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STABILITY OF HIGH QUALITY QUARTZ CRYSTAL OSCILLATORS: AN UPDATE

M.B. BLOCH and J.C. HO, Frequency Electronics, Inc., Long Island, NY 11553

C.S. STONE and A. SYED, Brightline Corporation, Cedar Park, TX 78613

F.L. WALLS, National Institute of Standards and Technology, Boulder, CO 80303

ABSTRACT

Historically, quartz oscillator stability has benefited from ever-better understanding of oscillator circuit noise mechanisms, while quartz resonator design and fabrication have also made important advances, notably as represented in the contemporary, high-quality, low-anomaly, SC-cut, overtone-mode resonator units. Recently, two specially modified low-level, high-quality 5 MHz oscillators were tested for spectral purity and stability at the National Institute of Standards and Technology. Using a third, high-quality, prior-technology oscillator for triangulation the individual phase-noise power spectral density (PSD) of one of the oscillators was determined to be $S_\phi(f)$ = -133 db ±2 dB below 1 rad^2/Hz at a Fourier frequency of 1 Hz, while the second oscillator exhibited -125 dB ±2 dB at 1 Hz. Such oscillators can exhibit parts-in-10^{14} flicker floor stability in high- precision quartz, frequency-source applications. Extensive details of measurement methodology will be given.

PART I-PROGRESS IN QUARTZ OSCILLATOR STABILITY

Twenty-five years ago quartz-crystal-oscillator short-term stability near 4×10^{-12} [1] was exciting performance! In retrospect, however, we know that even the finest crystal frequency standards of that era were designed without regard to two important--but at the time unidentified--noise processes. The first of these came to light with the discovery that significant, direct, intrinsic, phase-noise modulation having a 1/f- or "flicker"-distributed power spectral density (PSD) signature is a universal property of transistors and other active devices---and that something can be done about it [2,3]. With this realization, the stage was set for a new generation of quartz frequency standards: by 1971, short-term stability improved by a hundredfold (in mean square terms) over the earlier figure was reported at that year's Frequency Control Symposium [4] as shown in Figure 1.

The next milestone was set in place when phase-bridge measurements showed that the phase of a carrier passing through a crystal resonator acquires significant random noise-modulation in transit; further, with the benefit of today's perspective we can say that this modulation appears at a level that assures that it will dominate the flicker-floor stability region of well-designed quartz oscillators [5-9]. The PSD signature suggests that it may be ascribed to flicker-noise modulation of the crystal's resonant frequency, which in turn may be modeled as microflicker of either of the crystal's motional reactances. By 1978 the phase bridge method had demonstrated flicker-floor stability

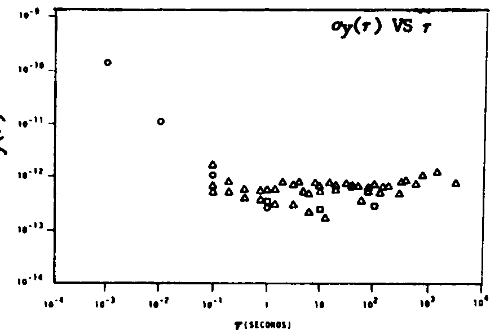

Fig. 1 Fractional frequency stability, $\sigma_y(\tau)$, of high-quality quartz oscillators from Brandenberger et. al. 1971 [4]. The measurement bandwidth was 1 kHz for the squares and circles and about 25 Hz for the triangles. The squares and circles data have some dead time.

slightly below the 10^{-13} level in a commercial 5 MHz resonator. However, achieving the same performance in an active oscillator continued to be elusive [6]. It is easy to believe that this is due, at least in part, to fleeting, transient activity-dips [10-12] that are known to infect virtually [10-12] all earlier designs of AT-crystal resonators. Such resonators include those high-precision overtone types designed for the lower end of the HF spectrum which have long been associated with superior stability, both long-term and short-term. It may be noted that activity-dips, or "band-breaks", are usually believed to be the result of intrinsically noisy partitioning of energy, via nonlinear elastic pumping, between the desired mode and a nearby inadvertent secondary mode of the resonator. This harmonic syntonization often occurs only briefly as a complex accident of temperature, excitation level, tuning, stress, etc. The effects of activity-dips can range from totally disabling the oscillator to having a barely perceptible effect on frequency, crystal resistance, etc. over a few hundredths of a degree span of resonator temperature---except where resonator noise is concerned. Even virtually imperceptible activity-dips may degrade crystal noise by more than 3 dB. Activity-dip noise provides the most likely explanation for the non-stationary quality of Allan variance flicker-floor that is sometimes observed in otherwise well-behaved oscillators.

In this context the prediction of the Stress-Compensated (SC) resonator in the middle seventies and its later debut as a high-stability, high-precision, quantity production component must be considered a pivotal development [13-15]. With the Q of SC-cut resonators generically improved over the Q [13-15] of the workhorse AT-cut devices by approximately 15%, the SC crystal could promise a modest phase-noise superiority of about 2.5 dB. This expected advantage (not at all unique to the SC) as it has turned out has been far overshadowed by other predicted--and realized--qualities of SC-cut behavior: some of these, e.g. insensitivity to thermal shock, often make the SC-cut devices an attractive choice for reasons not immediately related to phase noise. However, it is the relative freedom of the practical SC-cut resonator from activity-dips at high excitation level that differentiates the SC from the AT, BT, and virtually all other quartz resonator types, and raises the hope of realizing the full potential of quartz crystals for uniformly reproducible short-term stability.

Oscillator Improvement Program

As part of a continuing program of improving products through in-house technology insertion, Frequency Electronics, Inc. recently tasked Brightline Corp. to upgrade the high-precision quartz oscillator used as the time base generator subassembly of a disciplined time-frequency standard. This 5 MHz source represented the state-of-the-art at the beginning of its model life, which was well before the advent of SC resonators. Accordingly, the improvements were to include retrofitting the oscillator with a premiere-grade-production, 5-MHz, fifth-overtone, SC resonator plus installation of other modifications required to bring the oscillator system to a fully contemporary configuration.

Phase-Noise Results

While not all contemplated improvements have yet been made, preliminary phase-noise testing of modified high performance oscillator units indicates that a high order of short-term stability has been attained [16]. The best phase-noise results obtained thus far at Brightline are shown in Figure 2. Converting the flicker-frequency component of phase-noise density ($\mathcal{L}(f) \sim [-134 - 30\log(f)]$ dBc) obtained from Figure 2 to the corresponding two-sample, time-domain-stability, yields flicker-floor $\sigma_y(\tau)$ near 6.6×10^{-14}. However, we have also observed that a random-walk component is evident in some (but by no means all) of the phase-noise records extending to f=0.1 Hz and involving several oscillators and crystals. At its typical level ($\mathcal{L}(f)$ approximately $[-140 - 40\log(f)]$ dBc), the random-walk contribution would match the flicker-floor at a sampling time of only 3.6 s, and parts in 10^{14} stability could be expected in direct measurements only for a narrow range of sampling intervals near 1 s, if at all. The origin of this random-walk behavior has not yet been identified; however, we do not believe that it is due to excessive crystal current or any intrinsic property of the crystal. Hopefully, further investigation will lead to extending the flicker-floor dominance, that we now see in the vicinity of 1 Hz, out to the equivalent of multi-day sampling, which recently has been demonstrated by other high-quality oscillators employing AT-crystals [17].

Future Developments

The very short-term time-domain performance can readily be enhanced by using an existing-art, low-noise, crystal postfilter. In this case the wide-band noise would be expected to be reduced by approximately 20 dB. The fractional, time-domain frequency stability under these conditions should be approximately $\sigma_y(\tau) \sim 1.6 \times 1^{-15}\ \tau^{-1}$. If the reduction in random-walk frequency modulation can be achieved and the postfilter added without degrading

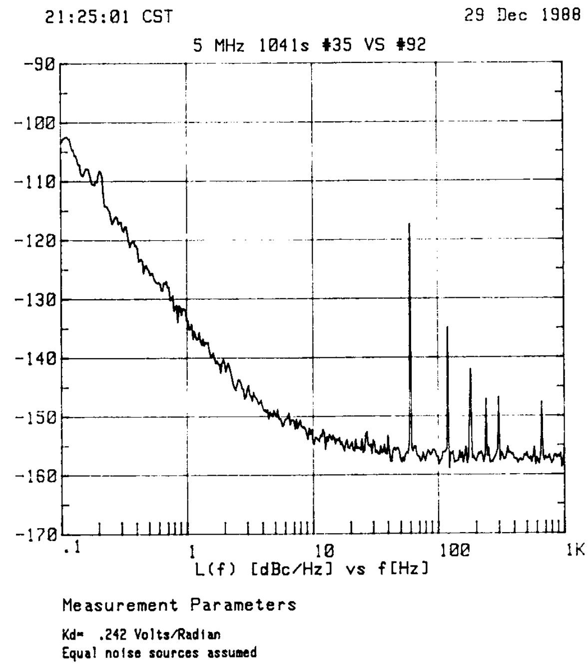

Fig. 2 Phase-noise PSD of improved oscillators [16].

the present flicker performance, parts in 10^{14} stability could be realized from approximately 20 ms to several days. Given the experience of data compiled on a pilot quantity of crystal units showing frequency domain performance that implies flicker-floor performance of parts in 10^{14} in a number of units, we can look forward with cautious optimism to the production of quartz oscillators with stability of a few parts in 10^{14}.

Two selected high-performance oscillators [16] were furnished to NIST to assist in a calibration; Part II of this paper describes experimental results obtained, and the methodology of the NIST measurements.

PART II- DESCRIPTION OF PHASE NOISE MEASUREMENTS

Very precise phase-noise measurements between three different oscillators to obtain unbiased estimates of the phase noise of each oscillator were made at NIST. Relative precision of ± 0.2 dB and accuracies of ± 0.6 dB were necessary to obtain reliable results because one oscillator (92) had substantially better phase noise than the others. The general block diagram of the measurement system is shown in figure 3. First, a precision NIST noise standard was used to check the spectral density function and the internal voltage reference of the FFT [18]. The difference between the voltage PSD measured on the FFT and the value independently determined from first principles with our noise standard was less than 0.01 dB from 20 Hz to 20 kHz (see figure 3).

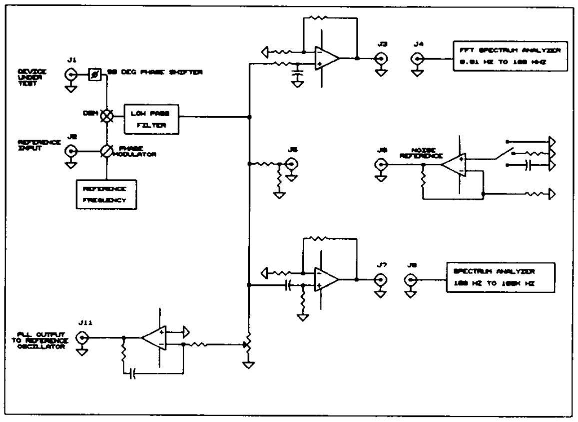

Fig. 3 Block diagram of NIST phase noise measurement system [16].

Second, the sensitivity of the mixer and amplifier for converting small phase deviations from phase quadrature to voltage was determined for each oscillator pair at a beat frequency of about 0.12 Hz. The FFT was used to digitize and analyze the beat waveform. The time base was set to 10 s to accurately determine the beat period and then reduced to 0.2 s to determine the slope through the zero crossing, GK_d, in volts per radian. Both the negative- and positive-going zero crossings were measured. The difference between the two slopes was less than 10%, which indicated that there was no significant injecting locking at this frequency and that the mixer was symmetric, that is, that there were no bad diodes. The accuracy for the determination of the mixer sensitivity and amplifier gain was typically ± 1%, which corresponds to ± 0.1 dB in the measurement of $S_\phi(f)$, the spectral density of phase fluctuations for the pair.

Third, the frequency dependency of both the amplifier following the mixer and the action of the phase lock loop was determined using an ultra-flat phase modulator. This modulator produces phase-modulation side bands on the carrier which are demodulated by the mixer to produce a reference signal which is constant in amplitude to better than 0.2 dB from dc to well beyond 200 kHz as shown in figure 4 [19]. By sweeping the frequency of the

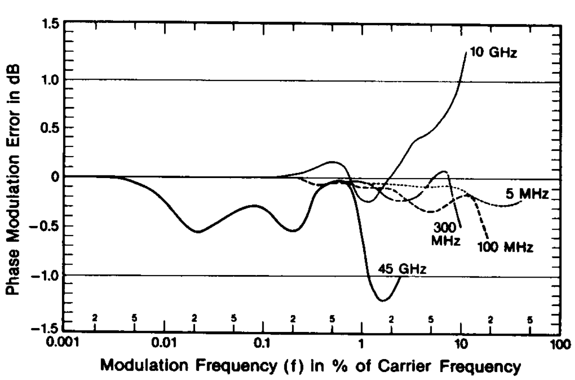

Fig. 4 Error in the phase modulation reference signal as a function of the modulation frequency [16].

modulation over the entire range of measurements, one can correct the measurement system for all baseband frequency dependent effects [19]. The corrections due to the phase lock loop were typically -1.3 dB at 0.2 Hz and -0.24 dB at 1 Hz. Corrections at all higher frequencies in these measurements were small compared to 0.1 dB and neglected.

Fourth, the phase noise was measured with the FFT using the Hanning window. Generally, 1000 samples were taken. The rms (67%) fractional statistical confidence interval of these spectral estimates can be calculated using Table 1 to be approximately 1 ± 0.032 which corresponds to ± 0.14 dB [17].

Table 1. Confidence Intervals for FFT Spectral Estimates

power law noise type	uniform	window Hanning	flattened peak
f^0	$1.02/\sqrt{N}$	$0.98/\sqrt{N}$	$0.98/\sqrt{N}$
f^{-2}	$1.02/\sqrt{N}$	$1.04/\sqrt{N}$	$1.04/\sqrt{N}$
f^{-3}	unusable	$1.04/\sqrt{N}$	$1.04/\sqrt{N}$
f^{-4}	unusable	$1.04/\sqrt{N}$	$1.04/\sqrt{N}$

Table 1. Fractional confidence intervals for several FFT spectral density estimators as a function of noise type and N, the number of independent samples. $S = S_m(1 \pm \frac{V(w,f)}{\sqrt{N}})$ where S is the time spectral density, S_m is the measured spectral density and $\frac{V(w,f)}{\sqrt{N}}$ is the appropriate table entry.

Figure 5 shows $S_\phi(f)$, for oscillator pair 483 and 92 with all corrections applied. Additional measurements against oscillator 8600 are shown in figure 6. These and other measurements were used to obtain the following estimates of $S\phi(f)$ for oscillators 92 and 483:

$$S\phi_{92}(f) = 10^{-13.31}f^{-3} + 10^{-13.6}f^{-1} + 10^{-15.46}$$

$$S_{\phi 483}(f) = 10^{-12.46}f^{-3} + 10^{-13.6}f^{-1} + 10^{-15.46}$$

The coefficients for the power law spectra of $S_\phi(f)$ for oscillator 92 where then used in a new NIST software program SIGINT, which calculates the fractional frequency stability, $\sigma_y(\tau)$ (also Mod $\sigma_y(\tau)$), using the primary definition

$$\sigma_y(\tau) = \left[\int_0^{f_h} 2 \; \frac{f^2}{\nu^2} \; S_\phi(f) \; \frac{\sin^4 \pi f \tau}{(\pi f \tau)^2} \; df \right]^{\frac{1}{2}} .$$

Here, f_h is the noise bandwidth of the $\sigma_y(\tau)$ measurement system, and ν is the carrier frequency, i.e., 5 MHz. The accuracy of the SIGINT software has been extensively checked and the errors are less than 3%. The results for oscillator 92 are shown in figure 7 for measurement bandwidths of 100 Hz and 1 kHz. Also shown is time-domain stability of oscillator 92 derived from direct measurements of $\sigma_y(\tau)$ made between the three oscillators. Unfortunately, the noise floor of our present time-domain measurement system precludes verifying the time domain stability of oscillator 92 at 1 s. By the time the measurement floor is low enough, random-walk has degraded the stability above

1×10^{-13}. Oscillators 92 and 483 were installed in separate closed containers to stabilize the humidity and pressure. The random-walk appeared to decrease by about a factor of 2. Earlier work on oscillator 8600 had also demonstrated significant improvements in the random-walk performance when the humidity was controlled [17]. These results suggest that humidity and possibly temperature play a role in the random walk process.

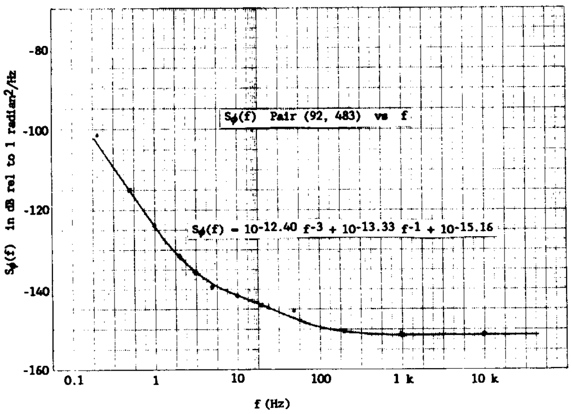

Fig. 5 Spectral density of phase fluctuations, $S_\phi(f)$ of oscillator pair 483-92 as a function of Fourier frequency offset.

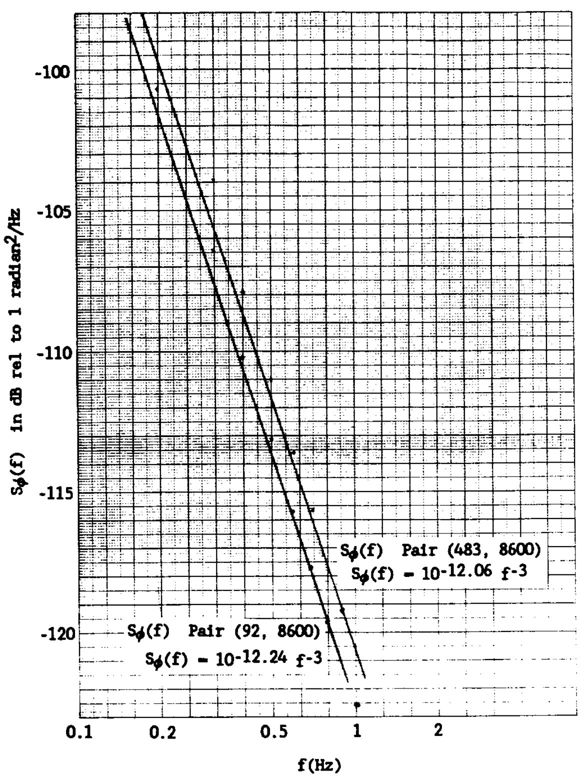

Fig. 6 Spectral density of phase fluctuations, $S_\phi(f)$ of oscillator pairs 483-8100 and 92-8600 as a function of Fourier frequency offset.

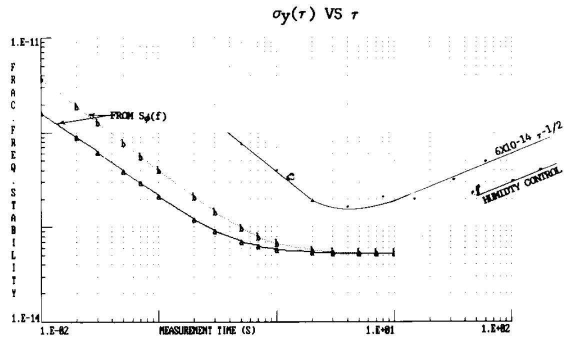

Fig. 7 Fractional time domain frequency stability, $\sigma_y(\tau)$, of oscillator 92 derived from the phase noise, curves a and b. Curve c shows the initial measured time domain stability. Curve d shows the approximate effect of stabilization the ambient pressure and humidity on the logner-term frequency stability.

CONCLUSION

We have described a little of the history of ultra-low flicker phase noise in quartz crystal oscillators. We have also described measurement techniques for measuring the phase noise of oscillators pairs with a relative precision of ± 0.2 dB and accuracy of ± 0.6 dB. These techniques were then applied to the measurement of a set of three oscillators. By unfolding the results of the measurements, we have demonstrated that one of them (oscillator 92) had exceptionally low flicker noise, $S_\phi(1\ \text{Hz}) = 133 \pm 2$ dB. The fractional, time-domain frequency stability, $\sigma_y(\tau)$, calculated from the measured phase noise yields $\sigma_y(1\ \text{s}) = 5.2 \pm 1.3 \times 10^{-14}$. The relatively high level of random-walk frequency modulation (6×10^{-14}) thwarted our attempts to directly confirm this low flicker level.

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