Enhanced Method of the Quartz Resonator Self-Temperature-Sensing

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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.*

Keywords: Dual-Mode Crystal Oscillator, SC-out Resonator, Frequency Stability

1. Introduction

Conventional methods for sensing resonator's temperature in Temperature Compensated Crystal Oscillators (TCXO), for example, utilize a thermistor, placed in close proximity to the resonator. This method suffers from inaccuracies due to thermal lag stemming from differences in time constants and thermal gradients between the resonator and the thermistor, as well as thermistor aging. 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. Various applications related to the dual-mode excitation have been reviewed in [1], [2].

2. Enhanced SC-cut Self-Temperature-Sensing

We implemented an enhanced self-temperature-sensing of SC-cut quartz resonator with assistance of the DMXO and a field programmable gate array as it is illustrated in Fig. 1. The structure of particular crystal oscillators (XO) forming the DMXO we described in [3], [4], [5]. 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.

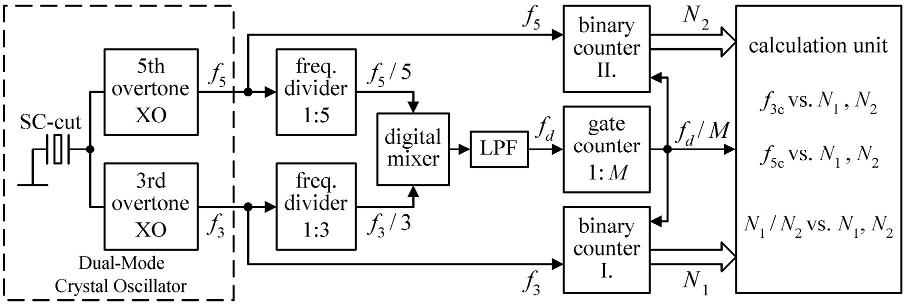

Fig. 1. Block diagram of the enhanced SC-cut resonator self-temperature-sensing implementation.

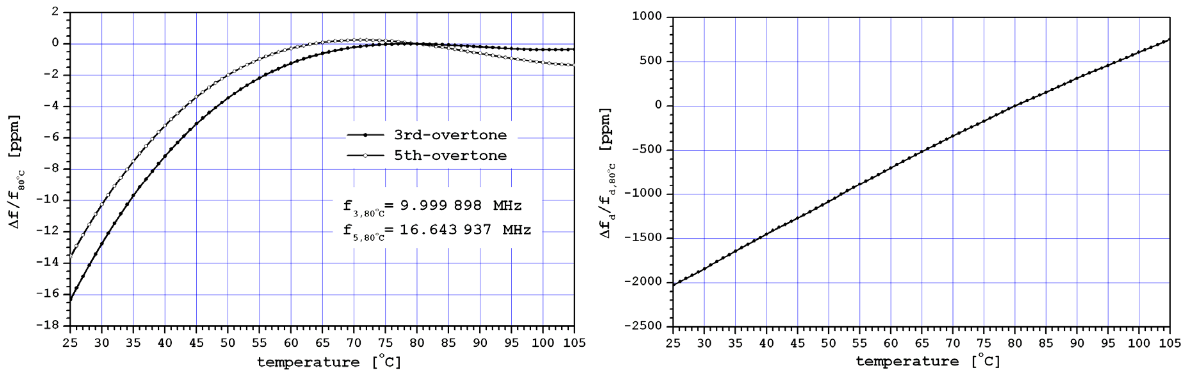

Fig. 2. Measured frequency vs. temperature dependencies of the two simultaneously excited modes in the SC resonator (left); the difference frequency vs. temperature (right).

The 5th overtone oscillator frequency divided by five is subtracted from the 3rd overtone oscillator frequency divided by three, with assistance of the digital mixer and low pass filter (LPF). The difference frequency at the LPF output can be expressed as follows:

$$f_d(\vartheta) = \frac{f_3(\vartheta)}{3} - \frac{f_5(\vartheta)}{5} \,, \qquad (1)$$

where ϑ is the temperature of the SC-cut resonator. Figure 2 (left) shows the measured frequencies of the two simultaneously excited overtones in the SC-cut vs. temperature. Figure 2 (right) shows that the difference frequency f_d is almost linear function of temperature. The difference frequency f_d is close to 4.5 kHz and its relative value rising with temperature approximately by +38 ppm/°C. The gate counter (Fig. 1) 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). At the end of each measuring cycle (time interval formed by the gate counter), the contents of both binary counters represent an actual temperature of the SC-cut resonator in the DMXO. After the clock pulses accumulation, the contents of the two binary counters can be expressed as follows:

$$N_1(\vartheta) = \mathrm{int}\left(\frac{f_3(\vartheta)}{f_d(\vartheta)} \cdot M\right), \text{ where } M = 4460 \,, \qquad (2a)$$

$$N_2(\vartheta) = \mathrm{int}\left(\frac{f_5(\vartheta)}{f_d(\vartheta)} \cdot M\right), \text{ where } M = 4460 \,. \qquad (2b)$$

Both the contents, $N_1(\vartheta)$ as well as $N_2(\vartheta)$, are again almost linear functions of temperature. The calculation unit (in Fig. 1) calculates actual frequencies of particular oscillators according to actual values of the independent variables $N_1(\vartheta)$, $N_2(\vartheta)$, with assistance of appropriate approximating polynomials, as follows:

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

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

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

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

The integers $N_{1,80°C}$ and $N_{2,80°C}$ in (3a) – (3d) represent the content of the two binary counters at selected temperature (e.g. at 80°C, which is approximately the lower turnover point temperature of the 3rd overtone) of the SC-cut. 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. 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. PC controls required temperature profiles in the chamber, controls the frequency measurements and collects all the measured data, as well.

Immediately after 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, which are 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 $N_1(\vartheta)/N_2(\vartheta)$ indicates the ratio between the two excited c mode's frequencies $f_3(\vartheta)/f_3(\vartheta)$.

3. Results and Conclusions

Figures 3 and 4 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. 5), as well.

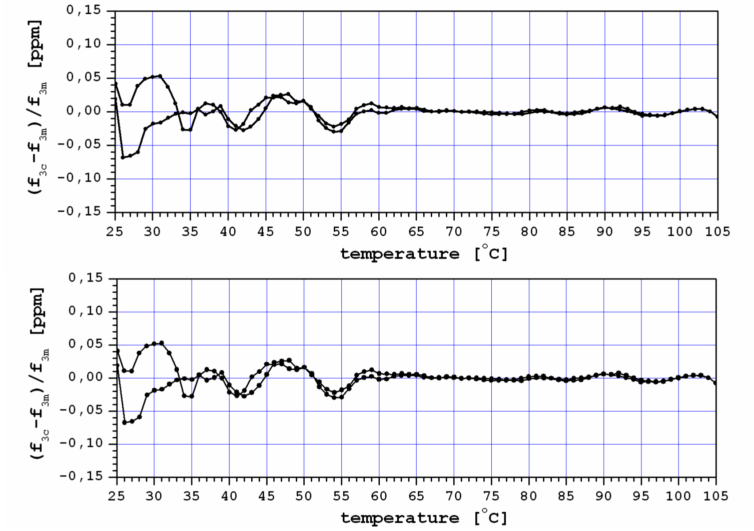

Fig. 3. Residuals vs. temperature in the case of 3rd overtone XO; data from calibration-run were fit to a single-segment 9th order polynomial (3a) – top, and polynomial (3b) – bottom.

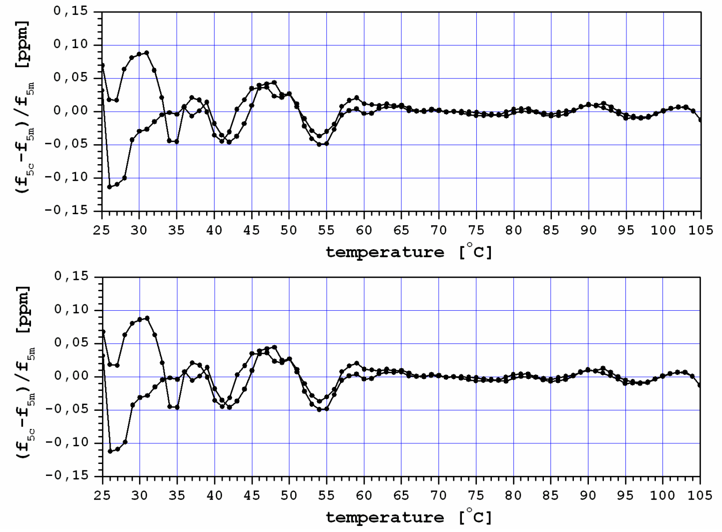

Fig. 4. Residuals vs. temperature in the case of 5th overtone XO; data from calibration-run were fit to a single-segment 9th order polynomial (3c) – top, and polynomial (3d) – bottom.

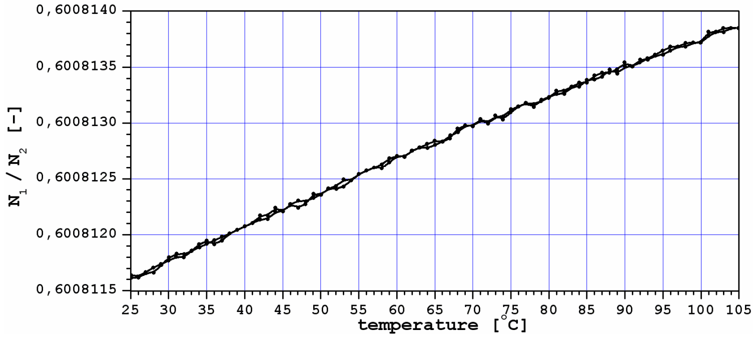

Fig. 5. Ratio of the numbers of clock pulses accumulated in the two binary counters N_1/N_2 vs. temperature of the SC-cut resonator; the clock pulses were accumulated during the time interval $4460/f_d$.

Acknowledgements

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