Self-Identification of Differences between Aging Rates of Two Frequencies Excited in the Dual-Mode Crystal Oscillator

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ABSTRACT

In this paper we introduce an extension of the self-temperature-sensing of stress compensated (SC) quartz resonator based on simultaneous excitation of two overtones (3rd and 5th overtone) - the slow thickness-shear modes (i.e. the c modes) in dual-mode crystal oscillator (DMXO). The extension is based on implementation of a self-identification of the differences between aging rates (long-term frequency instabilities) of the two mode's frequencies simultaneously excited in the quartz resonator. Processing of two excited c mode's frequencies enables to predict their shifts due to resonator's temperature variations in a wide range, where the characteristics of the c modes are free from significant anomalies.

INTRODUCTION

Simultaneous excitation of two modes of vibration in a piezoelectric resonator enables to realize the resonator self-temperature-sensing. The method eliminates temperature offset and lag effects, since no external temperature sensor is used. Possible applications of the self-temperature-sensing include: stabilization of the resonator's temperature with excellent accuracy; as well as precise compensation for frequency shifts due to the variations of the temperature in the resonator surrounding.

Self-temperature-sensing of an SC-cut utilizing simultaneous excitation of two slow thickness-shear modes (i.e. c modes) has been introduced in [1]. The history and many various applications related to the dual-mode excitation have been reviewed in [2], [3].

The differences between the agings of the two exited mode frequencies in the resonator cause an offset with a tilt in microcomputer compensated crystal oscillator (MCXO) output frequency over the operating temperature range; it limits the accuracy of the correction process implemented in the MCXO. The correction for frequency aging requires the nominal frequency from an external source that is fed to MCXO for few seconds. If the accuracy of the correction is not sufficient, then the MCXO has to be fully recalibrated. Such a recalibration is time-consuming process and usually can be carried out only in a lab [4].

THE STRUCTURE OF DUAL-MODE CRYSTAL OSCILLATOR

The DMXO we designed consists of two crystal oscillators (XOs) with similar structure shown in Fig. 1. Each of the XOs comprises of: the sustaining amplifier to provide regeneration for the respective mode of the SC-cut; and the isolation amplifier based on dual-gate MOS-FET to provide sufficient isolation and to minimize the effect of loading impedance. The resistor R3 forms negative voltage feedback of the sustaining amplifier with bipolar junction transistor (BJT) Q1. The value of resistance R3 is selected according to required driving level of the appropriate mode in the SC-cut. The automatic level control (ALC) may be implemented by replacement of the resistor R3 with junction field-effect transistor (JFET). Appropriate mode is selected by the two parallel combinations of capacitors: C11, C12, C13 and C21, C22, C23 and the inductor L1. Of course, in practice, other impedances: like parasitic impedances of the BJT Q1 and of the following amplifier, affect the oscillator frequency as well.

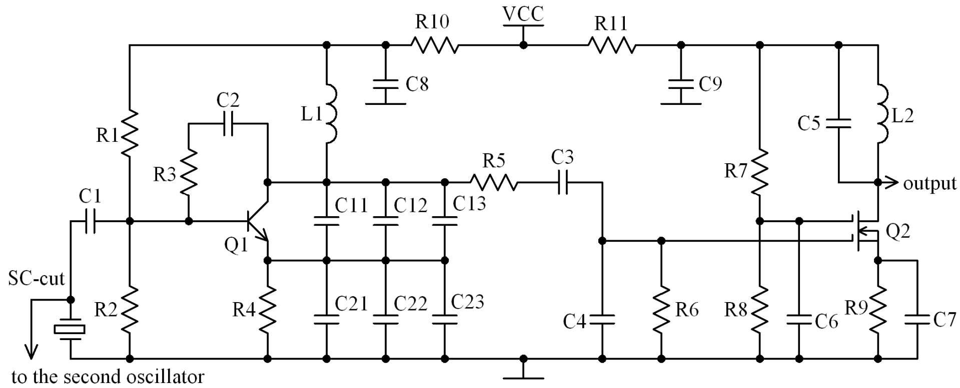

Fig. 1. Schematic diagram of the bridge-type crystal oscillator (XO) with isolation amplifier; the two similar structures form the DMXO.

If the compact ceramic inductor is utilized that cannot be tuned (the inductor L1), then the final tuning of the oscillator frequency can be done by connection of several surface mounted capacitors in parallel (as it is shown in Fig. 1). In the case of utilization of wire-wound air-core inductors at the place of L1, the final tuning of the oscillator frequency can be performed by manual stretching or compressing of the inductor turns as well. Figure 2 shows the measured frequencies of the two overtones simultaneously excited in the SC-cut vs. temperature.

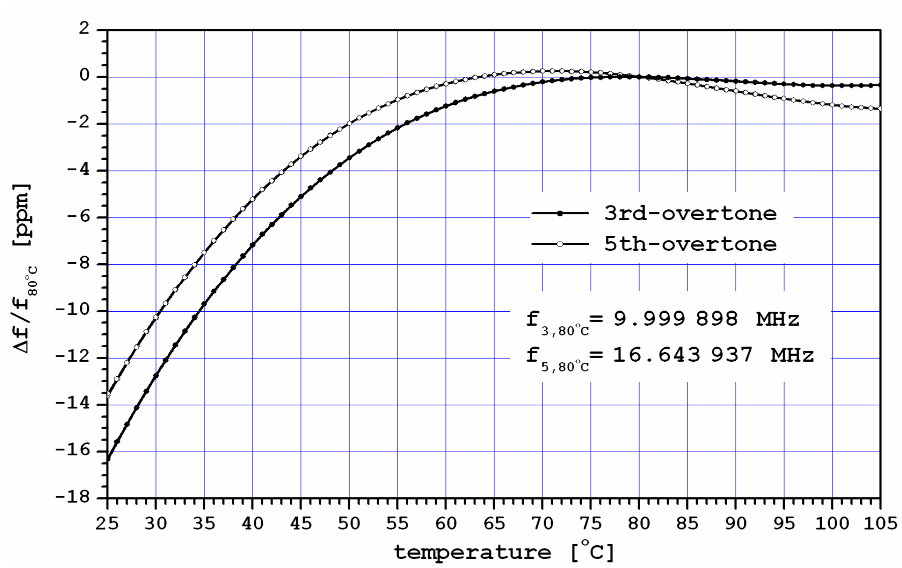

Fig. 2. Measured frequency vs. temperature dependencies of the two overtones (c modes) simultaneously excited in the SC-cut.

ENHANCED SC-CUT SELF-TEMPERATURE-SENSING

We implemented an enhanced SC-cut self-temperature-sensing with assistance of the DMXO and a field programmable gate array as it is illustrated in Fig. 3. Digital circuitry, we have designed, consists of two frequency dividers, digital mixer and two binary counters, which periodically measure the time interval derived from the difference frequency f_d that is derived from the two excited c modes. The 5th overtone oscillator frequency divided by five is subtracted from the 3rd overtone oscillator frequency divided by three, with assistance of the digital mixers and low pass filters (LPF). The difference frequency f_d at the output of the low pass filters can be expressed as follows:

$$f_d = f_3/3 - f_5/5 \ . \tag{1}$$

The difference frequency f_d is close to 4.5 kHz and its relative value rising with temperature approximately by +38 ppm/^{o}C.

The gate counter, shown in Fig. 3, produces approximately one-second time intervals (for $M = 4460$), during which the binary counters accumulate clock pulses. Clock of the first binary counter is driven by the first excited c mode (the 3rd overtone frequency f_3), while the clock of the second binary counter is driven by the second excited c mode (the 5th overtone frequency f_5).

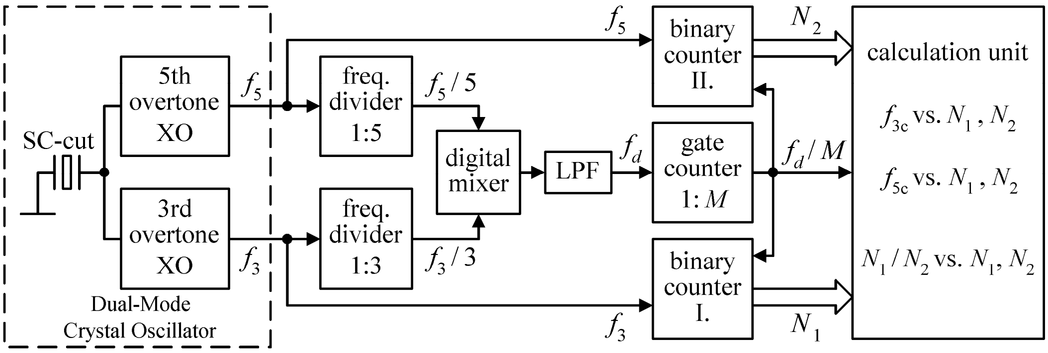

Fig. 3. Block diagram of the enhanced SC-cut resonator self-temperature-sensing implementation.

Figure 4 shows that the difference frequency f_d is almost linear function of temperature. At the end of each measuring cycle (time interval formed by the gate counter), which takes approximately one second (for $M = 4460$), the contents of both binary counters (N_1, N_2) represent an actual temperature of the SC-cut in the DMXO. After the clock pulses accumulation, the contents of the two binary counters can be expressed as follows:

$$N_1 = \mathrm{int}\left(\frac{f_3}{f_3/3 - f_5/5} M \right), \text{ where } M = 4460, \tag{2a}$$

$$N_2 = \mathrm{int}\left(\frac{f_5}{f_3/3 - f_5/5} M \right), \text{ where } M = 4460. \tag{2b}$$

Both the contents, N_1 as well as N_2, are again almost linear functions of temperature (Fig. 5) and they can be utilized for compensation for the frequency vs. temperature dependencies of both excited c modes.

The calculation unit (in Fig. 3) calculates actual frequencies of particular oscillators according to actual values of the independent variables N_1, N_2, with assistance of appropriate approximating polynomials, as follows:

$$f_{3c,1} = \sum_{k=0}^{9} a_k \cdot N^k, \text{ where } N = N_1 - N_{1,80\,^\circ\mathrm{C}}, \tag{3a}$$

$$f_{3c,2} = \sum_{k=0}^{9} b_k \cdot N^k, \text{ where } N = N_2 - N_{2,80\,^\circ\mathrm{C}}. \tag{3b}$$

$$f_{5c,1} = \sum_{k=0}^{9} c_k \cdot N^k, \text{ where } N = N_1 - N_{1,80\,^\circ\mathrm{C}}, \tag{3c}$$

$$f_{5c,2} = \sum_{k=0}^{9} d_k \cdot N^k, \text{ where } N = N_2 - N_{2,80\,^\circ\mathrm{C}}. \tag{3d}$$

The integers $N_{1,80\,^\circ\mathrm{C}}$ and $N_{2,80\,^\circ\mathrm{C}}$ in (3a) – (3d) represent the content of the two binary counters N_1 and N_2, respectively, at selected temperature (e.g. at 80°C, which is approximately the lower turnover point temperature of the 3rd overtone) of the SC-cut.

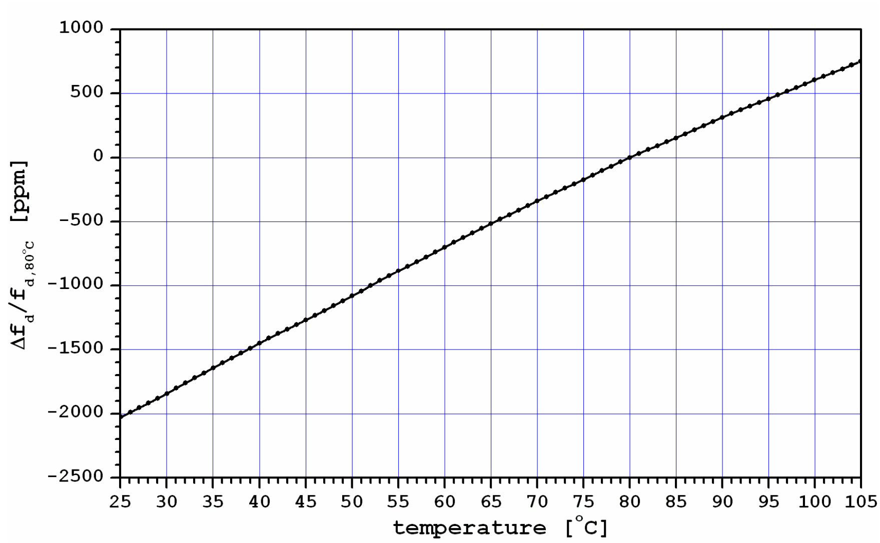

Fig. 4. The difference frequency f_d vs. temperature of the SC-cut resonator.

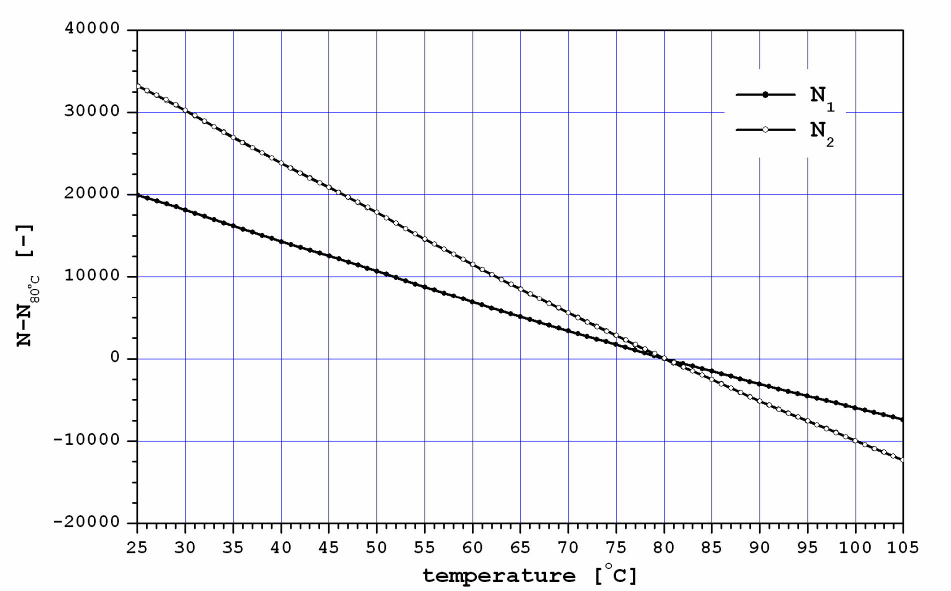

Fig. 5. Number of clock pulses accumulated in the two binary counters during the time interval $4460/f_d$ vs. temperature of the SC-cut resonator.

At first, the coefficients a_k, b_k, c_k and d_k in the polynomials (3a), (3b), (3c) and (3d), have to be determined according to collected data obtained from the calibration run. For each DMXO, the coefficients a_k, b_k, c_k and d_k have to be determined individually. The calibration process requires a dedicated computer (PC), controllable temperature chamber, two precise counters, and frequency reference. During the calibration run, the temperature of DMXO, which is inserted into the temperature chamber, is set to the required value. When the temperature of DMXO is stabilized, the frequencies of the two modes are measured simultaneously, with assistance of precise counters. The PC controls required temperature profiles in the chamber, controls the frequency measurements and collects all the measured data, as well.

Immediately after performing the DMXO calibration, the actual frequencies of the 3rd overtone XO calculated according to the polynomial (3a), as well as according to the polynomial (3b), have to be approximately the same; i.e. the differences between the two calculated values have to be within specified tolerance. However later, the two calculated values may start to differ due to different aging rates of resonant frequencies of particular modes simultaneously excited in the SC-cut. If the two calculated values, according to the polynomial (3a) and according to the polynomial (3b), differ too much (i.e. the difference between the two calculated values is outside of the defined tolerance), then it indicates that probably the aging rates of particular modes differ too much also. In this case, the system with the DMXO has to be recalibrated.

Similarly, in the case of the calculations of the actual frequencies of the 5th overtone XO, the calculated values according to the polynomial (3c), as well as according to the polynomial (3d), have to be approximately the same; i.e. the differences between the two calculated values have to be within specified tolerance. Moreover, the ratio between contents of the two binary counters (N_1/N_2) indicates the ratio between the two excited c mode's frequencies (f_3 / f_5).

RESULTS AND CONCLUSIONS

Figures 6 and 7 illustrate that the frequency residuals approximately 0.1 ppm, including hysteresis, can be achieved in the temperature range between 25°C and 105°C. After performing initial calibration runs in the chamber, we can utilize the content of binary counters (N_1, N_2) together with the ratio N_1 / N_2 for self-identification of the long-term frequency instabilities of the two c modes, which are simultaneously excited in the SC quartz resonator (Fig. 8), as well.

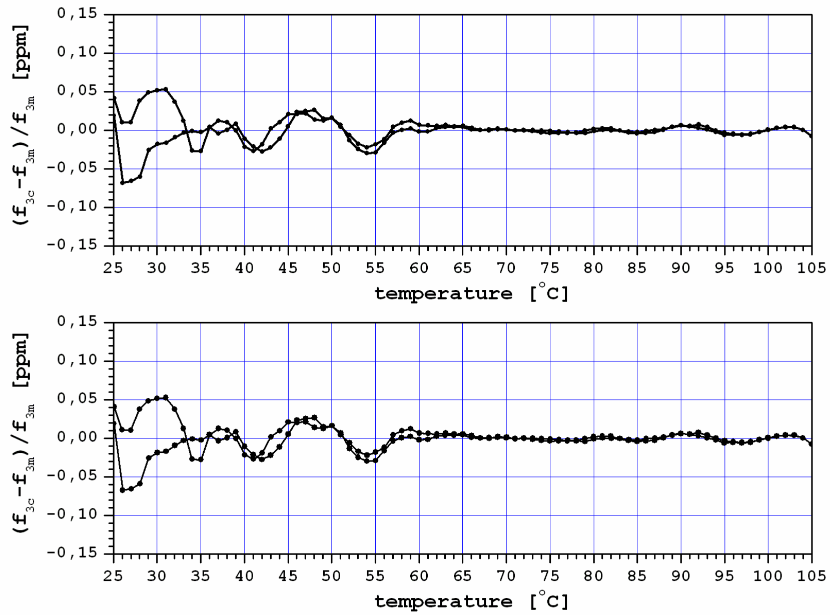

Fig. 6. Residuals vs. temperature in the case of 3rd overtone XO; data from calibration-run were fit to a single-segment 9th order polynomial (3a) – top, and polynomial (3b) – bottom.

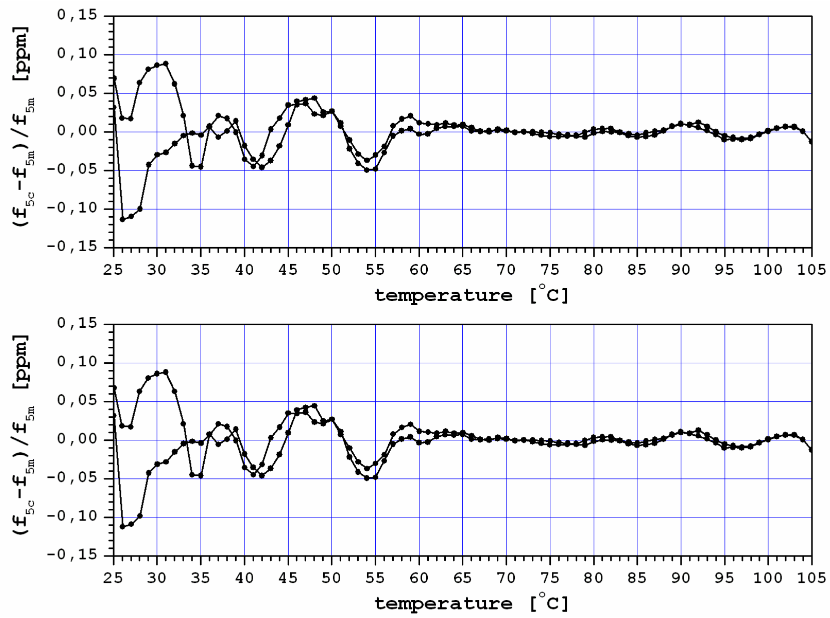

Fig. 7. Residuals vs. temperature in the case of 5th overtone XO; data from calibration-run were fit to a single-segment 9th order polynomial (3c) – top, and polynomial (3d) – bottom.

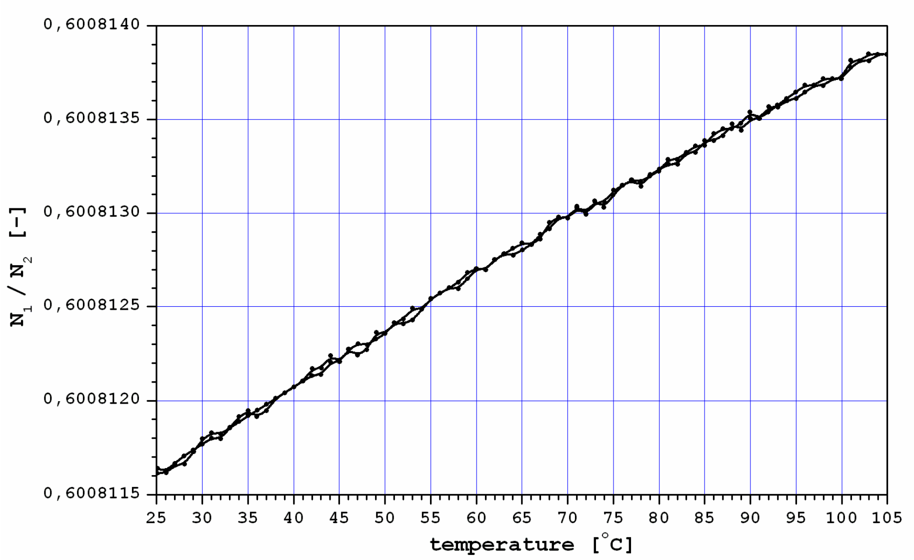

Fig. 8. Ratio of the numbers of clock pulses accumulated in the two binary counters N_1/N_2 vs. temperature of the SC-cut resonator; the clock pulses were accumulated during the time interval $4460/f_d$.

ACKNOWLEDGEMENT

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REFERENCES

[1] S. S. Schodowski, "Resonator Self-Temperature-Sensing using a Dual-Harmonic-Mode Oscillator," Proceedings of the 43rd Annual Symposium on Frequency Control, 1989, pp. 2-7.

[2] J. R. Vig, "Dual-mode Oscillators for Clocks and Sensors," Proceedings of the 1999 IEEE Ultrasonics Symposium, 1999, pp. 859-868.

[3] J. R. Vig, "Temperature-Insensitive Dual-Mode Resonant Sensors – A Review," IEEE Sensors Journal, Vol. 1, No. 1, June 2001, pp. 62-68.

[4] Y. Kim, "Aging of Dual Mode Resonator for Microcomputer Compensated Crystal Oscillator," Proceedings of the joint 2005 IEEE International Frequency Control Symposium and 2005 Precise Time and Time Interval Systems and Applications Meeting, 2005, pp. 171-175.

[5] V. Stofanik, I. Balaz and M. Minarik, "Dual-Mode Crystal Oscillator with Simultaneous Excitation of Two Overtones in a Stress Compensated Quartz Resonator," Proceedings of the joint 2007 European Frequency and Time Forum and the 2007 IEEE International Frequency Control Symposium, 2007, pp. 227-229.

[6] V. Stofanik, I. Balaz, M. Minarik and E. Cocherova, "Investigation of Self-Temperature-Sensing of SC-Cut with Simultaneous Excitation of Two Higher Overtones in Dual-Mode Crystal Oscillator," Proceedings of the 2008 IEEE International Frequency Control Symposium, 2008, pp. 170-173.

[7] V. Stofanik, I. Balaz, M. Minarik, and S. Kozinka, "Multi-Mode Crystal Oscillator for Simultaneous Excitation of Three Thickness-Shear Modes in Stress Compensated Resonator," Proceedings of the Joint 2009 European Frequency and Time Forum and the 2009 IEEE International Frequency Control Symposium, 2009, pp. 516-519.