HIGH QUALITY QUARTZ CRYSTAL OSCILLATORS: FREQUENCY DOMAIN AND TIME DOMAIN STABILITY*

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Summary

We measured the frequency stability of a pair of commercial 5-MHz quartz crystal oscillators which incorporate improved electronic design for enhanced short-term stability. The spectral density (frequency domain) of the phase noise, per oscillator, measured by each of our two laboratories, is

$$S_{\delta\phi} = + (10^{-11.8}\ \text{radians}^2\ \text{Hz}^2)\frac{1}{f^3} + (10^{-12.5}\ \text{radians}^2)\frac{1}{f} + (10^{-14.4}\ \text{radians}^2\ \text{Hz}^{-1})\, f^0 ,$$

over the range of about 10^{-3} Hz to 10^{+3} Hz.

Key Words (for information retrieval): Allan variance, Flicker of phase noise, Frequency stability, Oscillator noise models, Phase noise spectral density, Quartz crystal oscillator, Time domain stability.

Discussion

There are several aspects of electronic circuit design which must be carefully considered in order to achieve high short-term frequency stability in quartz crystal oscillators. We report an advance of more than ten decibels in the state-of-the-art for high quality $\approx$ 5 MHz quartz crystal oscillators in the noise frequency range of 1 to 100 Hz. The most important design factors were A) measurement and selection of transistors for the lowest possible flicker of phase noise[1] (oscillating loop and buffer stages), B) measurement and selection of transistors and diodes for the lowest possible DC flicker noise (voltage regulators, automatic gain control), C) massive negative feedback (DC and RF) in the RF circuitry to stabilize the RF gain and to reduce the flicker of phase noise of the transistors[1] (automatic gain control [AGC] amplifier, buffer amplifiers, oscillating loop amplifier). Because more negative feedback is used in the AGC amplifier and in the buffer amplifiers than can be used in the oscillating loop amplifier, the resultant flicker of phase noise performance of the oscillator is determined by the flicker of phase noise of the transistor in the oscillating loop.

Two commercial quartz crystal oscillators incorporating these design factors were measured in Neuchâtel, Switzerland and then shipped to Boulder, Colorado for further measurement. The spectral density (frequency domain) of the phase noise,[2,3] per oscillator, measured by each of our two laboratories, is

$$S_{\delta\phi} = + (10^{-11.8}\ \text{radians}^2\ \text{Hz}^2)\frac{1}{f^3} + (10^{-12.5}\ \text{radians}^2)\frac{1}{f} + (10^{-14.4}\ \text{radians}^2\ \text{Hz}^{-1})\, f^0, \qquad (1)$$

over the range of about 10^{-3} Hz to 10^{+3} Hz. See Figure 1. From Figure 1 we see that there is gratifying agreement between our two laboratories in the measurements of the noise spectral density. The reproducibility of our frequency domain measurements is equal to or better than ± 2 dB. Measurements made in the time domain (Allan variance[2,4]) gave results which were compatible with our frequency domain measurements. See Figure 2. This oscillator performance is obtained without the use of narrowband filters.

Each of our measurement systems (see Figs. 3, 4, 5, and 6) was based on the use of low noise double-balanced broadband mixers using Schottky-barrier diodes.[5,6] For most of the measurements, the oscillators are at zero-beat and in phase quadrature; the output of the mixer is amplified in a low-noise DC amplifier and sampled both in the frequency domain and in the time domain. The noise of our measurement systems can be measured easily; in each it is adequately lower than the noise of the oscillators.

The measured oscillator stability in the range 1 to 100 Hz is about 12 dB better than the prior state-of-the-art for oscillators of any type. The stability (time domain) in the 10 to 100 second range is not better than the performance of high quality quartz crystal oscillators which have been commercially available for the past eight years.[7,8] However, with a higher Q_ℓ for the quartz crystal resonance, improved stability in the 10 to 100 second range may be expected.

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To our knowledge, this has been the first successful application of low flicker of phase noise electronics to high quality quartz crystal oscillators. For examples of other devices, see references 1, 8, 9, and 10. Further improvement of the oscillator stability may be possible by further reduction of the multiplicative flicker of phase noise of the electronics. The present Q_ℓ is estimated to be about 1×10^6 on the basis of the noise measurements and is independently confirmed by an analysis of the circuit. A value of 3×10^6 is possible with 5 MHz crystals; this alone may allow a factor of three improvement in the 10 to 100 second stability, and may accrue in addition to the improvements in the electronics noise.

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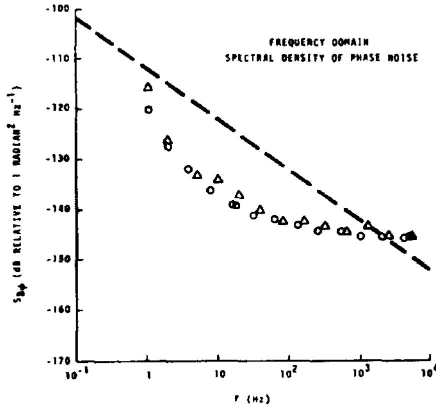

Figure 1 Spectral density of the phase noise of the improved commercial quartz crystal oscillator. The circles represent measurements made at Neuchâtel, Switzerland. The triangles represent measurements made at Boulder, Colorado. The measurements were made using 1 Hz bandwidth. The dashed line, in the region of 1 to 100 hertz, represents the prior state-of-the-art for quartz crystal oscillators.

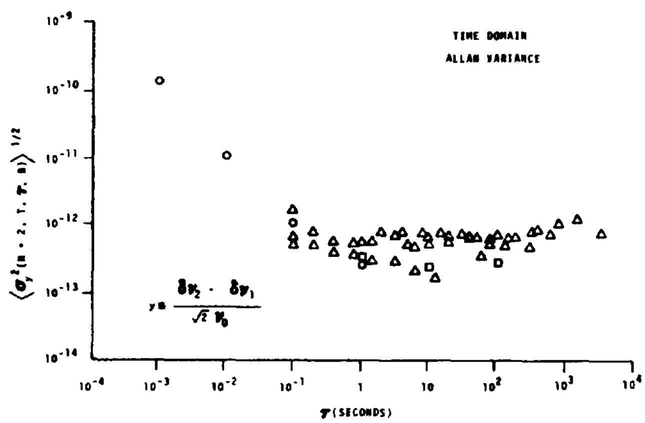

Figure 2 The square root of the Allan variance of the fractional frequency noise y is plotted against averaging time τ for the improved quartz crystal oscillator. The circles (zero-beat method) and the squares (non-zero-beat method) represent measurements made at Neuchâtel, Switzerland. The triangles represent zero-beat method measurements made at Boulder, Colorado. For all points, N = 2. For the circles, B $\approx$ 1000 Hz and the dead time is about 0.1 second except at τ = 1 second where the dead time is 1 second. For the squares, B $\approx$ 1000 Hz and the dead time is 1 second. For the triangles, B $\approx$ 25 Hz and the dead time is negligible.

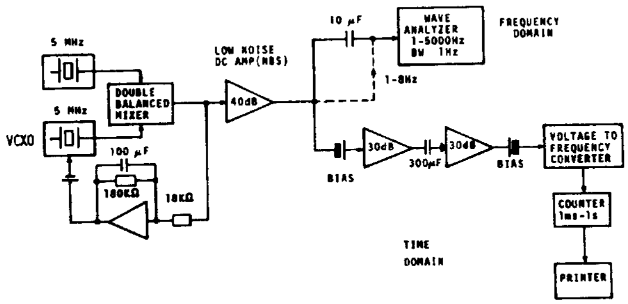

Figure 3 This setup was used at Ebauches for time domain measurements between 1 ms and 1 s (see Fig. 2). The voltage-controlled crystal oscillator (VCXO) is very loosely servoed (DC amplifier gain is about 10, servo loop time constant is about 18 s). The first amplifier following the mixer is a special design for low DC flicker noise. The voltage-to-frequency converter has a full-scale output pulse rate of 100 kHz.

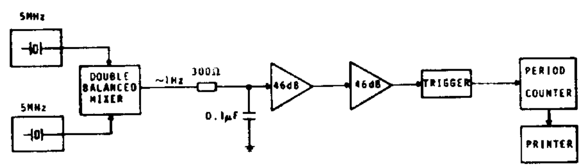

Figure 4 This setup was used at Ebauches for time domain measurements for sampling times τ of one second and greater (shown in Fig. 2). The trigger module is a Schmitt circuit of special design for low DC flicker noise.

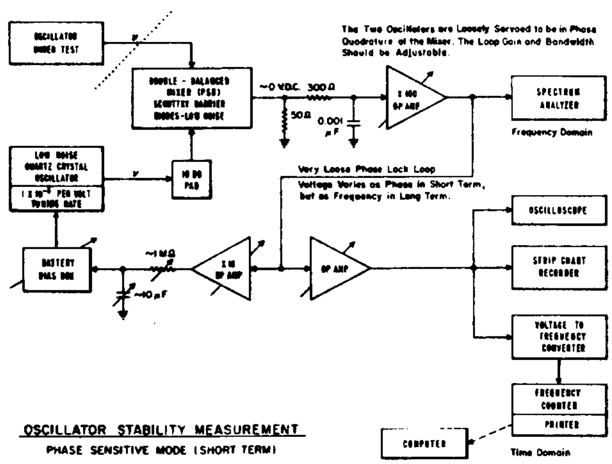

Figure 5 The frequency domain measurements by NBS (shown in Fig. 1) used this general method. The spectrum analyzer tunes from 1 to 5000 Hz and has measurement bandwidths of 1, 10, and 100 Hz. The first amplifier following the mixer is a special design for low DC flicker noise.

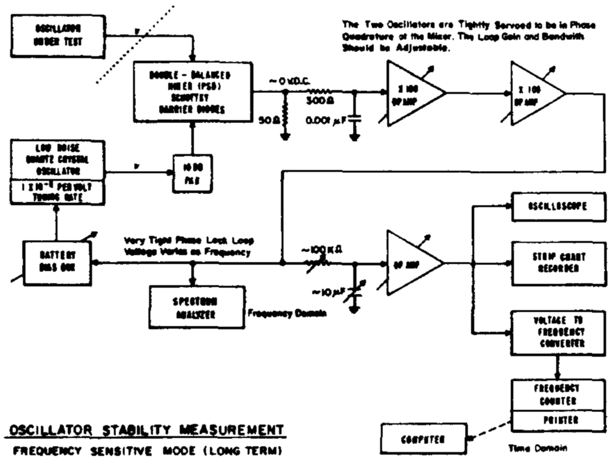

Figure 6 The time domain measurements by NBS (shown in Fig. 2) used this general method. The voltage-to-frequency converter has a full-scale output pulse rate of 100 kHz. The first amplifier following the mixer is a special design for low DC flicker noise.