Acceleration Sensitivity Characteristics of Quartz Crystal Oscillators

APP NOTE

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The resonant frequency of every quartz crystal is affected by acceleration forces. The nature of the effect depends on the type of force that is being applied. Changes in the static gravitational force being experienced such as tilting or rotation will cause a step offset in frequency. Time dependent acceleration or vibration will frequency modulate the output. A shock pulse will cause a sharp temporary perturbation in the output frequency.

The magnitude of these frequency shifts is determined by the quartz crystal's acceleration or "g-sensitivity" vector and the characteristics of the applied acceleration force. The range of typical g-sensitivities for bulk-mode quartz crystals can span several orders of magnitude, from less than 1×10^{-10} per g for a carefully made precision SC cut to greater than 1×10^{-7} per g for a low cost AT. [1]

Since the magnitude of these effects is relatively small, they go undetected in many applications with standard oscillators such as VCXO's and clocks.

However with precision ovenized oscillators or those that undergo severe environmental conditions, the inherent acceleration sensitivity can be very significant. If the oscillator is deployed in a high vibration environment such as an airborne platform, increased phase noise can degrade the system performance more than all other sources of noise combined. But even in a benign environment, a high stability OCXO may experience significant frequency shifts. With knowledge of the operating environment that an oscillator will experience and an understanding of the acceleration sensitivity of the quartz crystal, it is possible to predict and plan for the expected frequency errors.

Description of Quartz Resonator G-sensitivity Vector

A crystal oscillator's g-sensitivity is usually characterized by measuring the attributes along three mutually perpendicular axes. However, the intrinsic acceleration characteristic of quartz consists of a single vector at some angle which is usually not normal to any of the faces of the package. (See Figure 1)

By measuring the individual mutually orthogonal components in the x, y and z axes, it is possible to determine the magnitude and orientation of the g-sensitivity vector, Γ_{max}.

Using the following trigonometric identities, the characteristics of Γ_{max} may be calculated.

$$\Gamma_{max} = (g_x^2 + g_y^2 + g_z^2)^{1/2} \quad (1)$$

$$g_{xy} = (g_x^2 + g_y^2)^{1/2} \quad (2)$$

$$\Theta = \arccos(g_x / g_{xy}) \quad (3)$$

$$\Phi = \arcsin(g_z / \Gamma_{max}) \quad (4)$$

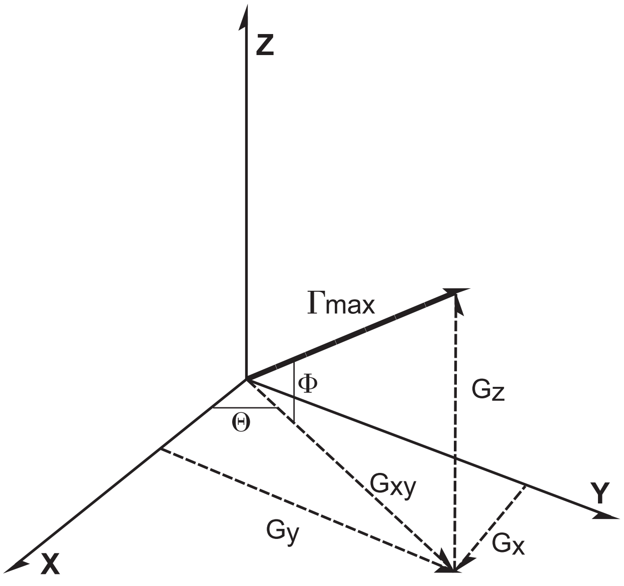

Figure 1

Once the magnitude and angular orientation of Γ_{max} are known, the expected effect of externally applied acceleration forces in any direction may be determined. When the direction of the applied force is parallel to the axis of Γ_{max} it will have the greatest influence on the crystal frequency. As the angle of the applied force moves away from the axis parallel to Γ_{max}, the resultant effect rolls off as the cosine of the angle Alpha. A circle is therefore defined as shown in Figure 2. Or, if viewed in all three dimensions, a sphere with Γ_{max} along its axis would be described. Therefore, the resultant g-sensitivity of the crystal in any direction as a function of Θ and Φ is given by:

$$g(\Theta, \Phi) = \Gamma_{max} \times \cos\Theta \times \cos\Phi \qquad (5)$$

Orientation to Achieve "Zero" G-sensitivity

When the force is applied in the opposite direction, a frequency shift of equal magnitude but opposite sign is produced, defining the second circle shown in Figure 2. Because of the vector and cosine nature of the g-sensitivity vector a plane of zero g-sensitivity is present as defined by the plane that is normal to Γ_{max}. This illustrates the fact that any force applied to the crystal which is perpendicular to Γ_{max} will have a minimal effect on the frequency. (See Figure 2)

G-sensitivity Measurement Methods

Relatively small frequency shifts must be measured when characterizing a crystal oscillator's g-sensitivity. One way of making basic measurements on a precision oscillator is to use changes in the earth's gravitational field to cause shifts in the oscillator frequency.

This technique is known as the "2-g Tipover" method. The frequency change is measured as the unit is turned upside down. The net effect is a change of 2g. Therefore, the amount of frequency shift measured divided by 2 is the oscillator's g-sensitivity in that axis. The procedure is then repeated for the other two axes. Although conceptually simple, this method requires a stable oscillator to be able to consistently measure the small frequency shifts that occur.

Relative Acceleration Sensitivity vs. Angle of Force Vector

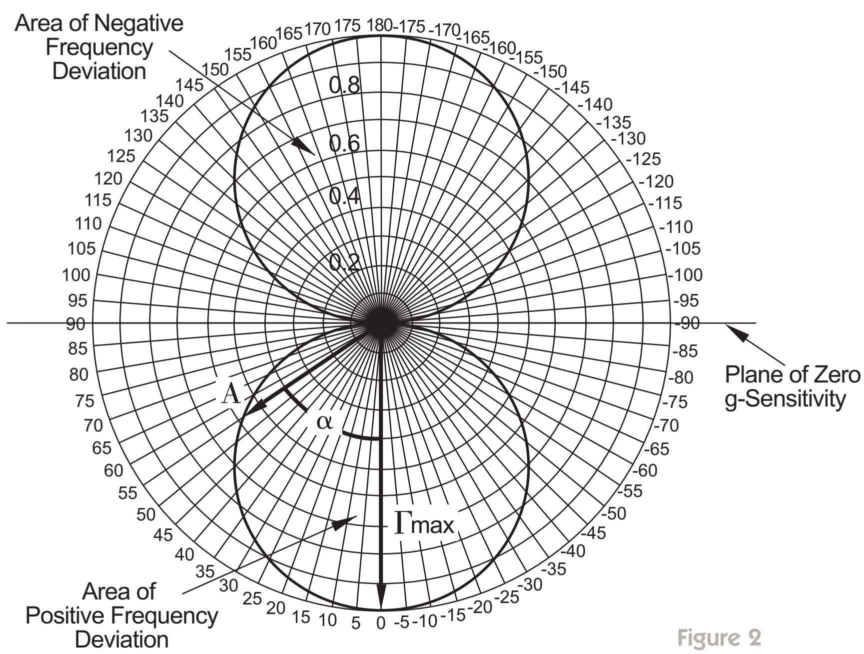

Figure 2

In order to obtain a precision dynamic measurement, the performance of the crystal is measured while vibration is applied. The level of the induced sidebands may be determined using the standard FM modulation index formula:

$$\text{Sideband Level (dB)} = 20 \log(\Delta f / 2f_m) \qquad (6)$$

Given that f_m equals the vibration frequency f_v and g is the peak applied vibration level, Δf is given by:

$$\Delta f = g \times \Gamma \times f_{nom} \qquad (7)$$

The formula may be rewritten as:

$$\text{Vib Sidebands (dB)} = 20 \log ((g \times \Gamma \times f_{nom}) / 2f_v) \qquad (8)$$

Using a narrowband spectrum analyzer with high dynamic range, it may be possible to measure these sidebands directly. If necessary, the modulation index and the sideband levels may be increased by multiplying the frequency of the crystal. This will result in an increase of sideband level of 20(logN) where N is the multiplication factor. It may be necessary, however, to increase the resolution of the measurement even further. This may be accomplished by phase locking another oscilla tor to the Unit Under Test to suppress the carrier signal. The standard test set-up for measuring vibration induced effects is shown in Figure 3. This configuration implements a sensitive low noise phase locked loop frequency discriminator.

While sinusoidal vibration generates discrete sidebands at the vibration frequency, the effects of random vibration cause a general rise in the noise floor.

By knowing the power spectral density of the vibration input, it is possible to compute the g-sensitivity of the crystal from the resultant phase noise plot.

The sideband formula given above is modified to use the PSD of the vibration input giving:

$$\pounds(f) = 20 \log (((2\text{xPSD})^{1/2} \times \Gamma \times f_{nom}) / 2f_{vr}) \qquad (9)$$

Phase Locked Loop Frequency Discriminator

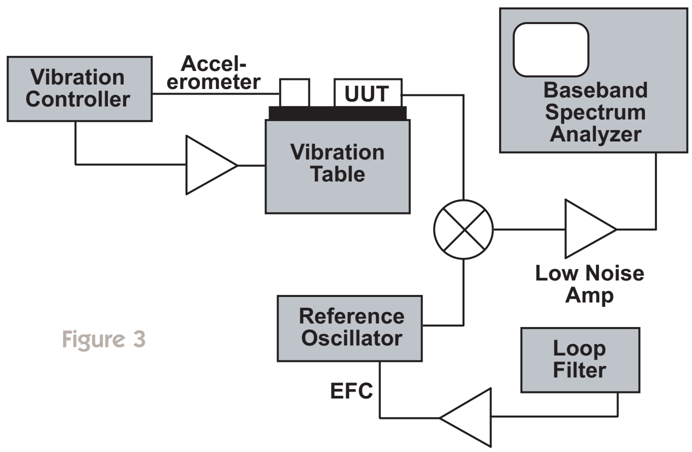

Figure 3

Figure 4 shows the phase noise of a low noise 100MHz OCXO at rest and also with random vibration applied. This illustrates that even moderate levels of random vibration can degrade the phase noise performance of an oscillator by 40 or 50dB.

100 MHz OCXO Random Vibration Z - AXIS

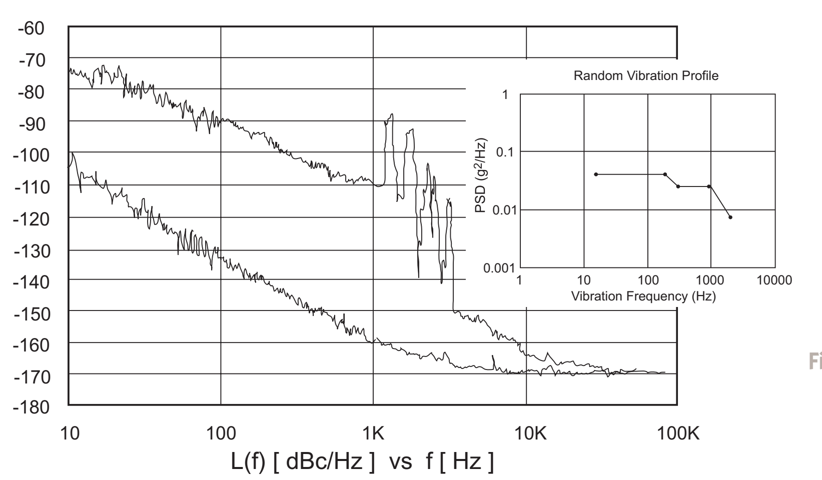

Figure 4

Typical g-Sensitivity Performance

Actual measurements of groups of crystals show that even with careful design, a large spread in the magnitude of the g-sensitivity vector as well as it's direction is typically present. Figure 5 shows the data from a group of 100MHz 5th overtone SC cut crystals in TO-05 holders. These crystals were all from a single group manufactured under supposedly identical conditions, but significant differences are still evident within the group.

Applications which require the lowest acceleration sensitivity will usually require SC cut crystals. The SC has been shown to have an average Γ_{max} that is 2 to 4 times better than a similar AT cut at the same frequency.

G-Sensitivity of 100MHz 5th Overtone SC-Cut Crystals

SN	gx	gy	gz	Γmax	Θ	Φ
5	1.38E-10	1.01E-10	2.27E-10	2.84E-10	58.6	20.9
9	1.95E-10	2.82E-10	4.79E-10	5.89E-10	67.8	28.6
29	3.89E-10	3.43E-10	5.02E-10	7.22E-10	52.2	28.4
21	7.08E-10	2.14E-10	7.68E-10	1.07E-9	47.3	11.6
23	4.79E-10	2.89E-10	6.10E-10	8.27E-10	51.9	20.4
10	4.73E-10	1.76E-10	4.52E-10	6.78E-10	43.7	15.0
7	2.48E-10	4.68E-10	1.30E-11	5.30E-10	3.0	62.0
39	2.32E-10	5.19E-10	2.69E-10	6.29E-10	49.3	55.6
33	6.31E-10	3.68E-10	1.04E-9	1.27E-9	58.6	16.9
11	3.59E-10	3.24E-10	7.33E-10	8.78E-10	63.9	21.6
26	1.64E-10	5.13E-10	5.63E-10	7.79E-10	73.7	41.2
28	3.16E-10	5.19E-10	5.89E-10	8.47E-10	61.8	37.8
12	3.13E-10	2.89E-10	6.24E-10	7.55E-10	63.4	22.5
27	5.19E-10	3.76E-10	6.31E-10	9.00E-10	50.6	24.7
20	4.79E-10	2.35E-10	9.34E-10	1.08E-9	62.8	12.6
24	4.12E-10	1.48E-10	4.03E-10	5.95E-10	44.3	14.4
60	3.06E-10	2.85E-10	3.89E-10	5.71E-10	51.9	30.0
48	2.95E-10	1.02E-10	3.72E-10	4.86E-10	51.5	12.2
45	5.02E-10	5.31E-10	1.14E-10	7.39E-10	12.8	45.9
55	1.72E-10	2.66E-10	5.96E-11	3.22E-10	19.1	55.7
61	3.55E-10	3.35E-10	1.82E-10	5.21E-10	27.2	40.0

Avg. = 7.17E-10 Stdev = 2.4E-10

Figure 5

Conclusions

Although it is not possible to completely eliminate the effects of acceleration on the frequency of a quartz crystal oscillator, by understanding the vector nature of the crystal's g-sensitivity characteristic, the impact in most applications can be minimized and managed acceptably.

References

[1] J.R. Vig, "Quartz Crystal Resonators and Oscillators – A Tutorial," June 1999

[2] R.L. Filler, "The Acceleration Sensitivity of Quartz Crystal Oscillators: A Review," IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control VOL. 35, No. 3, May 1988, pp.297-305

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Precision quartz-based oscillators for the wireless, wired telephony, aerospace, military, satellite, and other communications markets.

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