Acceleration "G" Compensated Quartz Crystal Oscillators

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Abstract **- High dynamic environments common to most platforms in motion such as helicopters, track-vehicles, ships, missiles and even spacecraft degrade the performance of quartz crystal oscillators. To generate the precise frequencies and time signals crucial to system performance quartz crystal oscillators and rubidium vapor atomic oscillators are commonly utilized. However quartz crystal oscillators whether stand alone or parts of traditional rubidium oscillators, exhibit degraded performance when subject to accelerating forces, i.e. sine and/or random vibrations. Although the spacecraft environment has traditionally been considered "vibration-free," it is increasingly clear that low level accelerations and vibrations due to reaction wheels, thrusters, etc. degrade quartz oscillator output enough to impact, in many cases, system level performance. In addition, mechanical vibrations in ground stations/gateways degrade quartz oscillator performance and greatly affect beam-forming networks for communications satellites.**

In this paper we shall discuss a "g" (acceleration) compensated technology that has greatly increased the performance of quartz crystal oscillators in challenging environments. We will present data on technology break-through in two main areas (a) new methods of quartz resonator design and manufacturing that result in minimum cross-coupling between the three resonator axes and (b) new sensing devices that can be mounted and aligned in each resonator axis. In addition, we will present actual test data for oscillators performing in high "g" environments as well as lower "g" environments such as in spacecraft and ground stations/gateways.

I. Introduction

There has been a long-recognized need for "g"- compensating technologies that significantly reduce the wide range of environmental dynamic effects on quartz crystal oscillators, and that can be manufactured in large quantities and at reasonable costs. Frequency Electronics, Inc. (FEI) fulfills this need, and below we shall discuss a "g" (acceleration) compensated technology that has greatly increased the performance of quartz crystal oscillators in challenging environments.

II. Effects of Vibration

Stress compensated (SC) cut quartz crystals have been extensively used as the resonating element in oscillator circuits as a reliable element to generate accurate frequencies. Under static conditions, *i.e.*, an acceleration-free (vibration-free) environment, a well-designed ovenized SC-cut quartz crystal oscillator will produce an output signal at a particular carrier frequency with relatively low sideband frequencies with respect to the carrier frequency. However, when the same oscillator is subjected to vibration, undesirable spurious sidebands occur in the output signal and phase noise degrades. Both phenomena are demonstrated in Figure 1 and Figure 2 respectively.

In Figure 1 the frequency generating system consists of a 10 MHz oscillator multiplied up to 200 MHz. The oscillator is manufactured with a 10 MHz, 3rd overtone, SC-cut crystal resonator. The system is hard mounted and subjected to a 20 Hz sinusoidal vibration with an amplitude of 4.5g, hence the unwanted sidebands caused by the 10 MHz oscillator appear at 20 Hz intervals—the sinusoidal frequency. These sidebands are, in essence, spurious signals that will degrade the performance of higher frequency sources that are directly or indirectly synthesized from the oscillator. In Figure 2 the same 10 MHz oscillator is subjected to a random vibration applied from 10 Hz to approximately 200 Hz with a power spectral density (PSD) of ~0.08 g^2/Hz (4 g RMS integrated vibration input). As illustrated by the upper plot in Figure 2 the resulting phase noise is significantly degraded with respect to the lower plot—the oscillator's intrinsic phase noise when at-rest. The magnitude of phase noise degradation between the at-rest and in-vibration conditions is almost 40 dB on the oscillator 10 MHz output. However, in a system in which the oscillator's output is multiplied to higher frequencies the impact is much worse. The system phase noise in this case is worse by 20 x log (n) where n is the multiplying factor. This results in noise degradation of approximately 6 dB across the board for frequency doubling, 10 dB for frequency tripling and 20 dB for decade multiplication. Microwave systems are particularly susceptible to reference oscillator phase noise because the process of frequency multiplication increases the power in the sidebands by the square of the multiplication factor. Hence, the precision oscillator is often the frequency source that ultimately defines the system performance specifications. Whenever motion and vibration are encountered, the oscillator's spurious

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sidebands, as well as unwanted signal noise, will translate into overall system errors. The g-compensated quartz oscillator technology presented below makes significant in-roads toward defeating dynamic degradations.

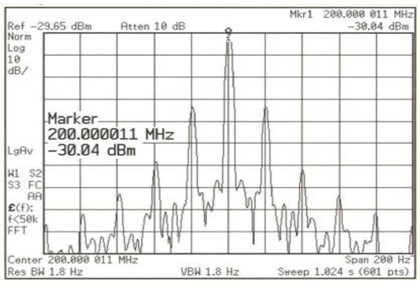


Figure 1. Oscillator produced side-bands when subject to 4.5g, 20 Hz sinusoidal vibration

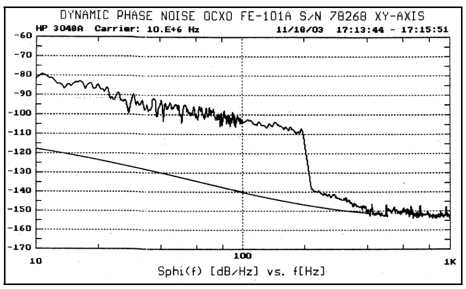


Figure 2. Oscillator phase noise degradation when subject to 4g RMS random vibration from 10 Hz to approximately 200 Hz

III. FEI G-COMPENSATION TECHNOLOGY

The FEI electronic g-compensation technology has already been deployed in a host of systems, providing performance improvements for critical military platforms in high dynamic environments. The technology is based on a break-through in two main areas:

a) New methods of stress-compensated quartz resonator design and manufacturing, which provides for minimum cross-coupling between the 3 axes. Referring to Figure 3, the objective is to achieve a crystal resonator that when subject to a g-force will transfer minimal force between axes. In other words, each axis is made as independent as possible of the others. Reducing cross-coupling is essential to achieve optimum g-compensation. Also note in Figure 3 that each specially produced quartz resonator with low cross-coupling and low g-sensitivity will have a resultant 3-axes response, defined as Gamma (Γ), which is minimized for each application.

b) New sensing devices that can more easily be matched and mounted to each resonator axis. As linear and oscillatory accelerations are applied the low cross-coupled resonator responds and so do the sensing devices. The compensation electronics adjusts amplitudes and phase relationships of the signals resulting in cancellation effects, which electronically compensate the oscillator's g-sensitivity and achieves tremendous improvements in side-band response and phase noise.

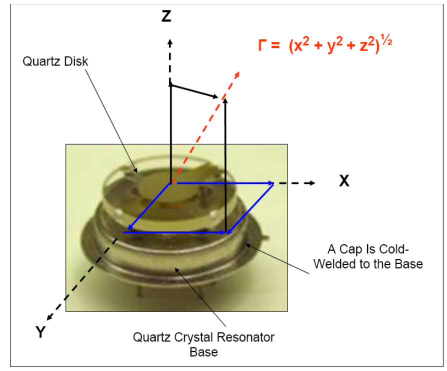


Figure 3. G-forces on a crystal resonator

Compensated quartz crystal oscillators find applications either as stand-alone, as part of a more complex master clock module, and as integrated frequency generating systems. Figures 4 to 6 demonstrate examples of stand-alone g-compensated oscillators, Figures 7 and 8 show examples of integrated clock modules where low g-sensitivity quartz oscillators are phase-locked with a rubidium atomic standard. For example in Figure 7, the GPS receiver provides the time and frequency synchronization for the rubidium oscillator that provides the hold-over performance. The Rb oscillator in turn disciplines a hard-mounted electronically g-compensated quartz crystal oscillator providing the system with excellent phase noise performance while operating in a severe vibration environment.

The phase noise performance of a 10 MHz ovenized oscillator that embodies the technology described above is shown in Figure 9. The utilized oscillator is depicted on left side of Figure 4. It is hard mounted, electronically g-compensated, designed with a 3rd overtone SC-cut crystal. The unit was subject to a typical aircraft random vibration environment of ~$0.08g^2$/Hz, 4g RMS, from 10 Hz to 200 Hz. The upper plot in Figure 9 indicates actual phase noise distortion during vibration when the oscillator is not electronically compensated. The lower curve illustrates the significant improvement in phase noise when electronic g-compensation is applied. The improvement varies from approximately 45 dB at 10 Hz to 20 dB at 200 Hz. The electronic g-compensation has, in essence, converted a quartz crystal resonator with a measured g sensitivity of 1E-9/g to one that exhibits an "effective" g-sensitivity of 6.3E-12/g (at 10 Hz), and 4.0E-11/g (at 200 Hz), as illustrated in the lower section of Figure 9. A more in-depth discussion on the "conversion" of g-sensitivity is presented in Section IV, where performance of oscillators in Military Track Vehicles is presented.

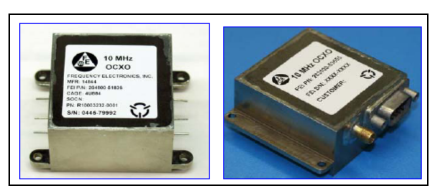


Figure 4. Hard mounted stand-alone g-compensated oscillators (Size L x W x H inches 2 x 2 x 1)

Figure 5. Hard mounted stand-alone g-compensated multiple-output frequency generator unit (Size L x W x H inches 3.7 x 2.5 x 1)

Figure 6. “Soft” mounted stand-alone g-compensate oscillator (Size L x W x H inches 4 x 1.6 x 0.8)

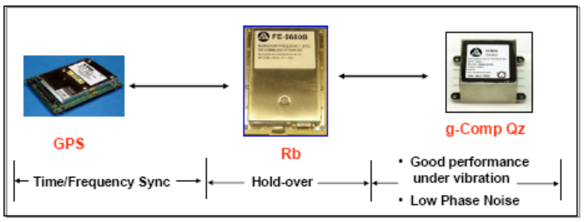
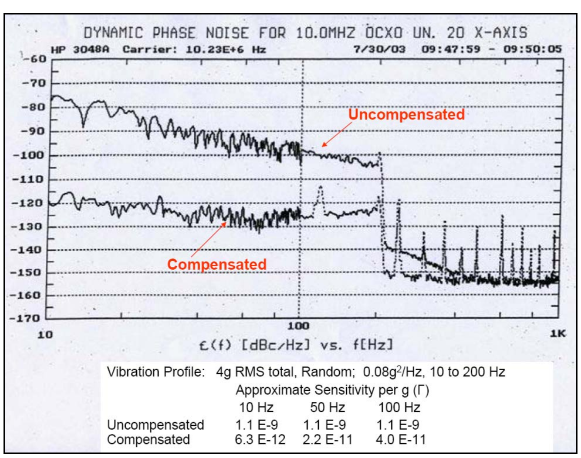


Figure 7. G-Compensated quartz oscillator integrated with GPS and rubidium atomic standard

Figure 8. G-Compensated quartz oscillator integrated with rubidium atomic standard



	10 Hz	50 Hz	100 Hz
Uncompensated	1.1 E-9	1.1 E-9	1.1 E-9
Compensated	6.3 E-12	2.2 E-11	4.0 E-11

Figure 9. Dynamic phase noise of a 10 MHz hard mounted oscillator

IV. Applications and Performance for Various Platforms

A. Unmanned Air Vehicles (UAV) Helicopters and Fixed Wing Aircraft:

The vibration environment that exists on UAV, on helicopters, and on jet fighters is very severe. Large engines, propellers and piston/turbine drivers cause vibration levels in the frequency range of a few Hertz from the carrier to 2000+ Hz. Mechanical isolating systems are utilized to mitigate the vibration effects of onboard weighty and bulky electronic systems, but mechanical vibration isolation systems are typically only effective for the high frequency vibrations--approximately 100 Hz and above. These platforms often carry sophisticated radar, weapon guidance systems, and other sensors that rely on the performance of the internal oscillator. Since quartz oscillators are used as sources for the generation of very stable low noise frequency signals, the oscillator phase noise degradation during vibration needs to be minimized. It is important to note that radar reflected signals arrive within microseconds of the transmitted wave; hence the performance of the oscillator phase stability over these short periods is extremely critical.

Figures 10, 11 and 12 below show the phase noise performance per vibration axis of an integrated rubidium oscillator and quartz oscillator, 10 MHz, frequency generation system that employs an optimized combination of electronic g-compensation and mechanical vibration isolators. The mechanical vibration isolators utilize resilient rubber mounts or steel springs that provide low pass filtering of vibration inputs. Mechanical resonances as low as 6 Hz are achievable with roll-off of 9 to 15 dB/octave. The housing is approximately 5 x 4 x 3 inches. In this application, the operating environment includes random vibration from 1 Hz to 2000 Hz, with an integrated PSD of approximately 4.5g RMS. In this precision frequency generating system the rubidium oscillator provides the long term stability and the quartz oscillator, consisting of a 10 MHz, 3rd overtone, SC-Cut crystal, provides for the excellent phase noise performance. The “effective” resulting g-sensitivity of the system is reduced from approximately 1E-9/g to better than 1E-10/g on all axes.

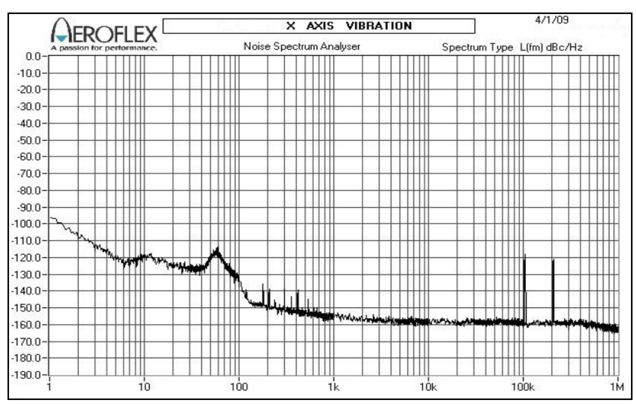


Figure 10. Dynamic X-axis phase noise performance

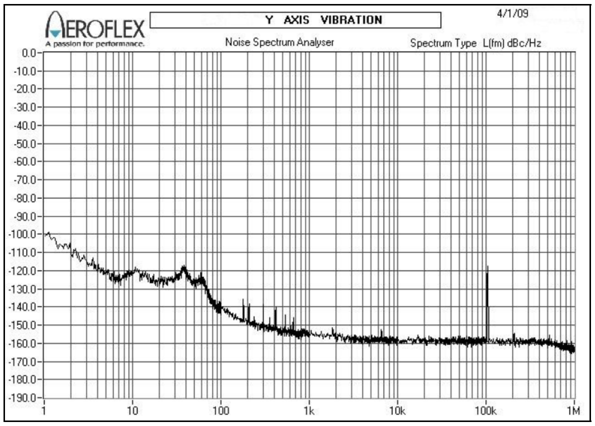


Figure 11. Dynamic Y-axis phase noise performance

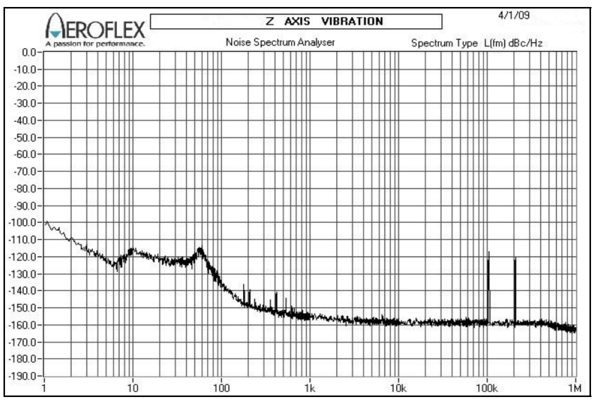


Figure 12. Dynamic Z-axis phase noise performance

The phase noise performance of the precision frequency generating system described is crucial for optimum operation of other on-board systems (radar, communications, targeting, emitter detection and others) that multiply the 10 MHz reference frequency to much higher frequency bands. As discussed in section II above, the degradation in phase noise when multiplied up in frequency is 20 x log10(n), where n is the multiplying factor. Therefore, achieving the best phase noise possible in challenging environments is paramount. Hundreds of units with the same performance have been successfully tested at the FEI facility.

These precision frequency generating systems are designed to survive thousands of hours of operation in a constant vibrating environment. Consequently, the following critical parameters must always be applied in order to achieve a robust design:

- The rubidium atomic standard must not loose lock under any environmental conditions
- A phase lock loop with appropriate time constant must be incorporated in order to benefit from the long term stability of the Rubidium, but without deteriorating the short term stability and spectral purity of the quartz crystal oscillator
- All components must operate under all specified environmental conditions
- All cables must be staked to prevent unwanted resonances
- The mechanical package must be designed in a manner that will eliminate or reduce resonances within the operating band
- Other parameters that need to be considered are discussed in the literature [1]
- Must be producible and affordable

B. *Military Track Vehicles*

Tanks, High Mobility Multipurpose Wheeled Vehicle (Humvee) and other armored carriers, typically employ multi-frequency communications devices that must operate in all types of terrains. The vibration environment is often more severe than in the airborne platforms. The communication devices typically consist of highly sophisticated software-defined radios that must be capable, while on-the-move, of receiving and transmitting numerous forms of protocols or waveforms by employing diverse software communications architectures. The radio communication systems use internal oscillators (quartz based or a combination of rubidium and quartz oscillators) to generate a precise and stable frequency. The radio's performance is very much dependent on the performance of the oscillator during all operating environmental conditions. Any oscillator noise limits the channel capacity of the communication system. For example, the presence of spurious signals compete with the desired signal and often mask weak signals from being received rendering the data link useless. The vibration environment is very dependent on the platform's dynamics; however, oscillators typically operate in a random vibration environment with integrated PSD of 1g RMS to as high as 30+g RMS. The communication system is typically mechanically isolated on the platform but as explained above mechanical systems are only effective for the high frequency vibrations. Hard mounted electronically g-compensated oscillators or an optimized combination of electronic g-compensation and mechanical vibration isolators is utilized.

An example of the phase noise response of a dynamically g-compensated quartz crystal oscillator designed for track vehicle communication systems is shown in Figure 13. The applied vibration profile consisting of ~22g RMS is shown in Figure 14.

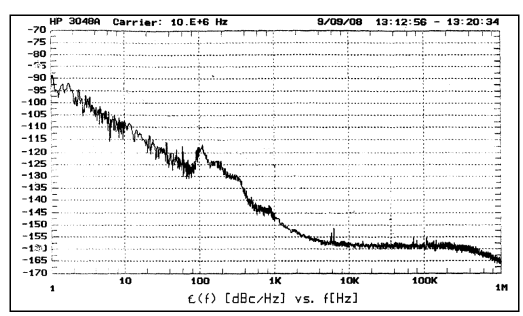


Figure 13. Dynamic phase noise performance g-compensated 10 MHz oscillator in track vehicle applications

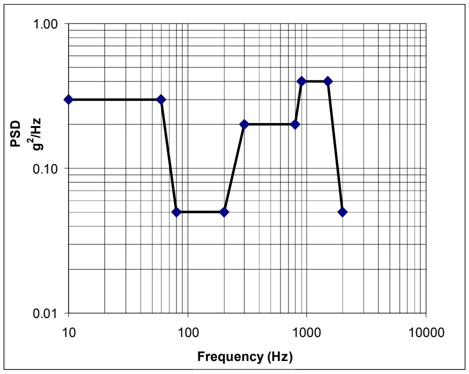


Figure 14. Track vehicle vibration profile

The compensating technology employed in this oscillator has, in essence, converted a quartz crystal resonator's intrinsic g-sensitivity of ~1E-9/g into an oscillator that performs as if its g-sensitivity is ~1E-11/g; an improvement of approximately 40 dB. This improvement in g-sensitivity is best explained by referring to the simulated plots in Figure 15. The lowest plot demonstrates the oscillator's phase noise at rest. The top-most plot demonstrates the theoretical phase noise degradation that would be expected from an oscillator with a g-sensitivity of 1E-9/g when subject to the vibration profile of Figure 14. The plot labeled "rendition of actual dynamic phase noise…" is intended to roughly replicate the actual phase noise shown in Figure 13 and to compare it to the theoretical response of an oscillator with a g-sensitivity of 1E-11/g. Except for the frequency band around 100 Hz to approximately 400 Hz an improvement of 40 dB is attained. The demonstrated performance is realized in a compact package size measuring 2 x 2 x 1 inches (L, W, H).

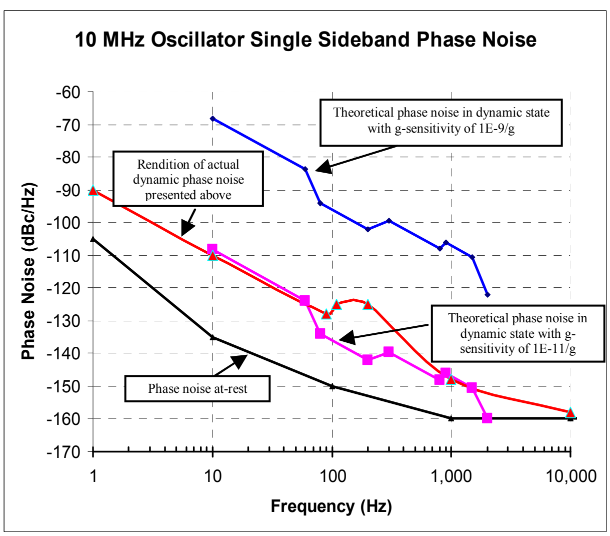


Figure 15. Comparison of oscillator phase noise per different values of g-sensitivity

C. Satellite Applications

For the past 40+ years it has been generally assumed that no on-orbit vibrations of consequence occurred that could affect the on-board communication systems and various other sensors. Obtaining reliable measurements from satellites that would reveal vibration induced distortions is very difficult and the magnitude of the problem has been to a large extent ignored. The major focus has been on the launch random vibration environment. However, in recent years FEI in concert with various satellite manufacturers has recognized that the on-board environment is dynamic with the presence of micro vibrations caused by thrusters, moment wheels and other moving systems. These micro vibrations generate low level spurious outputs and noise within commercial and military communications bands and actually do degrade system performance. For example the performance of broadband, high data rate communication systems are significantly affected, since low noise frequency sources play a major role in achieving a high data rate. Platform dynamics can degrade the signal, which in turn increases the BER (bit error rate), potentially forcing the system to decrease its data rate to maintain a required BER. Communication links between satellites may degrade or completely fail if the low noise frequency oscillator is affected by the vibration environment. The effects of micro vibration on communication link have been studied on test satellites by ESA and others [2].

As previously explained, any phase noise degradation in the master oscillator is magnified in higher frequency sources that are directly or indirectly synthesized from the master oscillator. A high precision, quartz-based, multi-output, triple-redundant space master oscillator is shown in Figure 16. Typically these oscillators utilize a dual-oven construction, and a 10 MHz, 5th overtone, SC-cut crystal resonator.

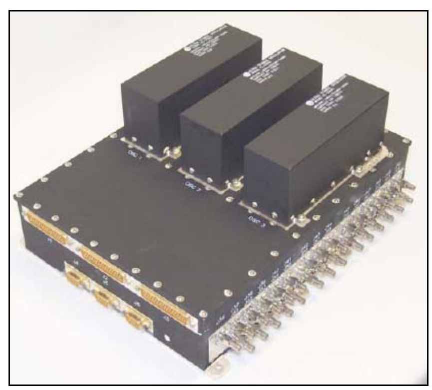


Figure 16. Triple-redundant space master oscillator

For certain demanding applications the master oscillator is required to maintain exceptionally low spur levels—better than -120 dBc in the frequency band of 10 Hz to 10 KHz and above. The expected spurious levels and degraded phase noise caused by the on-board micro vibrations, is illustrated in the following example:

- Assume a 10 MHz master quartz oscillator on a space vehicle operating in a typical on-orbit dynamic environment.

- The random and sinusoidal vibration levels are specified in Table I below
- The at-rest phase noise of the 10 MHz oscillator is specified in table 3.
- The g-sensitivity of the 10 MHz oscillator is 2E-9/g
- The required spurious levels are specified as -120 dBc from 0.5 Hz to 10 KHz

TABLE I. RANDOM AND SINUSOIDAL VIBRATION

Random Vibration Frequency (Hz)	Power Spectral Density (g^2Hz)	Sinusoidal Vibration Frequency (Hz)	Vibration Acceleration (g)
1	0.00005	10	0.04
70	0.00009	40	0.06
130	0.00005	100	0.03
300	0.000004	300	0.006

TABLE II. OSCILLATOR PHASE NOISE AT-REST

Off-set Frequency (Hz)	Phase Noise (dBc/Hz)
1	-116
10	-140
100	-150
1000	-155
10000	-160

The resulting theoretical performance is shown in Figure 17. The phase noise has been very much degraded by the random micro vibrations, and un-acceptable spurious output levels have been generated due to the sinusoidal vibrations. Note that the sinusoidal vibration at 10 Hz has caused a spurious level of -88dBc that is 32 dB greater than the specification requirement of -120dBc. Similarly, at 10 Hz the phase noise is 40 dB worse than the quiescent level of -140dBc/Hz.

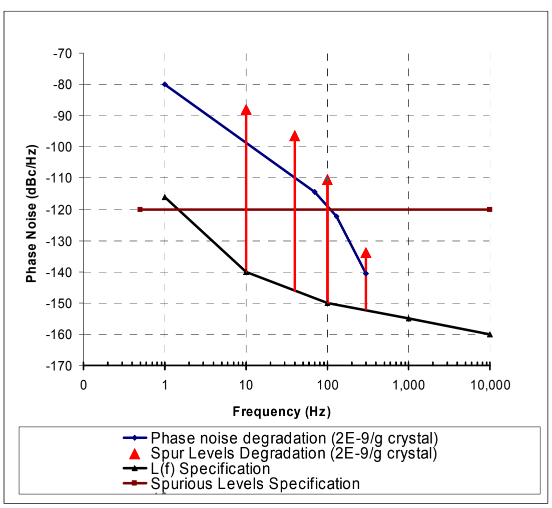


Figure 17. Single sideband phase noise and spurious levels degradation caused by typical satellite random and sinusoidal micro vibrations

The performance of the onboard master oscillator can be significantly improved when subject to the vibration levels shown in Tables I. One approach is to select crystals with better g-sensitivities. Assuming that a crystal with a g-sensitivity of ~5E-10/g is used, the phase noise and spurious levels in the above example will only improve by approximately 12 dB. Manufacturing 10 MHz, 5th overtone, SC-cut crystals with significantly better g-sensitivity than 5E-10/g is very expensive and usually impractical.

A potentially better solution is to incorporate dynamic g-compensation. This approach is presently being tested by FEI on space type oscillators and preliminary data suggest that oscillators designed for space applications can achieve effective g-sensitivities of better than 5E-12/g.

In addition to satellites, g-compensated oscillators are also effective in satellite ground-segment applications as explained by Ernst, et al [3].

V. CONCLUSION

FEI has developed quartz oscillators in which the inherent resonator sensitivity to acceleration is effectively reduced. This is accomplished using new methods of quartz resonator design and manufacturing that result in minimum cross-coupling between the three resonator axes and new sensing devices that can be mounted and aligned in each resonator axis. The basic performance achieved with this approach is as follows:

- Acceleration sensitivities better than 2E-12/g
- Improvements of greater than 40dB for vibration sidebands
- Optimized compensation from DC to 2 kHz
- Economies in manufacturability
- Small package < 5 in^3

Applications and resulting performance from employment of this technology have been presented.

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