Drive level dependence and origin of noise in ultra-stable piezoelectric crystal resonators

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ABSTRACT

Under storage, a phenomenon known as drive level dependency (DLD) or drive level sensitivity (DLS) may appear that prevents the starting of oscillation. Limits of the best oscillators based on this type of piezoelectric materials are known. As well as we remind about various experimental set-ups, and measurement procedures used to obtain very low drive level motional parameters, we are interested in investigating different designs and topologies to ensure stable solutions. Understanding the problem of starting piezoelectric oscillators after a long storage period may help for settling optimized devices to understand origin of noise. We are not only interested in the description of phenomena from the point of view of electrical or optical schematization, but concretely in implementing solutions to resolve them and find lasting technological solutions.

Keywords: Drive Level Dependency, Drive Level Sensitivity, quartz, resonator, oscillator.

1. INTRODUCTION

When an ultrastable quartz oscillator is manufactured and characterized, the frequency delivered is carefully adjusted. The oscillator typically delivers 5, 10 or 100 MHz. The oscillator are then placed in operating condition. It can be powered for example by mains or battery. The first part of its "life" while in operating condition is used to get rid of the initial defects. The oscillators that remain in operating condition with the best characteristics are those that can be kept. The oscillator will then live its life. For example, it can be taken into a device and used as a backup oscillator for a few years. When it is used, it is possible that its nominal frequency has varied. This can be due to multiple reasons. This is what we will call its "drive level sensitivity". We must understand where this phenomenon could come from.

Those phenomena were investigated by H. F. Tiersten [1,2] or J.-J. Gagnepain et al [3].

Several laboratories tried to understand Drive level dependency in quartz resonators [4]. Mihir S Patel and Y. K. Yong worked on Drive level dependency in quartz resonators [5,6]. Lee and his colleagues worked on thickness vibrations of a piezoelectric plate with dissipation [7]. Many progresses were achieved thanks to Raymond Besson with his improvement of quartz oscillators [8].

To try to understand where the origin of the noise may come from as well as the variation in the frequency initially delivered, it is necessary to consider each particular phenomenon, which can potentially have an influence on the parameters of the oscillator.

We will first remind about the aspects of the variation of the expected frequency and the degradation of the performances and then write about DLD.

2. UNWANTED VARIATION OF NOMINAL FREQUENCY OR PERFORMANCE DEGRADATION

The interest of this DLS problem is the following. Just imagine that if a quartz oscillator delivering an ultra-stable signal is in a difficult to access environment and it starts to deliver a frequency that is no longer the right one, this really poses a problem. It is easy to understand, for example, that the backup quartz placed in a satellite cannot be replaced. It may be a quartz that is part of a frequency synthesis chain [9]. This is why its delivered frequency must be the one expected.

For keeping good performances, the quartz has to be thermostated. The control of th etemperature is necessary for the frequency to be less dependent of the temperature variation. The chosen temperature is that where the frequency variation is the least sensitive. Nevertheless, it may happen that a particle from the manufacturing process has remained in the thermostat. To illustrate this fact, it should be known for example that a mass ratio of 1 ppm between the particle and the resonator would induce a 100% increase in the series resistance [4]. In addition, this value would increase considerably if the resonance frequency of the particles is close to the resonant frequency of the quartz resonator.

The performances of the best quartz oscillators that have been manufactured for a long time are no longer improving. It seems that, either the limit has been reached for performance improvement, either the needs for ultra-stable oscillators do not require performance improvement. There is also less research and fewer manufacturers. The best commercial crystal oscillators usually operate with a short-term frequency stability of 8×10^{-14} in terms of Allan deviation. The best frequency stability ever measured on a quartz crystal oscillator was then obtained in 2010. This new BVA oscillator has an estimated flicker frequency modulation (FFM) floor of 2.5×10^{-14} at 5 MHz [10]. This was highlighted as an important step. It was obtained using a double-rotated SC cut quartz with low phase noise, good aging characteristics and low sensitivity to drive level dependence, placed in a suitable thermostat in the first oscillator prototype oven-controlled crystal (OCXO) made in Switzerland by the company Oscilloquartz [11]. To get an idea of the performance, such frequency stability is equivalent to a variation of only one second for 1.3×10^{6} years, but measured in terms of frequency stability over an integration time of a few seconds, because the main interest of such oscillators is to deliver an ultra stable signal in the short term. The measured FFM floor is $3.2 \times 10^{-14} \pm 1.1 \times 10^{-14}$ at 5 MHz [12]. It is obtained for an average integration time of 20 s. This measurement result and its associated uncertainty are consistent with the best FFM floor measured previously [10]. It can be noted that the aging of the oscillator masks the FFM floor for a higher integration time. The level of performance can be ensured with good distribution of the radio frequency signals delivered by the quartz crystals [13]. Other relevant papers can also be consulted [14, 15]. Discussions of the estimated errors are given here [16]. Fred Walls and his colleagues from NIST described the principle of phase noise and its calculation [17, 18]. Progress in quartz oscillators were discussed [19]. To ensure comparison between performances of benches in different laboratories, some comparisons are organized [20]. Possible applications of a better understanding of those phenomena could be as cited here. [21].

3. DRIVE LEVEL SENSITIVITY

Concretely, it happens that the signal delivered by the quartz oscillator is not as it was after having been measured right after its manufacture. This results in a difference between the expected frequency and the measured frequency. If the problem is detected early enough, it is possible to correct and adjust the frequency to obtain the desired frequency. Usually the expected frequency of the quartz resonator is chosen slightly different from the one it is when the quartz is mounted as an oscillator. The rectification is reached through electronics. There is a drift effect in the early moments of the oscillator's life. Then the frequency is becoming almost stable. When the requested nominal frequency is achieved and stable, DLD can occur with a non negligible effect. Starting of oscillation in a quartz crystal oscillator requires a resonator's input power in the range of – 20 dBm typically, but under storage DLD may appear that prevents the starting of oscillation.

Various experiments have proved the relationship of cause and effect between the surface pollution with DLD. It could potentially be caused by several possible phenomena. There are several reasons, such as surface stresses, surface scratches, particles of metal or quartz or abrasive, thin coat of resin or oil, poorly adhesive electrodes or blisters, or flaking of quartz surface or metal electrode.

A surface trapped particle model was decribed [4]. This model satisfactorily depicts various behaviours observed experimentally except the hysteresis phenomenon.

A Physical model was also discussed [5]. In this model, it can be shown that the particle introduces a perturbation term in the denominator of the series–branch admittance that has the form given by an equation. The perturbation term can be expressed as a function of the particle resonant frequency, and the mass ratio of the particle to the mass of the actively vibrating quartz region.

4. CONCLUSION

In this paper, we have reviewed the performances of the best quartz oscillators in the radio frequency domain. We draw attention to the possible effects of surface pollution during the manufacture of quartz oscillators. These processes can cause DLD. In this case, the oscillator may not start properly due to lack of power or its frequency will be different from that expected. Various experiments have demonstrated the cause-effect relationship between surface pollution and DLD. For example, talc blown near an unsealed quartz resonator can induce DLD, and there is a correlation between surface contamination and DLD.

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