A SYSTEMS APPROACH TO HIGH PERFORMANCE OSCILLATORS

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Abstract

The purpose of this paper is to show how systems composed of multiple oscillators and resonators can achieve superior performance compared to a single oscillator. Experimental results are presented for two systems based on quartz crystals which provide state-of-the-art stability over a much wider range of averaging times than has been previously achieved. One system has achieved a factor of five improvement in noise floor compared to all previously reported results.

Introduction

The purpose of this paper is to point out the important role that a systems approach can play in making significant improvements in high stability oscillators. The role of simple oscillators is not thereby reduced, but it will be seen that in a system it is possible to isolate problems and solve them in an individual, nearly non-interactive way. A better understanding of the problems and limitations of oscillators can also be gained which may suggest novel solutions. Application of this concept has already led to an improvement of more than a factor of 5 in the long term stability of quartz crystal oscillators.

The designer of a high-performance oscillator frequently faces a choice between short-term and long-term stability; to optimize one, he must sacrifice the other. But there are situations in which both short-term and long-term stability are required of one signal. A solution to this problem is to design two separate oscillators, one optimized for short-term stability and the other optimized for long-term stability, and to combine them into a system which permits the strength of each oscillator to compensate for the weakness of the other. This is but one example of a generally useful systems approach to the design of high-performance instruments.

The systems approach is also valid when one of the devices is a passive resonator. For many years, quartz crystal oscillators have been used in atomic frequency standards in such a way that the short-term stability of the crystal oscillator complements the long-term stability of the atomic resonance. In many of these devices the resonance is passive. In this paper, we present a similar system in which the long-term stability of a passive quartz crystal resonator complements the short-term stability of a crystal oscillator. We will also show how similar systems can be used to improve the radiation hardness and acceleration insensitivity of high stability oscillators. The systems approach is also valid in many other situations whose details are beyond the scope of this paper. For example, high-order frequency multiplication produces a signal which has excessive noise sidebands. But an oscillator which is free from such noise can be locked to the multiplied signal in such a way that the long-term frequency stability of the multiplied signal is combined with the clean spectrum of the oscillator. Another example is a communications receiver in which the tunability of an LC oscillator is combined with the superior long-term stability of a quartz crystal oscillator.

Systems Approach To Long Term Stability In Quartz Crystal Oscillators

The goal of improved quartz crystal oscillator stability still remains both extremely important and relevant. Atomic frequency standards are already well into development which have much improved long term stability but which require better flywheel oscillators in order to reach their noise floor in a reasonably short integration time. Small, inexpensive, low power devices are needed for this application and a quartz crystal oscillator system will maintain all of these properties virtually unchanged from currently available quartz oscillators while providing the needed improvement in stability. The new data which we will present suggests that quartz crystal oscillator systems may directly replace some atomic standards in applications requiring stability as good as 10^{-14} and drift as low as 10^{-12}/week. If expected improvements in acceleration sensitivity are made, quartz oscillator systems would be ideal for portable clock applications. Measurements of the inherent frequency stability of AT cut quartz crystal resonators have been made using pairs of nearly identical resonators in a passive phase bridge.[1] These measurements indicate that the frequency

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stability realized in traditional oscillator designs from ~10^{-4}s to 10 s was far worse than the inherent resonator stability and provided the motivation to understand the mechanisms by which the electronics limits the frequency stability in traditional quartz crystal oscillator designs.

Major problem areas have been identified which appear to limit the performance of simple oscillators. The first, which is principally a property of the electronics, is phase stability around the oscillating loop. A phase fluctuation, $\Delta\phi$, produces a change in frequency given by $\Delta\nu/\nu = \Delta\phi/2Q$, where Q is the quality factor of the crystal. The phase can vary for a number of reasons: as the result of transmission line length changes, or reactance fluctuations, or because of stray signals injected into the oscillator among others. In order to achieve a frequency stability $\Delta\nu/\nu = 10^{-13}$ for a Q of 2.5×10^{6} and a motional resistance of 70Ω, it is necessary to limit $\Delta\phi$ to 5×10^{-7} rad which corresponds to a $1^{0}C$ temperature change of a 5cm length of RG58 coaxial cable, a change of 6×10^{-7} pF in a 25 pF tuning capacitor, or a change in the power reflected into the oscillating loop at the level of -126 dB.

The second problem area is the amplitude to frequency effect in the quartz crystal. In one very high quality 5 MHz 5th overtone AT cut resonator the frequency varied 1×10^{-9} per μW power dissipated in the resonator. For such a crystal it would be necessary to control the power level to better than 10^{-4} μW to obtain a frequency stability of 10^{-13} at 1 μW operating power level.

The third problem area is temperature control. Although the temperature coefficient of an AT cut crystal vanishes at the normal operating point, there is a residual thermal shock effect, due to stress applied to the crystal, with a magnitude $\Delta\nu/\nu = 10^{-9}$ for a 20 mK/s thermal transient. For such a crystal, the temperature fluctuations must be kept below 2 μK/s to reach a stability of 10^{-13}.

The original frequency stability measurements on AT cut resonators[1] were made in such a way that the effect of amplitude fluctuations and thermal shock cancelled out to a high degree. The frequency stability realized was considerably better than that obtained in any available oscillator. This indicated that one or both of these effects were major contributors to frequency fluctuations in AT cut resonators[2] therefore the crystal chosen to test the systems approach shown in Fig. 1. was a 3rd overtone, 5 MHz, SC cut resonator of the BVA_2 design.[3,4] The amplitude to frequency effect and the thermal shock sensitivity are both very much smaller than those observed in conventional AT cut resonators. The BVA_2 resonator design also features electrodes separated from the crystal surface by about 20 μm and resonator mounting via accurately positioned quartz bridges, both of which

help reduce the stress applied to the crystal plate and thus the stress induced frequency fluctuations.

An intermediate frequency discriminator servo system was chosen as the vehicle for obtaining long term stability in order to separate as much as possible circuit problems from crystal problems and to alleviate the known circuit problems. As illustrated in Fig. 1, the concept (described in detail in reference 5) is similar to passive atomic frequency standards and the superconducting cavity stabilized oscillator[5]: A portion of the signal from the voltage controlled oscillator (vco) is phase modulated external to the oscillator and then used to probe the frequency of the passive resonator. If the carrier is not exactly at the center of the resonance, the signal reflected from the crystal will be amplitude modulated and the phase of the am depends on the separation of the carrier from line center. Phase sensitive detection of the modulation envelope results in a discriminator signal which is used to servo the VCO to the center of the crystal resonance.

This particular discriminator significantly reduces the effect of phase changes on the output frequency. Since the frequency of the passive crystal is determined by its differential effect on the carrier and sidebands of the phase modulated signal, line length changes cause systematic offsets only as a result of dispersion. The previously discussed phase stability requirement is reduced in severity by the ratio of the modulation frequency to the carrier frequency. However, the most critical circuit element in this system is the phase modulator since any spurious am produced by this device causes a systematic frequency offset. It is possible to maintain the am sidebands 120 dB below the carrier when the pm sidebands are 6 dB below the carrier, resulting in a total offset from the center of the resonance of $10^{-6}\nu_0/Q$ due to this source.

The use of a directional coupler to detect the signal reflected from the passive crystal results in the second major advantage of this discriminator technique. The modulation frequency can be chosen to be much larger than the half bandwidth of the passive resonator thereby permitting the unity gain frequency of the servo system to be arbitrarily large with no loss in signal-to-noise ratio. Operational amplifier lag filters can be used to obtain a critically damped 2nd order loop response whose gain increases 40 dB per decade for frequencies well below the unity gain frequency and is limited only by the open loop gain of the amplifiers.

The results obtained for the systems of Fig. 1 using a BVA_2 type SC cut crystal are shown in curve a of Fig. 2. The dots represent the best estimate of the system frequency stability and the error bars are our best estimate of the 1 σ uncertainty from measurements against 5 other precision oscillators. Note that the system frequency stability reaches 1×10^{-13} at about 16 s and 6×10^{-14} at 128 s. This is the best frequency

stability ever documented for a quartz crystal oscillator and exceeds the frequency stability of all available - even atomic - commercial oscillators at 100 s.

Systems Approach to High Spectral Purity And Environmental Insensitivity

Either short-term stability (spectral purity) or environmental insensitivity can be obtained by locking a spectrally pure oscillator or an oscillator having the appropriate environmental insensitivity to a reference having the necessary long term frequency stability.

The spectral density of phase fluctuations of the system output is given by[6]

$$S_\phi(f,system) = S_\phi(f,reference) \left|\frac{G(f)}{1+G(f)}\right|^2 + S_\phi(f,VCO) \frac{1}{\left|1+G(f)\right|^2}$$

Typically the VCO is high pass filtered while the reference is low pass filtered.

For example, curves a and b of Fig. 3. show the phase stability of a VCO having very good spectral purity, and a ref oscillator having good long-term frequency stability, while curves c and d show the combined system performance for different loop attack times. Fig. 4. shows the block diagram of the dual oscillator system used to obtain curve d. The second order loop filter assures that the phase offset between the two oscillators approaches a very small value in long term.[7]

The time domain frequency stability $\sigma_y(\tau)$ of this system can be uniquely calculated from the data of Fig. 3. using:[8]

$$\sigma_y^2(\tau) = \frac{2}{(\pi\nu\tau)^2} \int_0^{f_h} S_\phi(f) \sin^4(\pi f\tau)\, df$$

where f_h is the high frequencycutoff i.e. the bandwidth of the measurement system.

The results calculated for measurement times up to 1 s are shown in Fig. 5. The frequency stability achieved by this system assembled from commercially available components is unexcelled by any currently available commercial frequency standard for any measurement time up to 100 s.

In a completely analogous way an oscillator exhibiting low vibration or radiation sensitivity can be phase locked to the long term stable oscillator in order to yield improved system performance. It should also be pointed out that the loop attack time is a free parameter which can be changed in order to optimize overall system perfomance. For example, under conditions of severe shock and vibration the output of the short-term stable oscillator may be the best signal available, therefore a "smart servo" would hold the VCO tuning input at its last value until the disturbance ceased.

Conclusion

In the above discussion we have illustrated several areas where a systems approach, with its increased degrees of freedom, can provide greatly improved frequency stability performance relative to a single oscillator. Specifically it was shown that the circuit problem areas which contribute to long-term frequency fluctuations in quartz controlled oscillators can be largely circumvented by a systems approach. Experimental data on a new oscillator system using a 3rd overtone 5 MHz SC cut resonator of the BVA_2 design yielded a frequency stability of $\sigma_y(16s) = 1 \times 10^{-13}$ and $\sigma_y(128s) = 6 \times 10^{-14}$ in a 1 KHz noise bandwidth This is the best medium-term stability ever measured for a quartz crystal controlled oscillator.

In addition it was experimentally shown that, using a systems approach, one could phase lock two commercially available quartz crystal oscillators and obtain state-of-the-art spectral purity and time domain frequency stability up to sample times of 100 s in a single output signal. The possibility of extending the above concepts to other areas, for example, radiation and vibration desensitization was also indicated.

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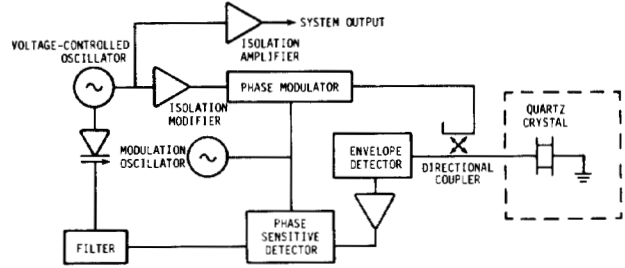
Figure 1 Block diagram of the passive dual crystal system, in which a VCO having good short-term stability is locked to a crystal resonator frequency discriminator
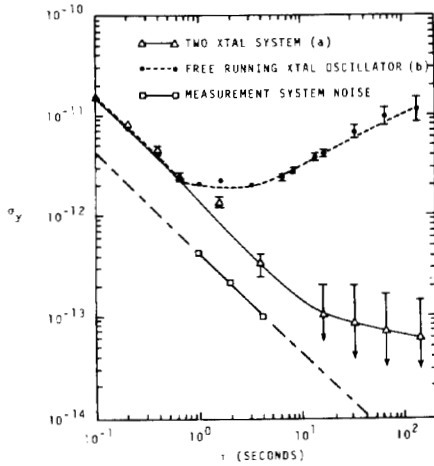

Figure 2 Fractional frequency stability $\sigma_y(\tau)$ of the dual crystal system of Fig. 1 (curve a) and free running stability of VCO (curve b). The stability values and uncertainties for curve a were obtained from combined measurements against 5 other oscillators.
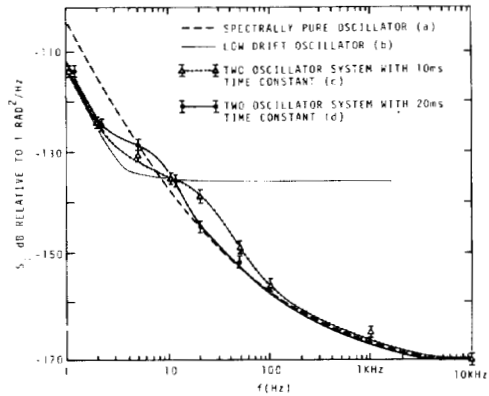

Figure 3 Spectral density of phase for a) 5 MHz VCO having excellent spectral purity b) 5MHz VCO having good long term stability c) system performance for an attack time of 10 ms and d) system performance for an attack time of 20 ms.
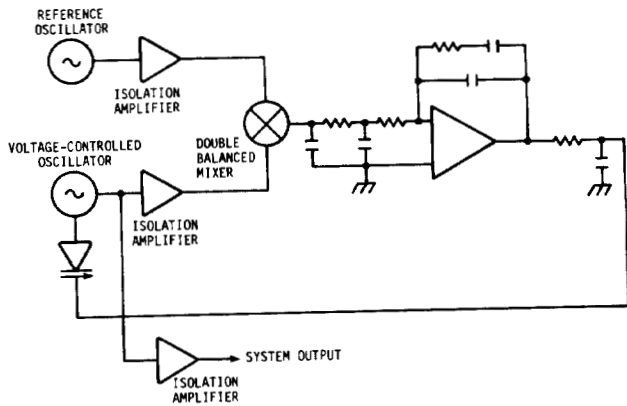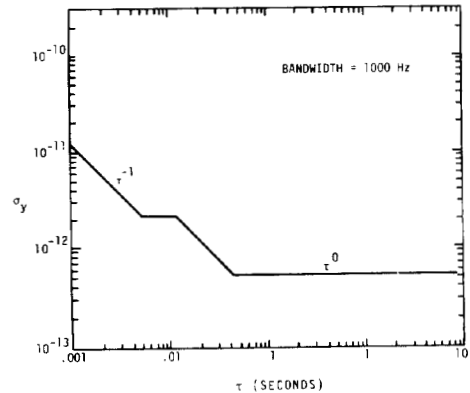

Figure 4 Block diagram of the dual oscillator phase lock system showing the second order loop filter used to obtain curve d of Fig. 3

Time domain stability of the dual oscillator system calculated from the data of curved, Fig. 4