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Flicker Noise in Quartz Crystal Resonator at 353 K as a Function of Q-Factor of Overtones and Anharmonic Modes at 4 K

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The unclear physical origin of flicker noise in ultra-stable quartz oscillators is still limiting some practical metrological applications. In this paper, we study experimentally the possible correlations between Q-factor measurements at low temperature (4 K) and the level of flicker noise at nominal operating temperature (353 K). Results for 10 Stress-Compensated-cut (SC-cut) resonators with a 5 MHz resonant frequency and different noise levels (some excellent) are presented and commented, for several overtones and anharmonic modes.

Keywords: Anharmonics; flicker noise; overtones; resonator.

1. Introduction

Over the past few decades, the performance of quartz resonators in terms of frequency stability has been greatly improved [1–5]. However, relative fluctuations of this frequency remain at 10^{-14} level and are limiting the use for some applications such as Doppler orbitography or radio-positioning integrated by satellite. Furthermore, in a same batch of fabrication process, the noise level of the produced resonators can spread over two orders of magnitude. The power spectral density of these fluctuations follows a $1/f$ slope at low baseband frequencies. The origin of this $1/f$ observed noise is still an unanswered question [6]. Defects in the structure can be a source of $1/f$ noise. As an example in transistor devices, many different relaxation times can give $1/f$ perturbation according to the lorentzian approximation [7].

Heterogeneity of the crystal structure (any kind of defects) can disturb the acoustic wave. Low temperature experiments done so far, have established that bulk acoustic wave quartz crystal resonators exhibit very high Q-factors at cryogenic temperatures [8–13], that could probably be correlated to the amount of crystal defects. The Q-factor is representative of the vibrating volume and the effective mass of the resonant cavity [13, 14]. The harmonic modes and the anharmonic modes due to the plano-convex-shape [15] give different vibrating zones inside the heart of the resonator. The vibrating volume of these different modes is well-known and can be observed by X-Ray technology [16]. Characterization of the Q-factor of all of these modes could give some information about the crystal quality. Hence, we have carried out measurements for Q-factors at 4 K, in order to study the possible correlation between noise results at ambient temperature and acoustic defects in the active volume of the resonator. The 5 MHz stress-compensated-cut quartz resonator (SC-cut), is a good candidate to explore this phenomenon since it is today considered as the best kind to be used in quartz oscillators, owing to its excellent performance for short-term stability (1–10 s) [5].

In this contribution, we first give some relevant information on the realization of the 5 MHz SC-cut resonators. Then, we report Q-factors for several overtones and anharmonic modes, measured at 4 K, as a function of the short-term stability of the resonator measured on their metrological vibrating mode at 353 K and conclude on the absence of correlations.

2. Resonator Characteristics and Measurement Setups

Ten quartz crystal resonators have been cut in the same crystal block supplied specifically for this study on $1/f$ noise. The resonators are typical 5 MHz SC-cut quartz crystals. The diameter of the resonator is 14 mm for a thickness of 1.09 mm. The plano-convex shape allows the energy trapping for the 3rd overtone of the slowest thickness shear mode (C-mode). The electrodes' diameter is 8 mm. A radius of curvature of 130 mm has been chosen to optimize the energy trapping according to the Tiersten–Stevens model [15]. The classical temperature turnover point of the resonator is chosen around 353 K by adjusting the cutting angles of the crystal. Table 1 gives the corresponding theoretical resonant frequencies for each modes that

Table 1. Theoretical values of resonant frequencies of the designed resonator for A-, B- and C- modes (overtones and anharmonic modes of C300 (Temperature = 4 K).

A-Mode								A300
Freq. (MHz)								9.362
B-Mode								B300
Freq (MHz)								5.487
C-Mode	C300	C320	C302	C340	C322	C304	C500	C700
Freq. (MHz)	5.000	5.119	5.131	5.237	5.248	5.2597	8.299	11.594

we observed, computed using (126) from [15]. Then, the experimental resonant frequencies are searched near these theoretical values using a network analyzer. The observed modes are both thickness shear and longitudinal ones (A: longitudinal, B: quasi-shear with fast velocity, C: quasi-shear with low velocity). In naming of the mode, the first letter represents the vibrating type, the first number is the overtone and the second and third numbers give the rank of the anharmonic modes.

The Q-factors of C-modes at different overtone ranks and anharmonic modes of C300 have been measured. For the A- and B-modes, only overtones have been tested.

The resonators have been characterized at cryogenic temperature. In our experiment, a two-stage pulse-tube cryo-cooler is used at the cryogenic system's core [11]. The device under test (DUT) is attached to a temperature-controlled copper block and enclosed in a vacuum chamber.

The phase noise of the metrological mode (C300) has been measured at the temperature turnover point (353 K) using a carrier suppression measurement setup [6], and a double oven [17]. The resulting flicker frequency floor of the resonators is given in terms of the Allan deviation (short-term stability σ_{y_floor}) [18, 19]. The noise results of the resonators are compared according to the overtone behavior on different vibrating modes (harmonics and anharmonics) in order to find a correlation with the intrinsic noise of the resonators.

3. Experimental Results

Ten resonators have been tested for this study. They are labeled *a*–*j* according to their noise levels at 353 K, from lower to higher σ_{y_floor} level. Figure 1 shows the Q-factor of the different modes of the resonators at the same 3rd overtone, measured at 4 K and/or 353 K, as a function of their σ_{y_floor}. The Q-factors of the C300 mode at the turnover temperature are all around $2.5 \cdot 10^6$ since it was a design requirement. Among the worst resonators in terms of noise (σ_{y_floor} around $2.3 \cdot 10^{-12}$), resonator *i*

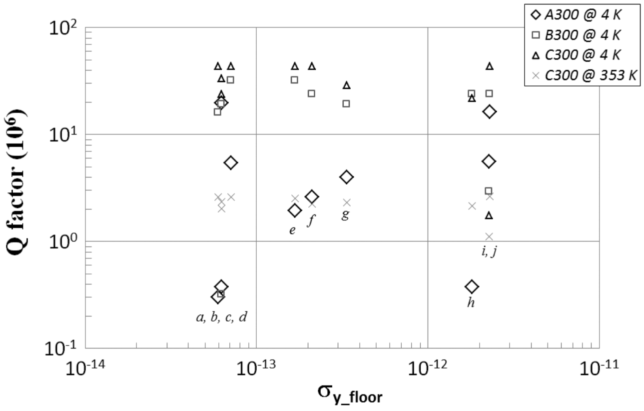

Fig. 1. Q-factor of the resonators for different modes of vibration (at 4 K and/or 353 K) as a function of the short-term stability level (σ_{y_floor}) at 353 K.

has the lowest Q-factor ($1.12 \cdot 10^6$) while resonator j has the highest Q-factor ($2.66 \cdot 10^6$), showing the non-exclusive correlation of these two quantities.

The Q-factor of the C-mode at 4 K is increased by a factor of 17 with respect to the results at 353 K for resonators a, d, e, f and j, while this factor is close to 10 for resonators b, c and g and only of the order of 1.5 for resonator i (measured at only $1.7 \cdot 10^6$). In terms of noise, the distribution of the results shows that the best and the worst resonators (e.g., a and j) have very similar Q-factors. Results in the B-mode are the most homogenous (all around $20 \cdot 10^6$, except for resonator i), so that they do not allow to distinguish the resonators. Finally, the spread of the results in the A-mode, either for the good or bad resonators, seems to show that this is also not a good indicator of the noise level.

Q-factors at 4 K for anharmonic modes of C300 are presented in Fig. 2 as a function of $\sigma_{y\_\mathrm{floor}}$ measured at 353 K. The anharmonic modes are representative of the energy trapping and of the shape of the resonators [15]. The Q-factors of the modes C320 and C302 have been measured for all resonators. They are in the range 10^6–10^7, and show no clear correlation with the measured noise. For the other modes, due to small signal and parasitic capacitance, Q-factors could not be measured even for some of the tested resonators (e.g., a, h and i for C322; b, d, g, h and i for C304; a, c, f, g and i for C340). The Q-factor values for the modes C322 and C304 are below $1 \cdot 10^6$ except for the resonator f which has an intermediate noise level. The Q-factor for the C340 mode seems to decrease with the noise level (b, d, e and h) but this tendency is contradicted by resonator j.

Figure 3 presents the Q-factors for the overtones of C300 mode (C500 and C700) as a function of the noise level. The Q-factor of the C700 mode could not be measured for resonators c, h and j. The worst resonator in terms of noise also has the minimum value for C500 and C700.

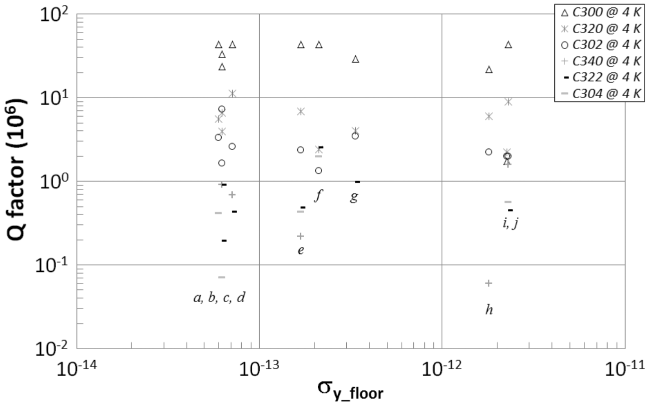

Fig. 2. Q-factor for anharmonic modes of C300 (measured at 4 K) as a function of the short-term stability level (measured at 353 K).

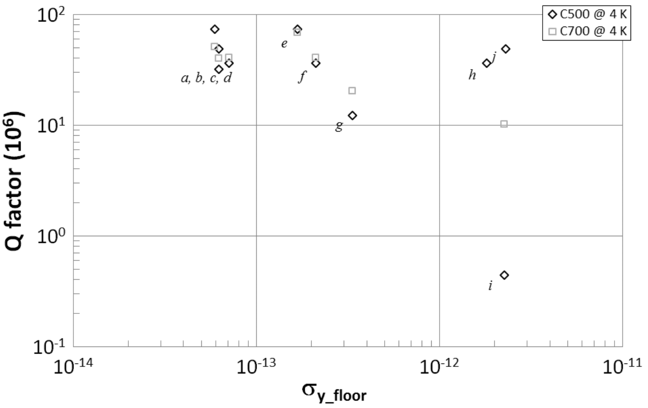

Fig. 3. Q-factor for overtone modes of C300 (measured at 4 K) as a function of the short-term stability level (measured at 353 K).

4. Conclusion

Experimentaly, no correlation has been found between the flicker noise level at turnover temperature and the Q-factors of overtones and anharmonics at low temperature. Further investigation could be done by measuring the noise directly at low temperature, but for that, in the case of quartz crystal, the thermal influence must be controlled with a better resolution [20] by finding a frequency–temperature compensated cut [21]. The $1/f$ frequency noise of the acoustic resonator remains in discussion.

Acknowledgments

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