Multi-Mode Crystal Oscillator for Simultaneous Excitation of Three Thickness-Shear Modes in Stress Compensated Resonator

Vladimír Štofanik[*,+]
[+] Department of Thermophysics
Institute of Physics, Slovak Academy of Sciences
Bratislava, Slovak Republic
vladimir.stofanik@savba.sk

Igor Baláž[*], Marián Minárik[*], Stanislav Kozinka[*]
[*]Department of Radio and Electronics
Faculty of Electrical Engineering and Information Technology, Slovak University of Technology
Bratislava, Slovak Republic

***Abstract*—This paper deals with evaluation of self-temperature-sensing of stress compensated (SC) quartz resonator with simultaneous excitation of three higher overtones - the slow thickness-shear modes (i.e. the c-modes) in multi-mode crystal oscillator (MMXO). We have designed the MMXO especially for excitation of three c-modes in standard 10-MHz 3rd overtone SC resonators: the 3rd overtone, the 5th overtone and the 7th overtone. Each excited mode has its own frequency vs. temperature characteristic that can be measured and approximated as well. Simultaneous excitation of the three modes of vibrations in the volume of the resonator enables us to enhance the self-temperature-sensing. Consequently, in addition to compensation for frequency shifts due to variations of the resonator's temperature, also frequency shifts caused by different aging rates of the particular modes can be identified autonomously (without necessity for any external frequency reference).**

I. INTRODUCTION

The conventional method for sensing resonator's temperature in Temperature Compensated Crystal Oscillators (TCXO), for example, utilizes a temperature-sensing element (e.g. 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 self-temperature-sensing of the resonator. The self-temperature-sensing method eliminates temperature offset and lag effects, since no external temperature-sensing element is used. The history and different applications related to the dual-mode excitation have been reviewed in [1], [2].

Self-temperature-sensing of Stress Compensated (SC) quartz resonator utilizing simultaneous excitation of fundamental slow thickness-shear mode (i.e. c-mode) together with the 3rd overtone c-mode in the resonator has been introduced in [3].

This work was supported by the Ministry of Education of Slovak Republic under the grant No. 3/7411/09 and by the Slovak Research and Development Agency under the grant No. APVV-0497-07.

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 c-modes are free from significant anomalies (so called activity dips).

This method has been employed in the Microcomputer Compensated Crystal Oscillator (MCXO) [4]. Since the MCXO is primary intended for military applications, it has to operate reliably in the wide temperature range between -55°C and +85°C. Optimal quartz resonators (not a standard SC cut) with the lower turnover temperature of the 3rd overtone frequency close to +20°C have been designed especially for the MCXO [5].

However later, author in [6] has presented that the differences between the agings of the two exited mode frequencies in the resonator cause an offset with a tilt in the 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. That is why the minimization of the differences between aging rates of the two excited c-mode's frequencies is very important for the MCXO.

Different combinations of two overtones (c-modes) simultaneously excited in 10-MHz 3rd overtone SC-cut resonators with lower turnover temperature of the 3rd overtone between +80°C and +85°C we investigated in [7], [8], [9].

Here we introduce the multi-mode crystal oscillator (MMXO) we have designed especially for simultaneous excitation of three overtones (c-modes) in standard 10-MHz 3rd overtone SC-cut resonator: the 3rd overtone, the 5th overtone and the 7th overtone. Each excited mode in the SC-cut resonator has its own frequency vs. temperature characteristic that can be measured and approximated as well.

978-1-4244-3510-4/09/$25.00 ©2009 IEEE

Simultaneous excitation of the three modes of vibrations in the volume of the resonator enables us to enhance the self-temperature-sensing. In addition to compensation for frequency shifts due to variations of the resonator's temperature, also frequency shifts caused by different aging of the particular excited modes can be identified autonomously, without necessity for any external frequency reference.

II. DESCRIPTION OF THE MMXO STRUCTURE

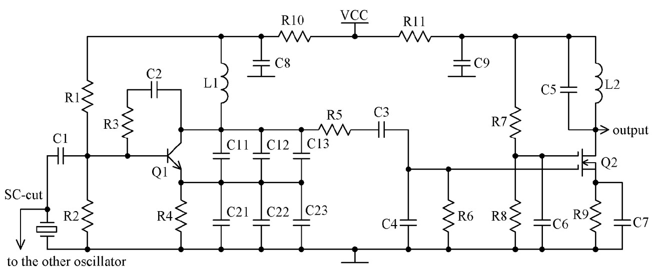

Figure 1. Schematic diagram of the bridge-type crystal oscillator (XO) with isolation amplifier; the three similar structures form the MMXO.

Investigated MMXO consists of three 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.

Appropriate mode in the particular oscillator is selected by the inductor L1 and the two parallel combinations of capacitors: C11 || C12 || C13 and C21 || C22 || C23. Of course, in practice other impedances: like parasitic impedances of the bipolar junction transistor Q1 and following amplifier, affect the oscillator frequency as well.

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.

In [7], [8], we investigated an impact of instabilities due to temperature variations of different types of inductors on the oscillator frequencies: - the air-core wire-wound inductors; - and the miniature multilayer ceramic inductors (HK1608 series from Taiyo Yuden Co. Ltd.). To be the influence more obvious, we replaced the SC-cut resonator in the particular bridge-type oscillator by the resistor with the resistance approximately equal to motional resistance of the appropriate mode, normally excited in the SC-cut. Inductance of multilayer ceramic inductors is more temperature dependent (approximately, three times) in comparison with the wire-wound air-core inductors [7], [8].

The resistor R3 forms negative voltage feedback of the sustaining amplifier with bipolar junction transistor 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).

Figure 2 shows the measured frequency vs. temperature dependencies of the three simultaneously excited overtones in the SC-cut.

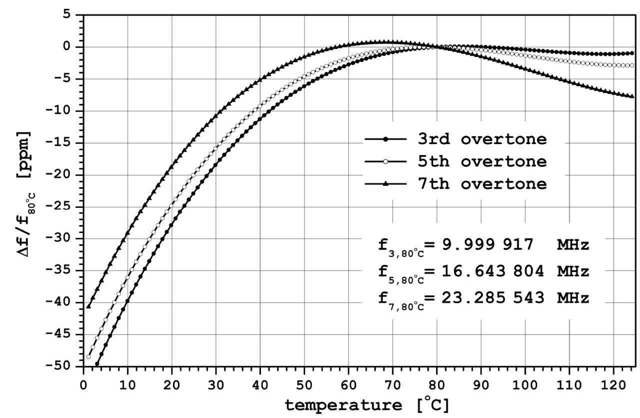

Figure 2. Measured frequency vs. temperature dependencies of the three overtones (c-modes) simultaneously excited in the SC-cut.

III. IMPLEMENTATION OF ENHANCED SC-CUT RESONATOR SELF-TEMPERATURE-SENSING

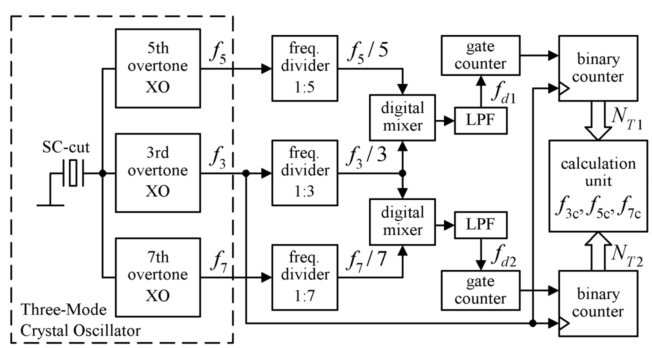

Figure 3. Block diagram of the enhanced SC-cut resonator self-temperature-sensing implementation.

Block diagram of the enhanced SC-cut self-temperature-sensing implementation is shown in Fig. 3. The 5th overtone (the 7th overtone) oscillator frequency divided by five (divided by seven) is subtracted from the 3rd overtone oscillator frequency divided by three, with assistance of the digital mixers and low pass filters (LPF).

The difference frequencies f_{d1} and f_{d2} at the output of the low pass filters can be expressed as follows:

$$f_{d1} = f_3/3 - f_5/5 \tag{1a}$$

$$f_{d2} = f_3/3 - f_7/7 \tag{1b}$$

Figure 4 illustrates that the both difference frequencies are almost linear functions of the SC-cut resonator's temperature. The difference frequency f_{d1} is close to 4.5 kHz and its relative value raising with temperature approximately by +38 ppm / ^{o}C. The difference frequency f_{d2} is close to 6.7 kHz and its relative value increases with temperature approximately by +75 ppm / ^{o}C. The sensitivity of f_{d2} to temperature changes of the SC-cut is approximately two times higher than the sensitivity of f_{d1}.

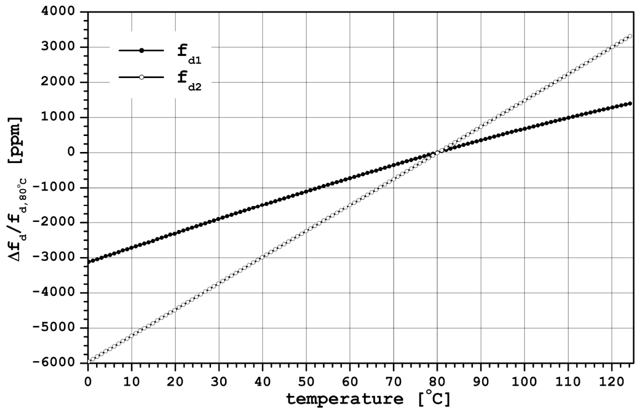

Figure 4. The two difference frequencies f_{d1} and f_{d2} vs. temperature of the SC-cut resonator.

The gate counters, shown in Fig. 3, produce approximately one-second time intervals, during which the binary counters accumulate clock pulses with frequency f_3 (i.e. frequency of the 3rd overtone XO).

After the clock pulses accumulation, the contents of the two binary counters can be expressed as follows:

$$N_{T1} = \mathrm{int}\left(\frac{f_3}{f_3/3 - f_5/5} 4460 \right) \tag{2a}$$

$$N_{T2} = \mathrm{int}\left(\frac{f_3}{f_3/3 - f_7/7} 6700 \right) \tag{2b}$$

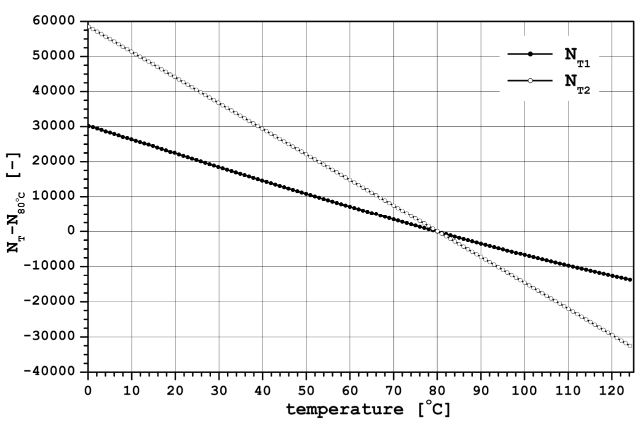

Figure 5. Number of clock pulses accumulated in the two binary counters during the time interval $4460 / f_{d1}$ (interval $6700 / f_{d2}$) of the SC-cut resonator.

The contents of the two binary counters N_{T1} and N_{T2} are used to form two independent variables $N_1 = N_{T1} - N_{01}$ and $N_2 = N_{T2} - N_{02}$. The both independent variables represent actual temperature of the SC-cut resonator. Figure 5 illustrates that the two independent variables N_1 and N_2 are almost linear function of temperature with the negative slopes of -38 ppm / ^{o}C and -75 ppm / ^{o}C, respectively.

The calculation unit (in Fig. 3) computes actual frequencies of particular oscillators according to actual values of the independent variables N_1, N_2, with assistance of appropriate approximating polynomials. For example, in the case of 3rd overtone XO frequency as follows:

$$f_{3c,1} = \sum_{k=0}^{9} a_k \cdot N_1^k \text{ , where } N_1 = N_{T1} - N_{01} \tag{3a}$$

$$f_{3c,2} = \sum_{k=0}^{9} b_k \cdot N_2^k \text{ , where } N_2 = N_{T2} - N_{02} \tag{3b}$$

The integers N_{01} and N_{02} represent the content of the two binary counters N_{T1} and N_{T2}, respectively, at selected temperature (e.g. at 80^{o}C) of the SC-cut (also the temperature of the MMXO).

At first, the coefficients a_k, b_k in the polynomials (3a) and (3b), have to be determined according to collected data obtained from the calibration run. For each MMXO, the coefficients a_k, b_k has to be determined individually.

The calibration process requires a dedicated computer (PC), controllable temperature chamber, three precise counters, and frequency reference. During the calibration run, the temperature of MMXO, which is inserted into the temperature chamber, is set to the required value. When the temperature of MMXO is stabilized, the frequencies of all three modes are measured simultaneously, with assistance of precise counters. The computer controls required temperature profile in the chamber, the measurements and collects all the measured data as well.

Immediately after performing the MMXO calibration, the actual frequency calculated according the polynomial (3a) as well as according to the (3b) has to be approximately the same; i.e. the differences between the two calculated values have to be within some 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 the polynomial (3a) and according to the (3b), differ too much (i.e. the difference between the two calculated values is outside of the defined tolerance), then it indicates that the aging rates of particular modes differ too much also. In this case, the system with the MMXO has to be recalibrated.

IV. RESULTS

Figure 6 illustrates relative differences between calculated frequency of 3rd overtone XO using approximating polynomial (3b) and measured frequency of the signal generated at the 3rd overtone XO output.

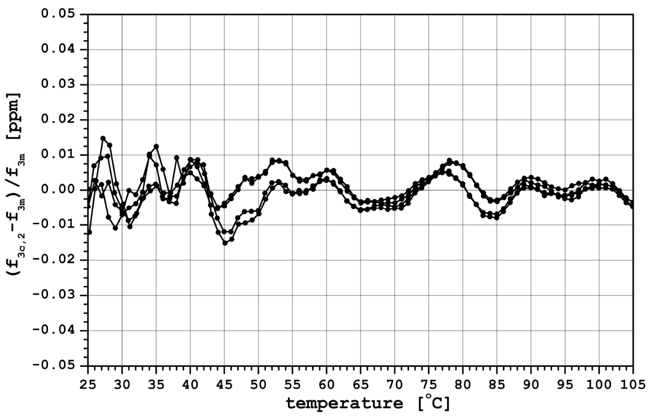

Figure 6. Residuals vs. temperature in the case of 3rd overtone XO; data from calibration-run were fit to a single-segment 9th order polynomial (3b).

V. CONCLUSIONS

To implement the resonator self-temperature-sensing, at least two modes of vibrations are necessary to be excited simultaneously in the resonator. However, simultaneous excitation of three modes of vibrations in the volume of the resonator enables us to enhance the self-temperature-sensing. In addition to compensation for frequency shifts due to variations of the resonator's temperature, also frequency shifts caused by different aging rates of the particular modes can be identified autonomously (without necessity for any external frequency reference). Moreover, autonomous compensations for long-term frequency shifts can be implemented as well; however, only if the aging rates of the particular excited modes in the used resonator are known or if the aging rates can be predicted accurately.

REFERENCES

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

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

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

[4] A. Benjaminson and S. C. Stallings, "A Microcomputer Compensated Crystal Oscillator using a Dual-Mode Resonator," Proc. of the 43rd Annual Symposium on Frequency Control, 1989, pp. 20-26.

[5] R. L. Filler and J. R. Vig, "Resonators for the Microcomputer Compensated Crystal Oscillator," Proc. of the 43rd Annual Symposium on Frequency Control, 1989, pp. 8-15.

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

[7] 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.

[8] V. Stofanik, I. Balaz and M. Minarik, "Employment of Miniature Multilayer Ceramic Inductors in the DMXO with Excitation of Two Overtones in SC-cut," Proceedings of the 2008 European Frequency and Time Forum (EFTF), Toulouse Space Show `08, 2008, paper: FPE-0035 (on DVD).

[9] 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.