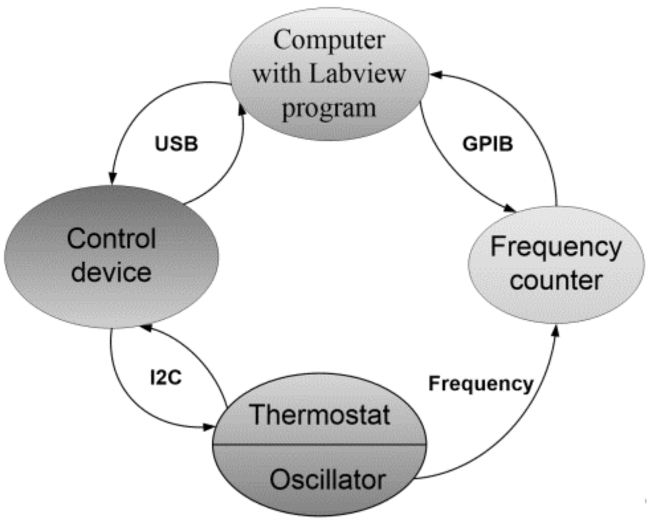

FIG. 1. Diagram of the system.

The main program searches the turnover temperature of the crystal oscillator in two stages: initially an approximate value is calculated and thereafter an exact value is obtained. For both steps, the program sends temperature value to the control device and reads the oscillator frequency from the frequency counter. The temperature variations at regular intervals are large for the first phase of program execution and small for the second one. Every time after changing the operating temperature the program waits for stabilization of the temperature in the thermostat. Once frequency is stable (normally 15 minutes for 10°C changing), the value of frequency is stored. After the first phase of program execution, the program computes the approximation function to third degree of the frequency-temperature curve of the crystal oscillator. The second (exact) phase of the program execution is based on the turnover temperature of the calculated function. Fig. 2 shows an example of turnover point search. There are 15 points of measurements (the temperature step is 1K for the first phase) and 22 points for the second one (the temperature step is 170 mK). The frequency counter has to be referenced by the oscillator with a stability of about 10^{-11} for a measurement time equal to 10 000s. Otherwise, the hysteresis problem can be observed for this second phase of program execution.

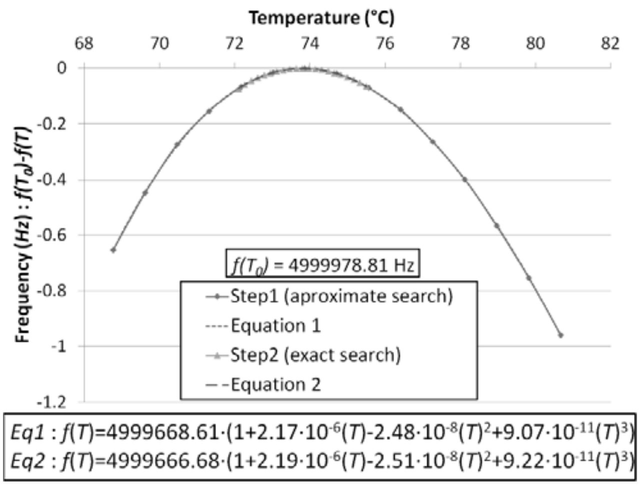

FIG. 2. An example of turnover temperature research for an ultra-stable 5 MHz oscillator.

The control device has a role of an interface between the PC and the double thermostat. In the same time, it has the function of human-interface (ability to display and control the main parameters of the thermostat). The heart of the control device is based around a 16-bit microcontroller.

The thermostat is used for maintaining a constant temperature around the quartz crystal resonator. The base of the thermostat is a vacuum flask that ensures good thermal isolation from the environmental variations. The external oven is a heavy aluminium block with the objective of reducing the thermal transients.

The external oven function is to filter the external temperature variations by closing the vacuum flask neck. Huge aluminum cup has natural isolation properties and large thermal inertia. The external oven temperature is controlled by a classic PI loop circuit. A thermistor included in a Wheatstone bridge allows to measure the temperature with high accuracy. The thermistor itself is placed near to the heating transistor. It increases the thermal stability of oven. A single MOSFET transistor and four power resistors have been chosen as heating elements for the aluminum cap. The temperature operation point is fixed at 50°C.

The internal oven is the most important piece regarding thermal performances. The aluminum bloc is perfectly adjusted to the resonators of HC40 type (smaller resonators can be used with an additional adaptor piece). The temperature-changing step of internal oven is 17 mK in the temperature range (+55 - +100) °C. The previous version of ultra-stable crystal thermostat[5] controlled by means of a tuning resistor. It gives the temperature-changing step of about 100 mK. Using a digital control allows increase the step by a factor 5. The structure of interior oven is shown in Fig. 3.

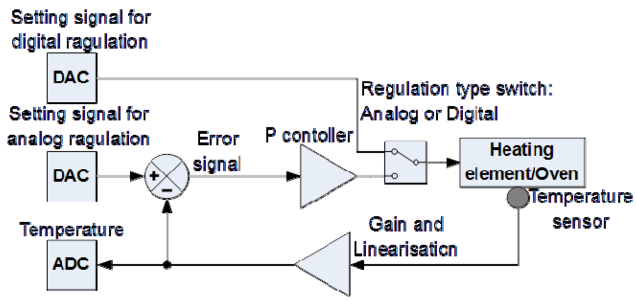

FIG. 3. Structure of interior oven.

The crystal oven can be controlled by two controllers: embedded analogical P(PI)- controller with digital temperature setting and digital PID-controller realized on microprocessor. The analog P(PI)-controller changes its operating temperature via a DAC with EEPROM, so in case of power failure, the converter does not lose its current value. Integrated 16-bit ADC provides the measurements of the crystal oven's temperature with a resolution of 4 mK. The use of a current source is allowed to simplify the adjustment of heating transistor and limited consummation of current at the warm up moment. The circuit of this oven is shown in Fig. 4.

CHARACTERIZATION

10 MHz SC-cut quartz crystal resonator working in an oscillator in B-mode is a very precise temperature sensor[5]. The B-mode frequency is close to f_B = 10.9 MHz. The frequency-temperature slope is measured to -230 $Hz{\cdot}K^{-1}$. The B-mode oscillator is a classical one-transistor ultra-stable oscillator. The resulting thermal stability of the digital thermostat is shown in Fig. 5.

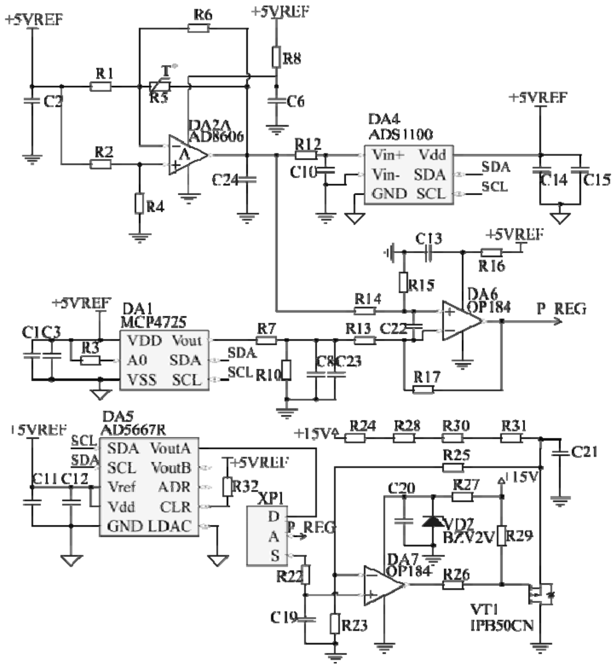

Fig. 4. Internal oven.

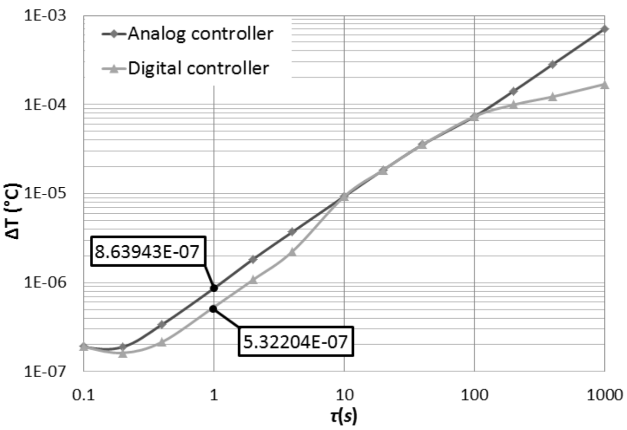

FIG. 5. Thermal stability of the thermostat for different controllers.

The ideal operating point for quartz crystal resonator is its turnover temperature. Our system can reach this ideal point with a precision of about $\delta T = \pm 17$ mK. For this δT, the frequency-temperature dependence of the C-mode is about $2\cdot 10^{-10}$. Thus, the relative frequency fluctuations, $\Delta f/f$, at 1s are:

$$\left.\frac{\Delta f}{f}\right|_{ANALOG} = a_C \cdot \Delta T = 2\cdot 10^{-10} \cdot 8.6\cdot 10^{-7} = 1.7\cdot 10^{-16} \quad (1)$$

$$\left.\frac{\Delta f}{f}\right|_{DIGITAL} = a_C \cdot \Delta T = 2\cdot 10^{-10} \cdot 8.6\cdot 10^{-7} = 1.1\cdot 10^{-16} \quad (2)$$

The advantages of digital controller for integration times until 10 s and after 100s can be observed. In fact, the advantage of a digital controller based on the presence of a D-controller component for short-term stability (0.1s – 1s) and an I-controller component for long-term stability (since 100s). Another advantage of a digital controller is its simplicity of configurations that cannot be said about analog controller. However, the digital controller has one big disadvantage. The controller device has to be always connected to the thermostat.

CONCLUSION

A digitally controlled thermostat has been designed to simplify the turnover point process setting. Now temperature adjustment takes one day against around one week before. The small temperature changing step 17 mK coupled with two turnover point measurements increase the thermal stability of OCXO. These digital thermostats present an Allan standard deviation of about $1.6\cdot 10^{-16}$ at 1 s in terms of relative frequency fluctuations.

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