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HIGH PRECISION TCXO

FOR RAPID ENVIRONMENTAL TEMPERATURE CHANGE

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Abstract - **Recently, the increased high speed of the transmission of mobile communication devices has necessitated higher stabilization of oscillators. Also, mobile communication devices are becoming more miniaturized. It is estimated the downsizing of a high precision frequency source will become necessary, too. Therefore, the method to get a precise frequency more easily is necessary. We study TCXOs to produce a small-sized high precision frequency source.**

When making small-sized TCXOs, TCXOs are strongly influenced by the environmental temperature. Currently, high stability must be kept in rapid environmental temperature change. But, because the temperature sensor and the crystal resonator have different thermal time constants, the frequency stability of TCXOs in rapid environmental temperature change is generally poor.

In this paper, we propose that the temperature estimate method of the change in rapid and complicated environmental temperature can be used, as a way of compensating for the temperature characteristic of TCXOs. We focus on using the temperature change of a sensor and a crystal resonator as the lag function. This method is the way of compensating for the temperature characteristic using the temperature estimate function. The temperature estimate function can support nth derivative of temperature T with respect to time t.

As a result, we have shown that it is possible to compensate frequency estimate with fewer errors in rapid environmental temperature change for which conventional TCXOs cannot compensate.

Next, we confirm that our proposed TCXO is useful by using simulation with actual circuit parameters and experiments. As an example, we applied this method to conventional TCXOs that have the estimated error of more than ±10[ppm]. As a result, we have shown that it is possible to decrease errors to less than ±0.01[ppm].

***Keywords* - TCXO, GPS, High Precision Oscillator.**

I. Introduction

Generally, atomic oscillators are used as a source of a precise frequency. But, in order to obtain high frequency stability of the atomic oscillator, the system become complicated and expensive due to the necessary stabilization of the local environmental temperature, the source voltage, etc.. Therefore, a method of obtaining an easy and cheap source of a precise frequency is studied.

From May 2000, since the accuracy of a GPS (Global Positioning System) transmitted signal has been improving, it is expected that frequency stability of the same grade as the output accuracy of the atomic oscillator will be acquired by using the signal of GPS [1][2].

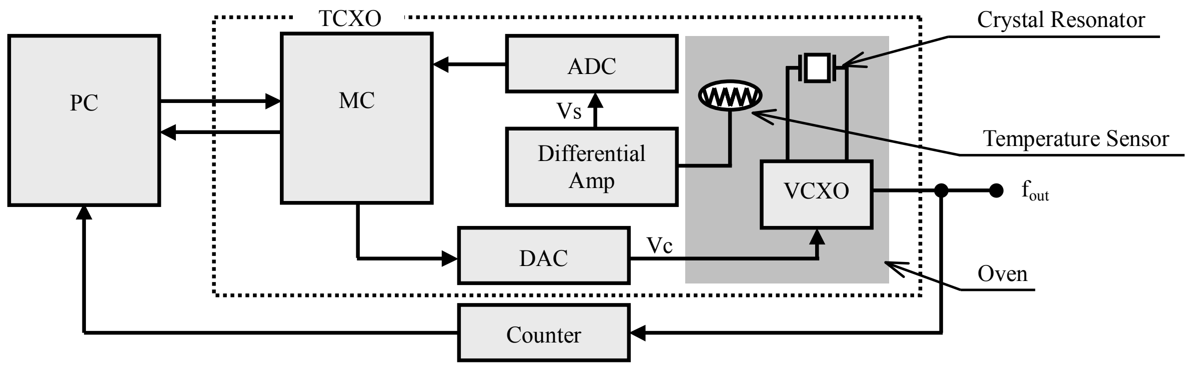

Fig. 1 Block diagram of TCXO.

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The high precision frequency source using GPS we proposed previously had VC-OCXO (Voltage Controlled - Oven Controlled Crystal Oscillator) [4]. But, mobile communication devices are becoming more miniaturized. We expect that the downsizing of the high precision frequency source will become necessary, too. The VC-OCXO has one or more ovens. Therefore, size increases and miniaturization is difficult. Moreover, because a crystal resonator is used at high temperature, the problem with the degrading aging characteristic occurs. We study high precision TCXO as the oscillator that can solve these problems. But, because type TCXO is temperature compensated, the frequency accuracy generally is poorer than OCXO [3]. Then, we consider the method of realizing accuracy equivalent to OCXO, by estimating the temperature of a crystal resonator precisely.

In this paper, we propose a temperature estimate method by which the change of rapid and complicated environmental temperature of TCXO can be supported, as the method of compensating for the temperature characteristic of TCXO. Then, we clarify validity by using simulation and experiment.

II. TCXO

Figure 1 shows the system of our proposed TCXO. The system is composed of a temperature sensor, VCXO (Voltage Controlled Crystal Oscillator), oven, differential amplifier, ADC (A/D converter), DAC (D/A converter), MC (Microcomputer), PC (Personal Computer), and frequency counter. In the operation of this system, the ADC converts analog voltage Vs from the temperature sensor into a digital signal. The signal is transferred from the MC to the PC. Next, the PC calculates the compensation values of the VCXO. The DAC generates control voltage Vc and Vc is compensating for the temperature.

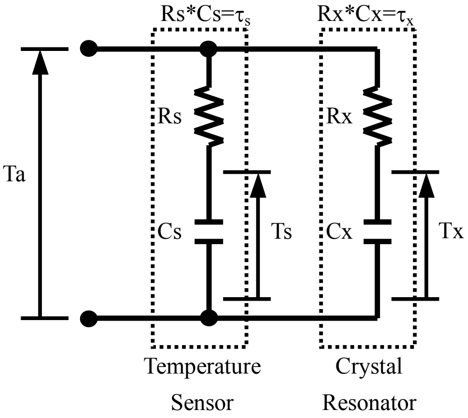


Fig. 2 Equivalent circuit of thermal system.

After start-up and setting operating values, the TCXO system works only in the broken line portion, excluding the oven in Fig. 1.

The conventional TCXOs interpret Vc from the data of the temperature sensor, and have been compensating for the temperature by the Vc. The relation of the temperature data and the Vc is determined from the measured data. The conventional TCXO causes a difference in temperature between the crystal resonator and the temperature sensor, when the local environmental temperature changes rapidly. This problem occurs when there is a difference between the thermal time constant of the crystal resonator and the

$$Ta(t_{i+1}) = Ta(t_i) + v(t_{i-1})\times\Delta t + \frac{d}{dt}v(t_{i-2})\times\Delta t^2 + \frac{d^2}{dt^2}v(t_{i-3})\times\Delta t^3 + \frac{d^3}{dt^3}v(t_{i-4})\times\Delta t^4 + \quad \cdots \quad + \frac{d^{n-2}}{dt^{n-2}}v(t_{i-(n-1)})\times\Delta t^{n-1} + \frac{d^{n-1}}{dt^{n-1}}v(t_{i-n})\times\Delta t^n \qquad (1)$$

$$\begin{cases} b_{1(n)} = n \\ b_{2(n)} = 1 + \sum_{j=2}^{n-1} b_{1(j)} \\ b_{3(n)} = 1 + \sum_{j=3}^{n-1} b_{2(j)} \\ \vdots \\ b_{m-1(n)} = 1 + \sum_{j=m-1}^{n-1} b_{m-2(j)} \\ b_{m(n)} = 1 + \sum_{j=m}^{n-1} b_{m-1(j)} \end{cases}$$

$$Ta(t_{i+1}) = b_{1(n)}Ta(t_i) - b_{2(n)}Ta(t_{i-1}) + b_{3(n)}Ta(t_{i-2}) - b_{4(n)}Ta(t_{i-3}) + \cdots$$
$$\cdots + (-1)^m b_{m-1(n)}Ta(t_{i-(m-2)}) + (-1)^{m+1} b_{m(n)}Ta(t_{i-(m-1)}) \qquad (3)$$

Where n =1,2,3, …, m=1,2,3, … ,n.

When n=m,

$$\sum_{j=m}^{n-1} b_{m-1(j)} = 0$$

thermal time constant of the temperature sensor. Therefore, when the local environmental temperature changes rapidly, the temperature difference occurs in both devices.

In this paper, we assume that the relation is the lag function in the thermal transfer in both devices. Figure 2 shows the equivalent circuit of the thermal system. In this figure, Ta is the environmental temperature. Ts, Rs, Cs, τ_s are temperature, thermal resistor, thermal capacitor, and thermal time constant, respectively, of a temperature sensor Tx, Rx, Cx, τ_x are the equivalent values of a crystal resonator.

III. Compensating method for rapid temperature change

In the system, Ta and Tx are calculated from Ts, which is measured every Δt. We assume that the relation between Tx and Ta and the relation between Ts and Ta are the first order lag function.

Equation (1) indicates temperature estimate function that the rapid change of local environmental temperature can be calculated. $v(t_{i-n})$ is the local environmental temperature change velocity at t_{i-n} and is described by

$$v(t_{i-n}) = \frac{Ta(t_{i-(n-1)}) - Ta(t_{i-n})}{\Delta t}. \quad (2)$$

The temperature estimate function (Eq. (3)) can be derived from Eqs. (1) and (2). From Fig. 2, the relation between $Tx(t_{i-(m-1)})$, $Ts(t_{i-(m-1)})$ and $Ts(t_{i-m})$ is described by

$$Ts(t_{i-(m-1)}) = Ta(t_{i-(m-1)}) \times (1 - \exp(-\Delta t/\tau_s)) + Ts(t_{i-m}) \times \exp(-\Delta t/\tau_s). \quad (4)$$

Therefore, $Ta(t_{i-(m-1)})$ is described by

$$Ta(t_{i-(m-1)}) = \frac{Ts(t_{i-(m-1)}) - Ts(t_{i-m}) \times \exp(-\Delta t/\tau_s)}{1 - \exp(-\Delta t/\tau_s)}. \quad (5)$$

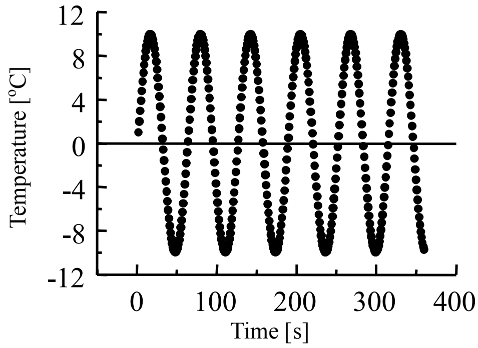
Equation (5) indicates that $Ta(t_{i-(m-1)})$ is obtained from $Ts(t_{i-(m-1)})$ and $Ts(t_{i-m})$. From Fig. 2, the relation of $Ta(t_{i+1})$, $Tx(t_{i+1})$ and $Tx(t_i)$ are given by

$$Tx(t_{i+1}) = Ta(t_{i+1}) \times (1 - \exp(-\Delta t/\tau_x)) + Tx(t_i) \times \exp(-\Delta t/\tau_x). \quad (6)$$

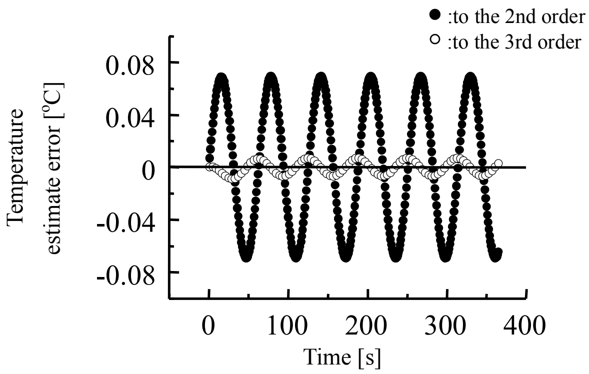
Equation (6) indicates that $Tx(t_{i+1})$ is obtained from $Ta(t_{i+1})$ and $Tx(t_i)$. Therefore, Eqs. (3), (5) and (6) indicate that $Tx(t_{i+1})$ is obtained from $Ta(t_{i-(m-1)})$ which was acquired from t_i.

The frequency temperature characteristic of the AT-cut crystal resonator can be approximated by a cubic function [3]. So, using the cubic function with coefficients α, β and γ, the equation is described by

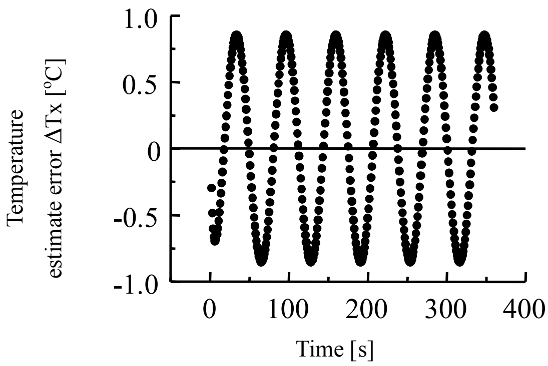
$$\Delta f / f_0 = \alpha Tx(t_{i+1}) + \beta Tx(t_{i+1})^2 + \gamma Tx(t_{i+1})^3. \quad (7)$$



(a) Environmental temperature Ta.



(b) Estimate result of Tx.



(c) Conventional method.

Fig. 3 Simulation results of proposed compensated method.

We simulated the temperature estimate of the crystal resonator with the rapid change of the environmental temperature. The parameters used for the simulation are τ_s=15[s] and τ_x=24[s].

Figure 3 shows an example of the temperature estimate result using simulation. Figure 3(b) shows an example of temperature estimate results of Tx, when given rapid change of the environmental temperature as shown in Fig. 3(a). In Fig. 3(b), ● shows the result with consideration to the 2nd order and ○ shows the result with consideration to the 3rd order. This figure shows that, when the method used to the 3rd order is used, the estimate error can be reduced to approximately 1/100th of the conventional method.

IV. TCXO using dynamic temperature compensation

We simulate a proposed TCXO in Fig. 1. Figure 4 shows the frequency vs. temperature characteristics of the VCXO using simulation. Figure 5(a) shows an example of the environmental temperature change over time. The values used for simulation are τ_s=15[s], τ_x=24[s], α= 0.31×10^{-6}, β= -6.42×10^{-9}, and γ= 8.11×10^{-11}.

Figure 5(b) shows an example of the frequency vs. temperature characteristics of the proposed TCXO.

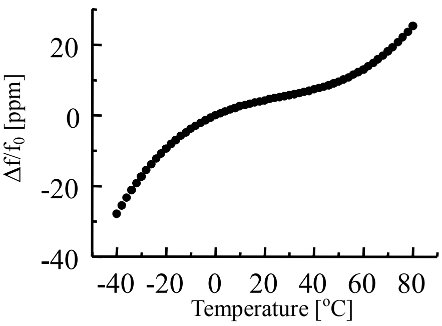
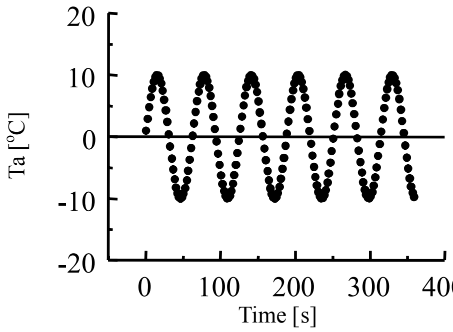


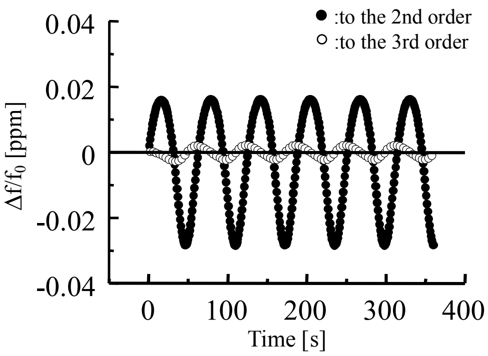
Fig. 4 $\Delta f/f_0$ vs. temperature characteristics of the VCXO.

In Fig. 5(b), ● shows the result with consideration to the 2nd order and ○ shows the result with consideration to the 3rd order. This figure shows that it is possible to reduce small estimate error by considering the higher orders. Moreover, it shows that it is possible to reduce within ±0.01[ppm] with consideration to the 3rd order.

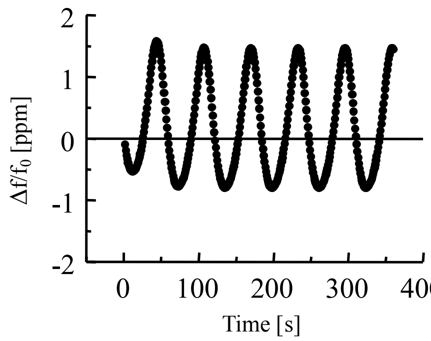
Figure 5(c) shows an example of frequency vs. temperature characteristics of a conventional TCXO. As a result, it shows that the proposed TCXO can decrease the compensation error of frequency by a conventional TCXO by about 1/200th.



(a) Environmental temperature Ta.



(b) Estimate result of TCXO.



(c) Conventional method.

Fig. 5 Temperature characteristics of frequency of the TCXO.

Next, we experiment using the system in Fig. 1. We use the circuit in Fig. 8 as a VCXO circuit, and the circuit in Fig. 6 as a temperature sensor circuit. This VCXO circuit is composed of a bridge, buffer specified by U_1, U_2 (JRC:4558), and a differential amplifier specified by U_3 (JRC:4558). The circuit parameters are R_1=10[kΩ], C_1=10[μF], and

C_2=0.1[μF]. The temperature sensor uses a thermistor (103-AT-1). The τ_s is 107[s].

Figure 7 shows an example of the response characteristics in Fig. 6. This figure shows that Vs output is linear. Therefore, we assume that the relation of Vs and Ts is a linear function. The circuit in Fig. 8 is composed of the frequency control part specified by U_1(JRC:4558) and the variable capacitor, and the oscillator specified by Tr1(2SC1815). The circuit parameters are R_1=10[kΩ], R_2=470[kΩ], R_3=1[kΩ], C_1=100[pF], C_2=100[pF], C_3=5[pF], C_4=20[pF], C_5=1000[pF]. τ_x is 33[s]. The crystal resonator parameters are $\alpha = -0.10 \times 10^{-6}$, $\beta = -6.42 \times 10^{-9}$, $\gamma = 7.85 \times 10^{-11}$.

Figure 9 shows the frequency vs. temperature characteristic of the crystal oscillator with Vc as a parameter without thermal shock. This figure shows that temperature compensation is possible in -25 °C to +60 °C range.

Figure 10 shows the experimental results of the proposed TCXO during rapid temperature change (1 °C /min). When having changes as shown in Fig. 10(a), Fig. 10(b) shows that with the proposed TCXO it is possible to compensate within ±0.2[ppm].

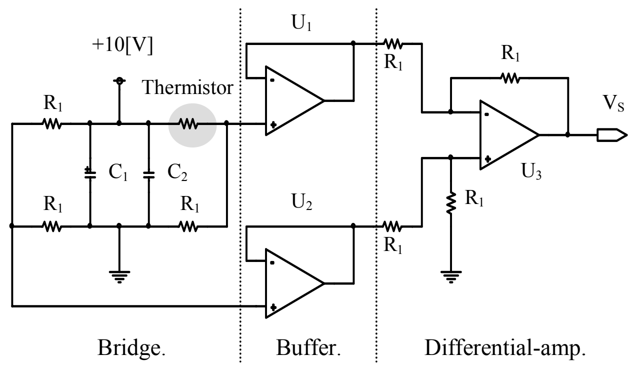


Fig. 6 Circuit of the temperature sensor.

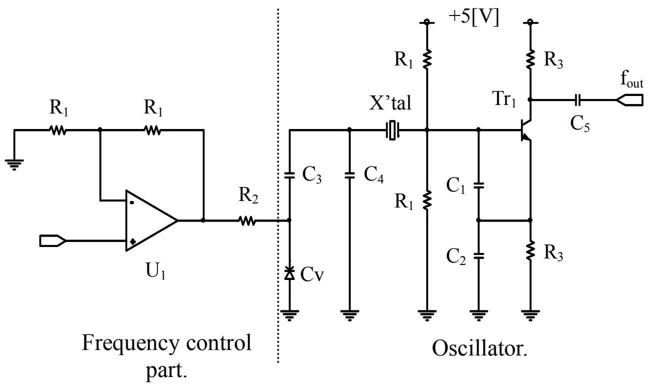


Fig. 8 Circuit of the VCXO.

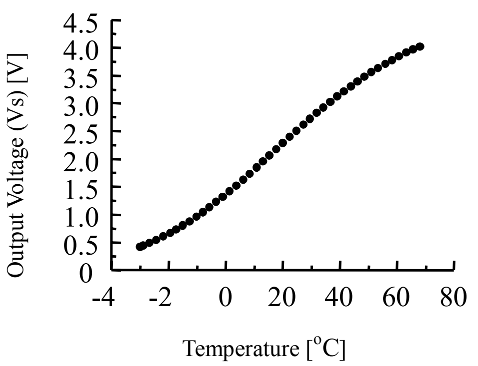


Fig. 7 Voltage response of temperature sensor.

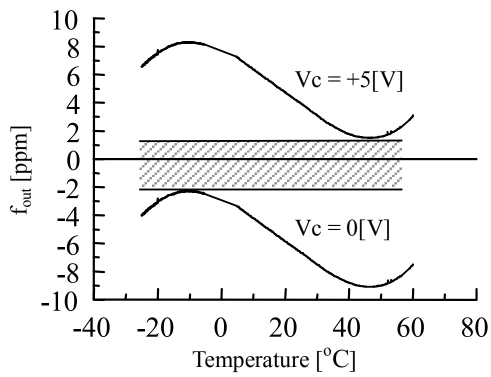
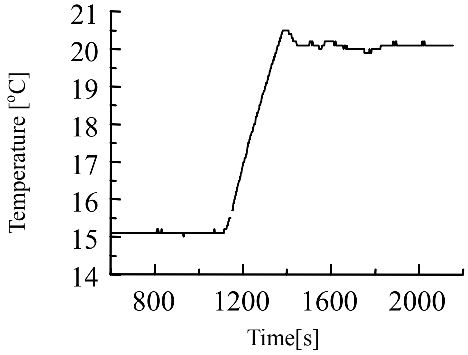
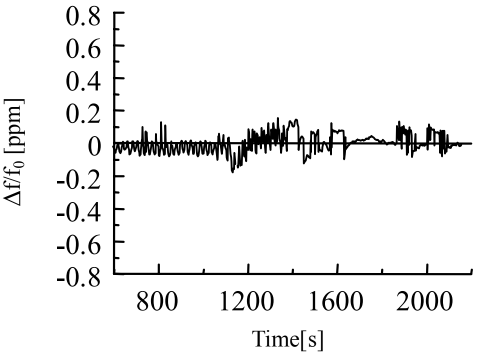


Fig. 9 Temperature characteristics of frequency of the crystal oscillator with Vc as parameter.



(a) Ta.



(b) Frequency stability results using compensation.

Fig. 10 Experimental results of the proposed TCXO.

V. Conclusion

We propose that the temperature estimate method can be used to compensate for temperature characteristic of TCXOs, including rapid and complicated changes in environmental temperatures.

We have shown that it is possible to compensate the frequency estimate with fewer errors in rapid environmental temperature change for which conventional TCXOs can not compensate.

Next, we have confirmed that our proposed TCXO is useful by using simulation with actual circuit parameters and experiments, during rapid temperature changes. We have shown that it is possible to decrease error to less than ±0.01[ppm] by using values to the 3^{rd} order with simulation. Using the experimental system, we have shown that the proposed TCXO can compensate within ±0.2[ppm].

In the future, we will discuss the quick acquisition method of the control data.

References

[1] H. Ujiie:"A Precision Frequency Source Using GPS", IEEJ, IM-97-42, pp.21-26, (1997)

[2] M. Komatsubara, Y. Sekine: "A Study on the Temperature Characteristic of a Precision Frequency Source Using GPS" , IEICE, A-1-8, (1998)

[3] QIAJ : "QIAJ Standards" , pp.9-10, pp.16-19, (2002)

[4] T. Shioda, K. Manju, H. Otsuka, Y. Sekine:" A study on Frequency Stability of High Precision Oscillator using GPS", IEEJ, Vol.122-C, No.5, pp.786-792 (2002)

[5] Y. Sekine, T. Ebisugi, K. Atobe, Y. Sakuta, M. Suyama:"An Improvement of Frequency Compensation Performance of D-TCXO", IEEJ, Vol.109-C, No.7, pp.523-529 (1989)