Application Note

Vibration and Mechanical Shock Performance of TI's BAW Oscillators

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ABSTRACT

BAW (Bulk Acoustic Wave) oscillators are a new entry to oscillator technology. Crystal-based oscillators have existed for many years, even before the introduction of MEMS technology. BAW technology brings benefits to reliability over Crystal-based and MEMS-based oscillators. The high grade reliability of BAW in terms of improved vibration, mechanical shock and mean time between failure (MTBF) performance, alleviates system designer concerns about oscillator performance in harsh environments, allowing designers to focus more on the overall system performance. Unlike quartz or mechanical elements used in the quartz oscillators, TI's piezoelectric BAW resonator is designed using a semiconductor process.

Mechanical shock and vibration can damage oscillators and degrade performance. Vibrations can result in increased phase noise or jitter and mechanical shocks can result in frequency shifts or spikes. This application note provides more details on BAW oscillator performance under stringent sinusoidal, random vibration, and mechanical shock conditions and describes various MIL-STD-883 test methods, test setup, and performance results.

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1 Introduction

The sensitivity to vibration and shock is a key consideration when designing systems with a crystal- or MEMS-based clock oscillator. Devices with high sensitivity to vibration can have a detrimental impact on the overall system performance, affecting the phase noise and jitter, frequency stability, and long-term reliability. The clock oscillator needs to provide a stable clock with strong resistance against acceleration forces, vibration, and shock, as resistance provides stability throughout the product life cycles under process and temperature variations.

The two important parameters for quantifying vibration are the acceleration force and vibration frequency applied to the devices. To quantify shock, acceleration force and the time duration for which the peak acceleration is applied are used. Vibrations and mechanical shock affect resonators by inducing noise and frequency drift, degrading system performance over time. In oscillators, vibration and shock are common causes of elevated phase noise and jitter, frequency shifts and spikes, or even physical damage to the resonator and resonator package. These degradations of phase noise and jitter directly impact the system performance. Typically, external disturbances couple into the micro resonator through the package. Since crystal oscillators fundamentally rely on the vibration and mechanical resonance of a piezoelectric material, external disturbances can couple into the device and degrade oscillator performance. Mechanical shocks of sufficient magnitude can also cause irreversible frequency shifts at the output of the crystal oscillator.

TI BAW oscillators fare better, when compared to quartz-based oscillators. TI's BAW oscillators are more immune to vibration and mechanical shock due to the smaller mass (by orders of magnitude) of the resonator and higher resonance frequency. The force applied to the device from external acceleration is much smaller due to smaller mass. The immunity of the device is further enhanced by the semiconductor manufacturing process of the BAW resonator. The BAW piezo and metal layers are surrounded by Bragg mirrors, which shield the resonator from environmental stresses. The BAW oscillator also includes a wafer-level encapsulation for making the oscillator a robust and reliable product. TI's dual-Bragg BAW resonators contains no moving parts, which provides resilience against environmental stress with improved device reliability.

Vibration sources are present in many end-applications including hand-held mobile devices, cooling fans in equipment chassis, factory automation equipment, construction equipment, moving vehicles or aircraft. The following table provides examples of the vibration levels at different environment conditions.

Table 1-1. Typical Acceleration Levels in Various Environments

Environment[(1)]	Typical acceleration (g)
Buildings	quiescent 0.02 rms
Tractor-trailer	(3 to 80 Hz) 0.2 peak
Armored personnel carrier	0.5 to 3 rms
Ship - calm seas	0.02 to 0.1 peak
Ship - rough seas	0.8 peak
Railroads	0.1 to 1 peak
Propeller aircraft	0.3 to 5 rms
Helicopter	0.1 to 7 rms
Jet aircraft	0.02 to 2 rms
Missile - boost phase	15 peak

A LMK6x oscillator from Texas Instruments is used to quantify the vibration and shock performance of BAW oscillators. The devices are subjected to sinusoidal vibrations at various frequencies along the X, Y and Z directions. The tests are repeated along each axis with random vibration profiles. The final test measures the transient frequency deviation of the units during operation in response to mechanical shock. Phase noise (including spurs) and frequency shift data are then recorded during these tests.

2 Test Standards and Test Setup

2.1 Test Standards

The tests in this application note are performed in accordance with the following standards and procedures.

- Random Vibration: MIL-STD-883F standard: Method 2026C
- Mechanical Shock: MIL-STD-883F standard: Method 2002.4B
- Sinusoidal vibration at 10 g with vibration frequencies of 50, 100, 200, 500, 1000, and 2000 Hz

Phase noise and jitter performance are recorded before, during, and after the random vibration, following the preceding MIL (Military) standards. Frequency drift is recorded as per the mechanical shock standard test setup. Sinusoidal vibration at different vibration frequencies is conducted and based on the phase noise result, the ppb/g value is calculated for the BAW oscillator. The test setup, procedure and test results are provided in later sections of the document.

2.2 Test Setup in Vibration Lab

The sinusoidal and random vibration test setup is shown in Figure 2-1.

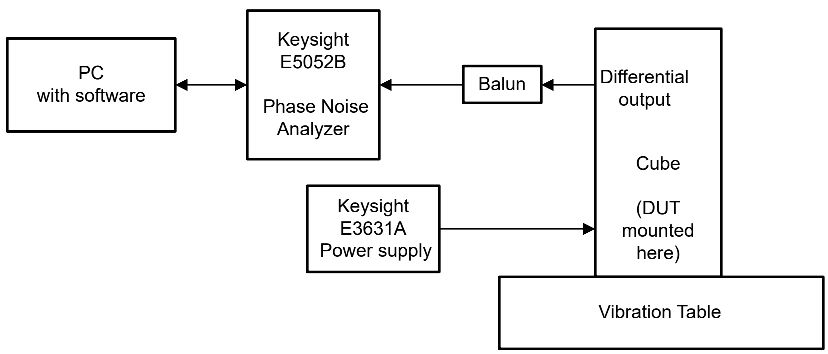

Figure 2-1. Sinusoidal and Random Vibration Test Setup Diagram

Figure 2-2 shows the lab setup for the sinusoidal and random vibration tests along the three axes.

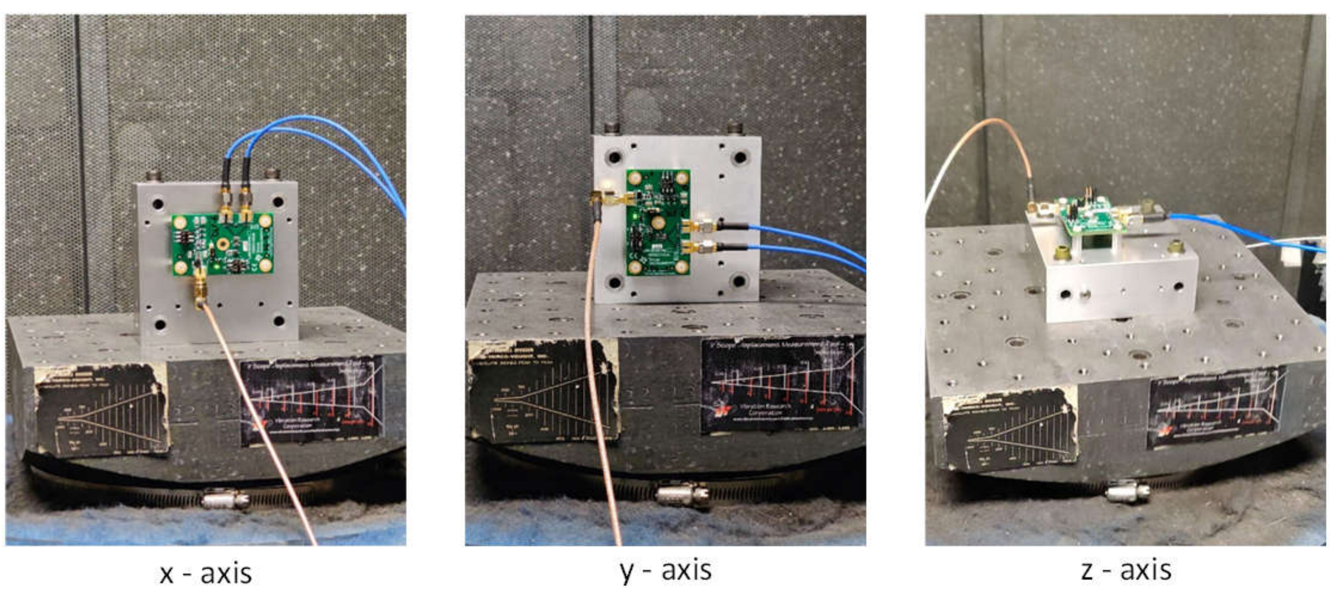

Figure 2-2. Vibration Test Fixtures With The Evaluation Board (having DUT) in the X, Y, Z Axes

3 Sinusoidal Vibration, Random Vibration, and Mechanical Shock Tests

3.1 Sinusoidal Vibration Test

3.1.1 Procedure for Sinusoidal Vibration Test

LMK6x BAW Oscillator has multiple packages for differential- and single-ended outputs, see the LMK6x Low Jitter, High-Performance BAW Oscillator data sheet for more details on the BAW oscillator package options.

For this sinusoidal vibration test, the following variants were selected.

- LVCMOS Output: DLE-4 (3.2 x 2.5 mm), DLF-4 (2.5 x 2.0 mm)
- Differential Output: DLE-6 (3.2 x 2.5 mm), DLF-6 (2.5 x 2.0 mm). BAW Oscillator has LVDS, LVPECL, HCSL output types. LVPECL output type oscillator is selected for this test.

The following are the steps involved in setting up the DUT (Device Under Test) board on the vibration fixture and for conducting the sinusoidal vibration test.

- Parts are soldered down on the LMK6x evaluation module (EVM) and bolted to the mating plate, which is connected to the vibration stand.
- The Keysight E3631A bench-top power supply is setup to supply 3.3 V for the EVM module.
- For differential outputs (DLE-6 and DLF-6 package devices), LVPECL output termination is provided on the EVM. A TC1-1-13MA+ surface mount RF transformer is used to convert the differential output to a single-ended output and the output is connected to a Keysight E5052B phase noise analyzer.
- Using VibrationVIEW® Control software, the vibration frequency is programmed to 50, 100, 200, 500, 1000, 2000 Hz at 10 g acceleration setting.
- Once the vibration machine achieves the targeted frequency and intensity, a single trigger is issued to the E5052B phase noise analyzer.
- Phase noise data is captured using the phase noise analyzer and phase noise plots and trace data are collected for each axis of vibration (X, Y, and Z axis).
- Using spur power (normalized mode), frequency deviation is calculated based on the following formula:

$$\mathrm{fm\_deviation} = \mathrm{fm\_frequency} \times 10^{\left(\frac{6 + \mathrm{Vib\_spur\_power}(\mathrm{dBc/Hz})}{20}\right)} \quad (1)$$

  where fm_deviation is the frequency modulation deviation and fm_frequency is the frequency of vibration.
- From frequency deviation, ppb (parts per billion) is calculated based on the following formula:

$$\mathrm{ppb} = 10^{9} \times \frac{\mathrm{fm\_deviation}}{\mathrm{carrier\_frequency}} \quad (2)$$

- The ppb value is then divided by the set g force, to calculate ppb/g.

3.1.2 Results From Sinusoidal Vibration Test

Sinusoidal test is conducted at a fixed sinusoidal vibration frequency of 50, 100, 200, 500, 1000, and 2000 Hz with 10 g acceleration for all three axes. Phase noise plots from these tests are captured. The following plots are for the Z-axis for DLF-4 package. A spur sticking out at the frequency of vibration can be observed in each graph. Based on the test results and captured data, the vibration sensitivity in terms of ppb/g is calculated for BAW oscillators.

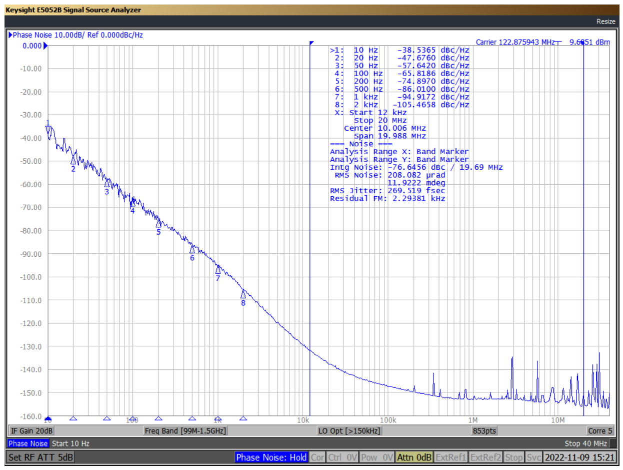

Figure 3-1. Baseline Capture Before Sinusoidal Vibration

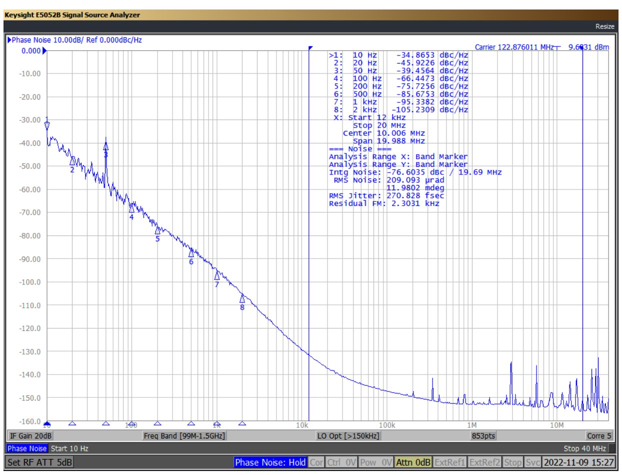

Figure 3-2. Capture of Sinusoidal Vibration at 50 Hz

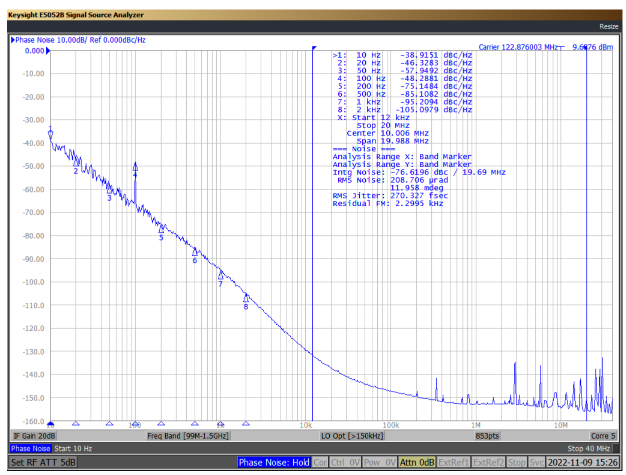

Figure 3-3. Capture of Sinusoidal Vibration at 100 Hz

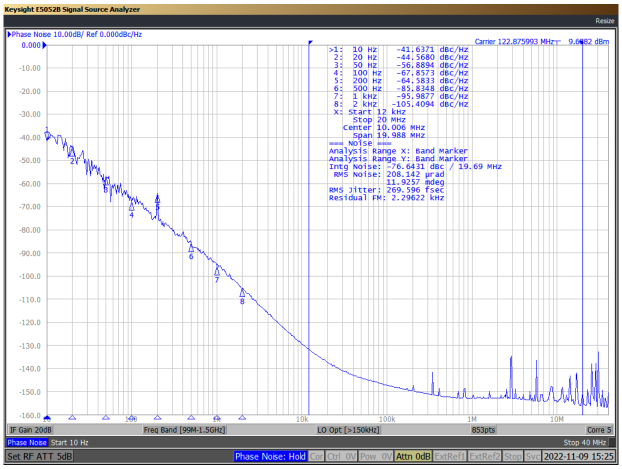

Figure 3-4. Capture of Sinusoidal Vibration at 200 Hz

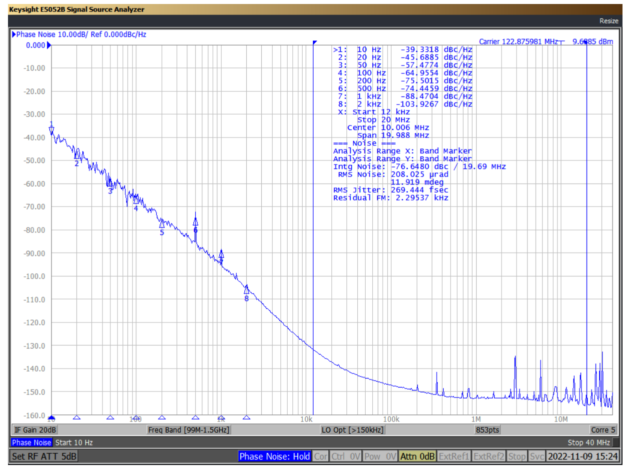

Figure 3-5. Capture of Sinusoidal Vibration at 500 Hz

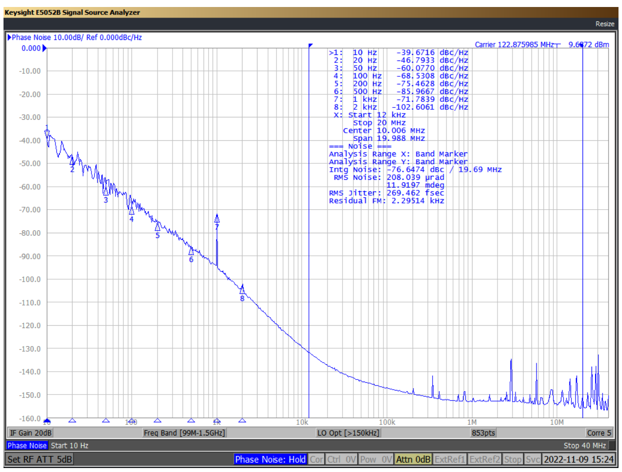

Figure 3-6. Capture of Sinusoidal Vibration at 1000 Hz

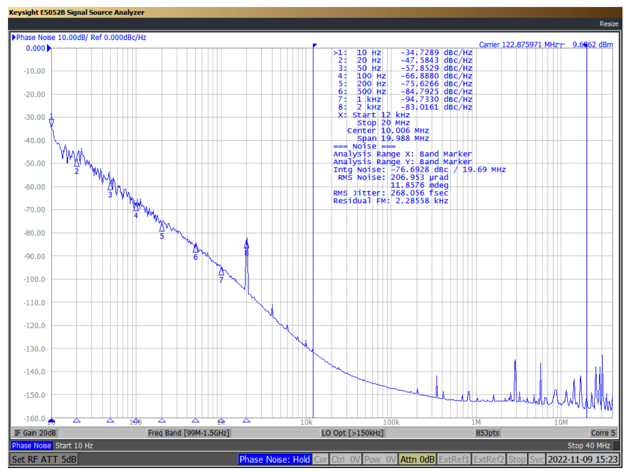

Figure 3-7. Capture of Sinusoidal Vibration at 2000 Hz

The combined, overlaid waveform for the phase noise plots with respect to vibration frequencies are shown in the following figures. The figures show waveforms for the DLE-4, DLF-4, DLE-6, and DLF-6 packages.

The ppb/g is calculated and plotted for both LVCMOS and LVPECL. Each of the following figures show Z-axis data with the device at 10 g acceleration.

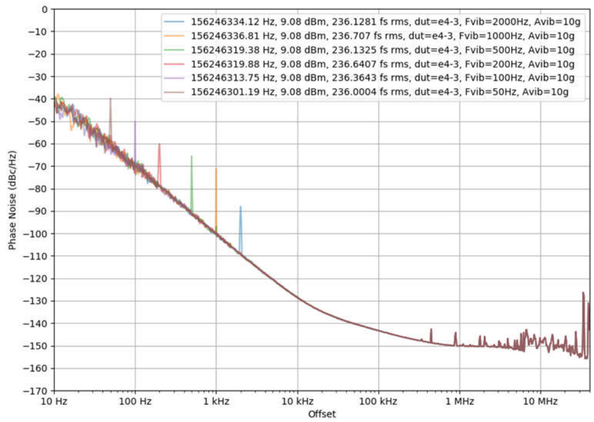

Figure 3-8. Combined Sinusoidal Vibration Phase Noise Plot on 4-pin DLE Package

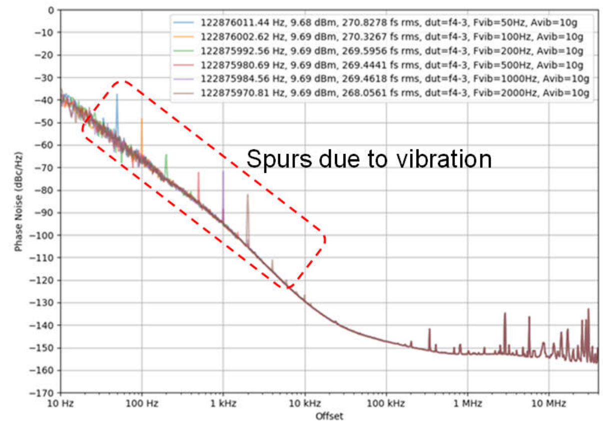

Figure 3-9. Combined Sinusoidal Vibration Phase Noise Plot on 4-pin DLF Package

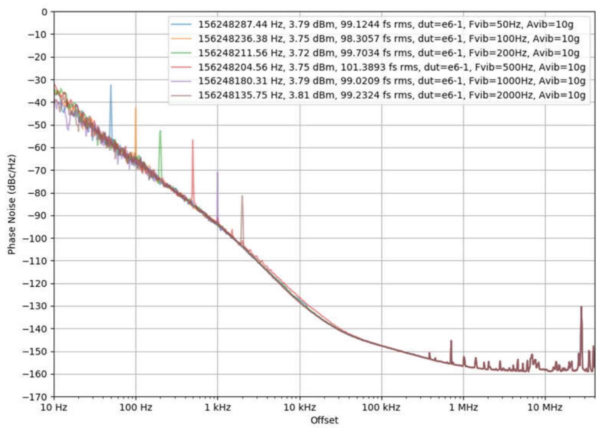

Figure 3-10. Combined Sinusoidal Vibration Phase Noise Plot on 6-pin DLE Package

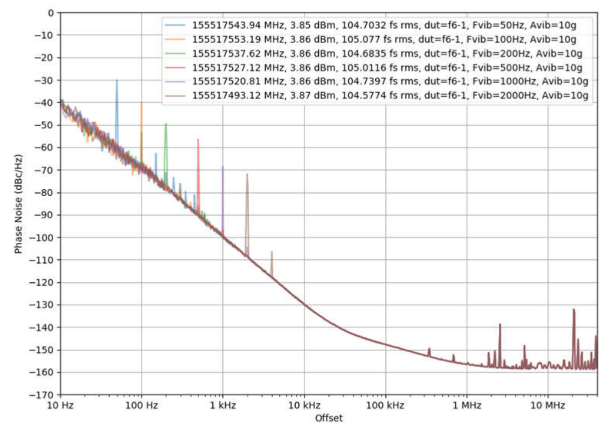

Figure 3-11. Combined Sinusoidal Vibration Phase Noise Plot on 6-pin DLF Package

The calculated ppb/g values for the LMK6x on LVCMOS and LVPECL devices for both the DLE and DLF packages are plotted for all the tested vibration frequencies. These calculations are based on the vibration frequency spurs in phase noise measurements for various vibration frequencies for different types of LMK6x packages and output types. The equations are provided in Section 3.1.1. Figure 3-12 shows the vibration frequency versus the ppb/g value. The vibration sensitivity of the LMK6x LVCMOS output type is less than 1 ppb/g and the vibration sensitivity for the LMK6x differential output is less than 2 ppb/g based on the plots. In Figure 3-12, the top plot is the X-axis, the middle plot is the Y-axis, and the bottom plot is the Z-axis ppb/g versus the vibration frequency. The blue line in Figure 3-12 represents the DLE package and the green line represents the DLF package. The vibration sensitivity of the crystal oscillators are in the range of 10 ppb/g, which shows that the BAW oscillators have less vibration sensitivity compared to crystal oscillators.

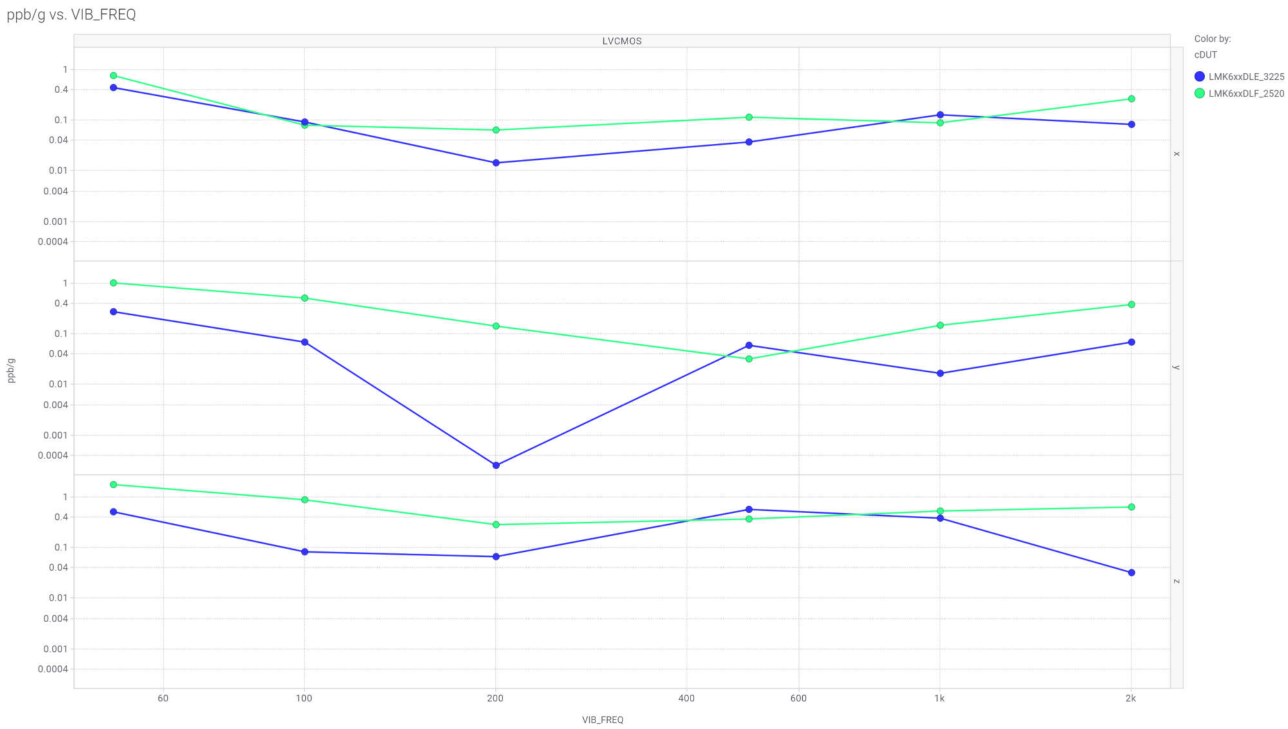

Figure 3-12. ppb/g Versus Vibration Frequency Plot for LVCMOS Output - DLE and DLF packages - X, Y, Z Axis

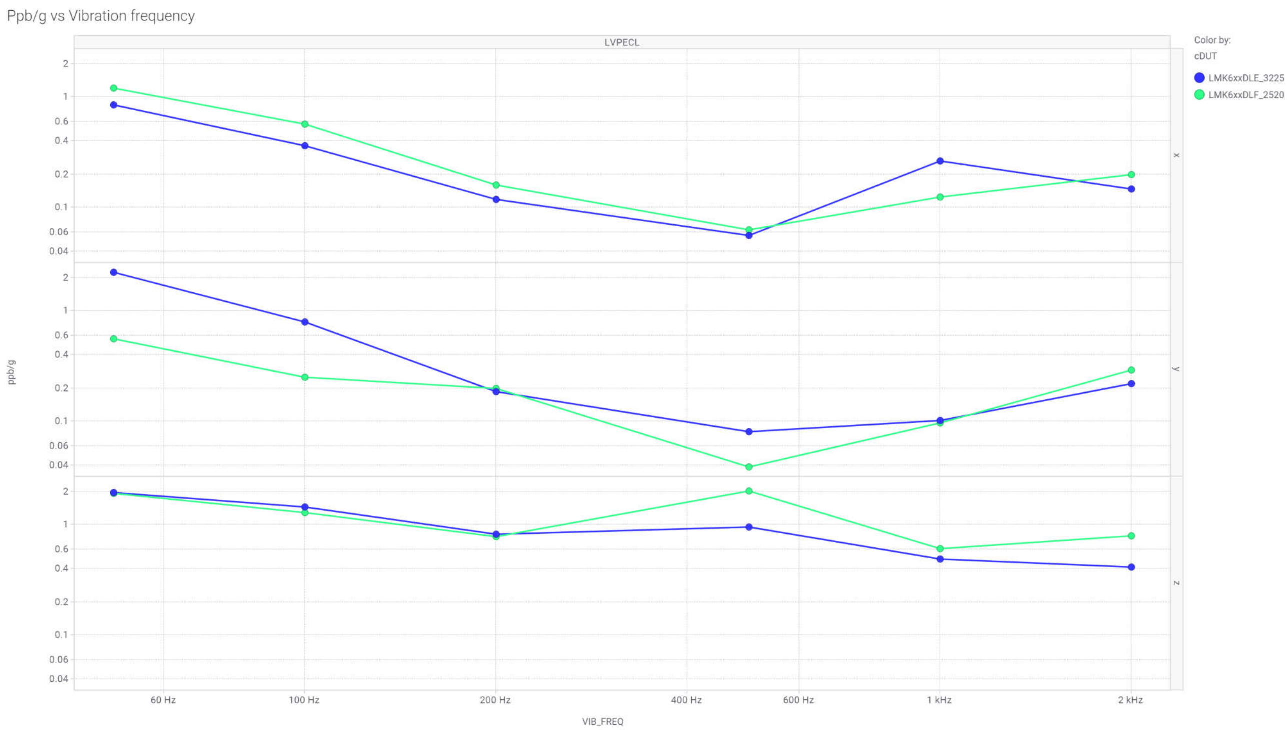

Figure 3-13. ppb/g Versus Vibration Frequency Plot for Differential Output - DLE and DLF Packages - X, Y, Z Axis

3.2 Random Vibration Test

3.2.1 Procedure for Random Vibration Test

The MIL-STD-883F method 2026C is followed for the random vibration test profiles and setup. Random vibration represents the true environment in which electronic systems operate. Random vibration contains all of the frequencies simultaneously and hence all product resonances are excited simultaneously, which is worse than exciting product resonances individually (as in sinusoidal vibration testing). Random vibration testing helps to identify failures that cannot be duplicated in a sinusoidal environment.

The EVM board setup is identical to what is shown in Section 3.1.1. However, the profile for random vibration is different. The acceleration spectral density with respect to frequency of vibration is shown in Figure 3-14 using VibrationVIEW®, which is used throughout this test.

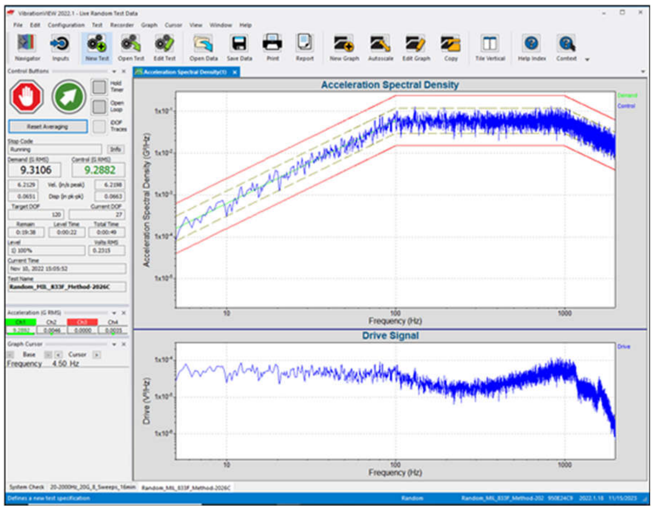

Figure 3-14. VibrationVIEW Software Tool Setup for Random Vibration

3.2.2 Results From Random Vibration Test

The plots shown in this section are captured before, during, and after the random vibration test, which are tested following the MIL-STD-883F method 2026C.

The capture data for the Z-axis movement of the DLE 4-pin (LVCMOS) oscillator is shown in Figure 3-15 and Figure 3-16.

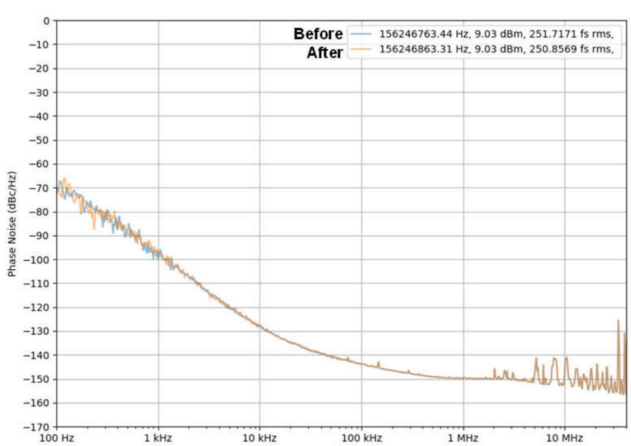

Figure 3-15. Plot of Before and After Vibration Test on 4-pin DLE (LVCMOS)

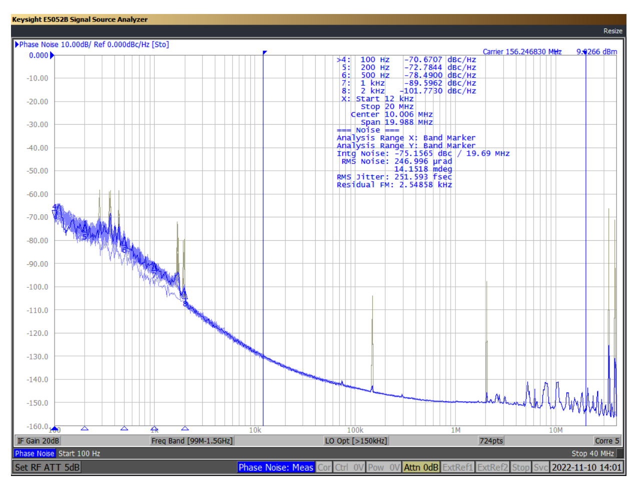

Figure 3-16. Capture During Vibration of the 4-pin DLE (LVCMOS)

The capture data for the Z-axis movement of the DLE 6-pin (LVPECL) oscillator is shown in Figure 3-17 and Figure 3-18.

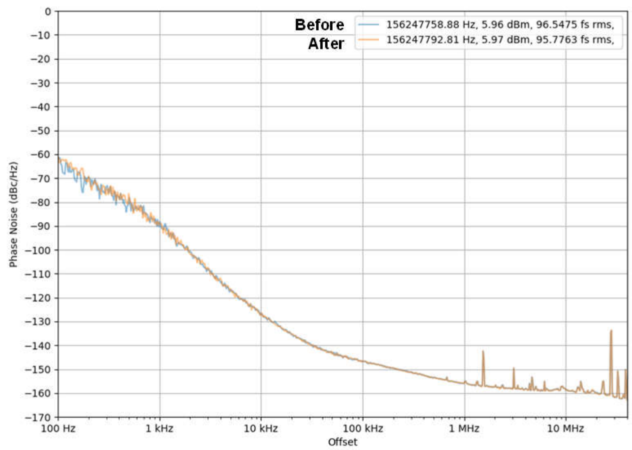

Figure 3-17. Plot of Before and After Vibration Test on 6-pin DLE (LVPECL)

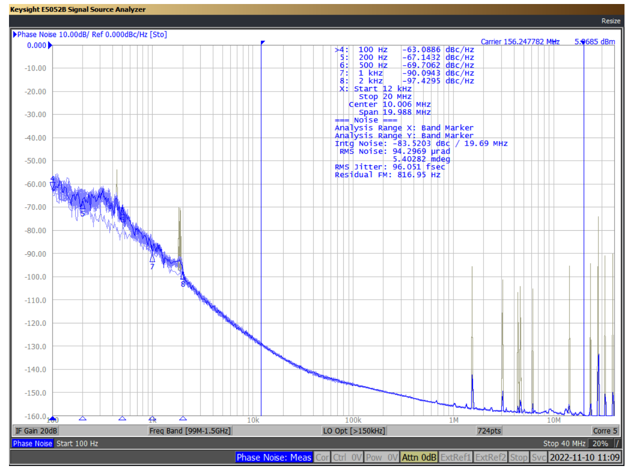

Figure 3-18. Capture During Vibration Test on 6-pin DLE (LVPECL)

The preceding plots show that the performance of the BAW Oscillator is robust during and after the vibration and the jitter performance is not degraded.

3.3 Mechanical Shock Test

3.3.1 Procedure for Mechanical Shock Test

For the mechanical shock test, the MIL-STD-883F Method 2002, Condition A profile (500 g acceleration) and Condition B profile (1500 g acceleration) is used.

For this sinusoidal vibration test, the following variants are selected.

- LVCMOS Output: DLE-4 (3.2 x 2.5 mm), DLF-4 (2.5 x 2.0 mm)
- Differential Output: DLE-6 (3.2 x 2.5 mm), DLF-6 (2.5 x 2.0 mm)

The following are the steps involved in setting up the Device Under Test (DUT) board on the vibration fixture and for conducting the mechanical shock test.

- Parts are soldered down on the LMK6x evaluation module (EVM) and bolted to the mating plate, which is connected to the mechanical shock testing machine.
- The Agilent E3631A bench-top power supply is setup to supply 3.3 V for the EVM module.
- For differential outputs (DLE-6 and DLF-6 package devices), the LVPECL output termination is provided on the EVM. A TC1-1-13MA+ Balun surface mount RF transformer is used to convert the differential output to a single-ended output and the output is connected to a Keysight E5052B phase noise analyzer.
- Shock parameters are set as below
  - For 1500 g, board is vertically lifted 10.4 inches.
  - For 500 g, board is vertically lifted 3.8 inches.
  - Air suction pulls fixture down to achieve appropriate g-force.

- At least 3 cycles of shock are performed for each tested sample.
- Transient data is acquired during shock test.
- Phase noise data is collected as a screenshot after shock test

The shock test fixture setup is in Figure 3-19, which shows the mounted LMK6x EVM.

Figure 3-19. Shock Test Setup

3.3.2 Results From Mechanical Shock Test

The results from the mechanical shock tests are shown in Figure 3-20 through Figure 3-23.

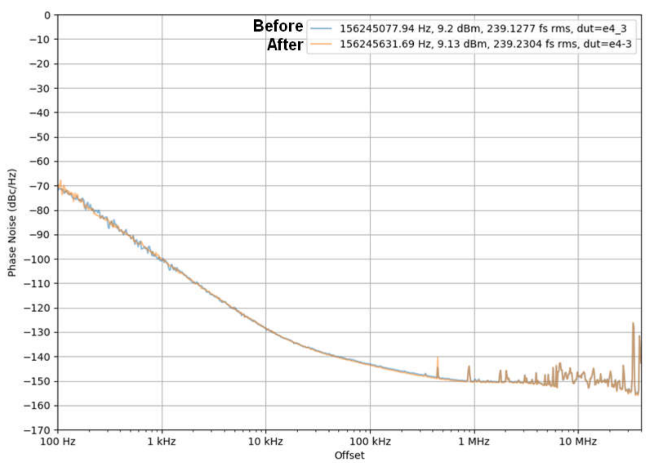

Figure 3-20. Plot of Before and After Mechanical Shock Test of 4-pin DLE, Z axis

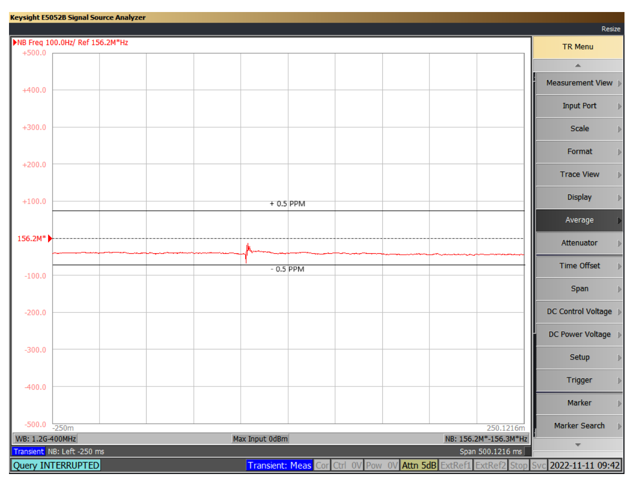

Figure 3-21. Capture During Mechanical Shock Test of 4-pin DLE, Z axis

The scale for the y - axis is in Hz (Hertz) and the markers are provided for 0.5 PPM on either side of the variation in the plot for easy reference for understanding PPM variation.

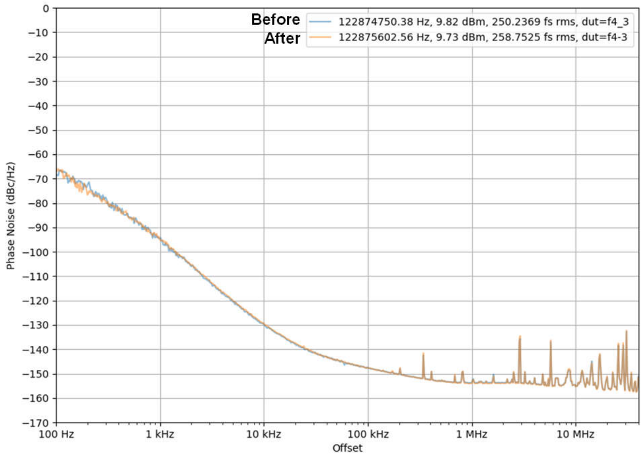

Figure 3-22. Plot of Before and After Mechanical Shock Test of 4-pin DLF, X axis

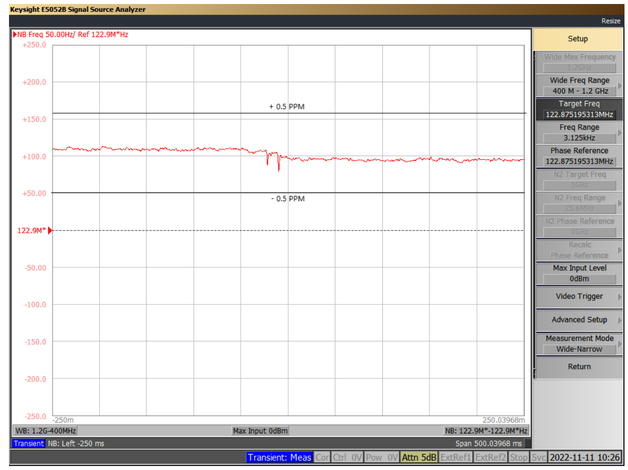

Figure 3-23. Capture of During Mechanical Shock Test of 4-pin DLF, X axis

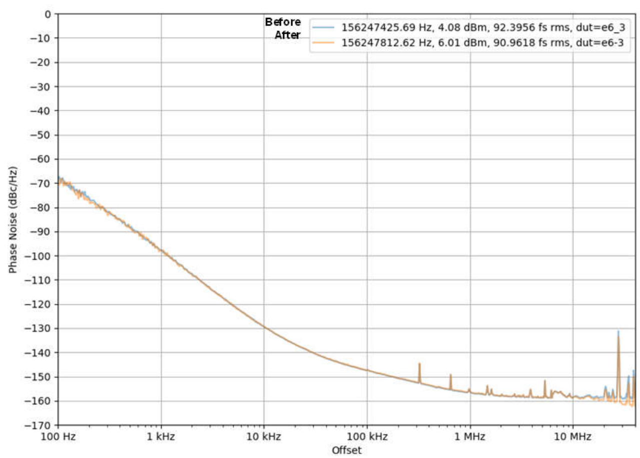

Figure 3-24. Plot of Before and After Mechanical Shock Test of 6-pin DLE, Y axis

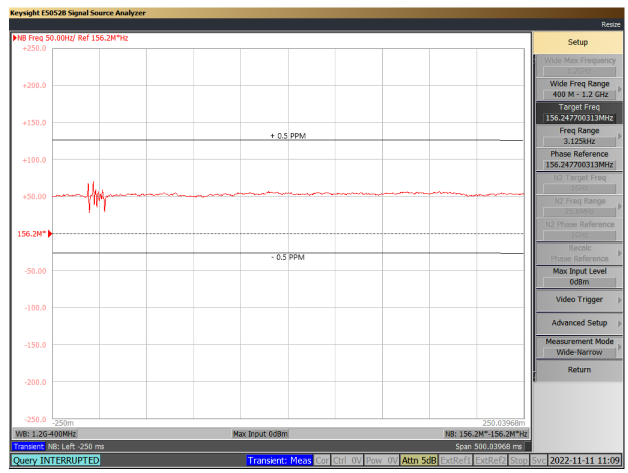

Figure 3-25. Capture During Mechanical Shock Test of 6-pin DLE, Y axis

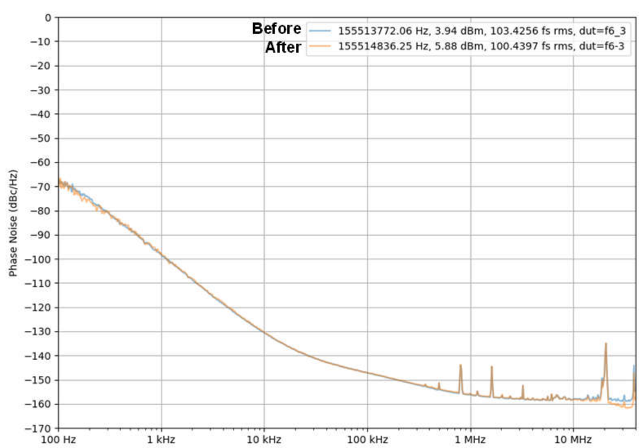

Figure 3-26. Plot of Before and After Mechanical Shock Test of 6-pin DLF, Y axis

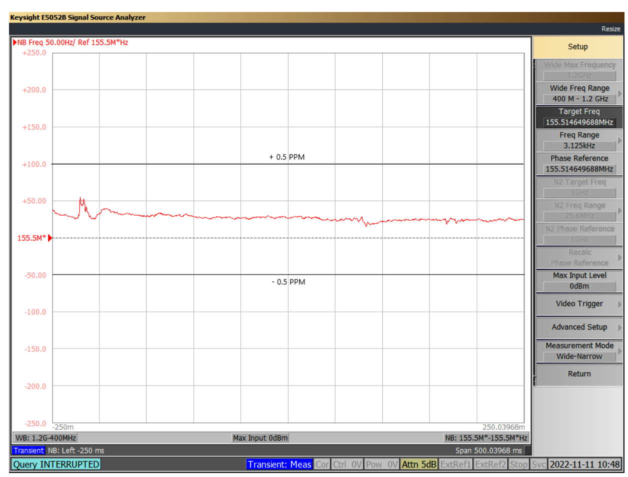

Figure 3-27. Capture During Mechanical Shock Test of 6-pin DLF, Y axis

The ppm variation is observed to be negligible during the mechanical shock test, with the variation at less than 0.5 ppm and the device operating normally after the test.

4 Comparison of BAW Oscillator Vibration Performance With Crystal Oscillator

To compare device performance under random vibration, a TI BAW oscillator and crystal oscillator device is selected and tested under the same test conditions.

Table 4-1. Comparison of TI BAW Oscillator and Crystal Oscillator Performance Under Same Conditions

Part number	Technology	Package	Frequency	VDD	Output	Accuracy
LMK6x BAW Oscillator	BAW	3.2 x 2.5 mm	156.25 MHz	3.3 V	LVPECL	±25 ppm
Crystal Osc 1	Quartz (integrated)					±50 ppm
Crystal Osc 2	Quarts (integrated)					±30 ppm

4.1 Comparison Test Setup

The MIL-STD-883H method 2026.B is selected for conducting a vibration comparison test. This test profile subjects the DUTs to an acceleration of 7.3-g rms. Figure 4-1 shows the vibration test setup created in the lab. The fixture is mounted on a vibration table, which is then subjected to an acceleration of a specific magnitude along the vertical axis. Three tests were performed on BAW oscillators and crystal oscillator devices. BAW oscillator shows better vibration immunity than its quartz counterparts.

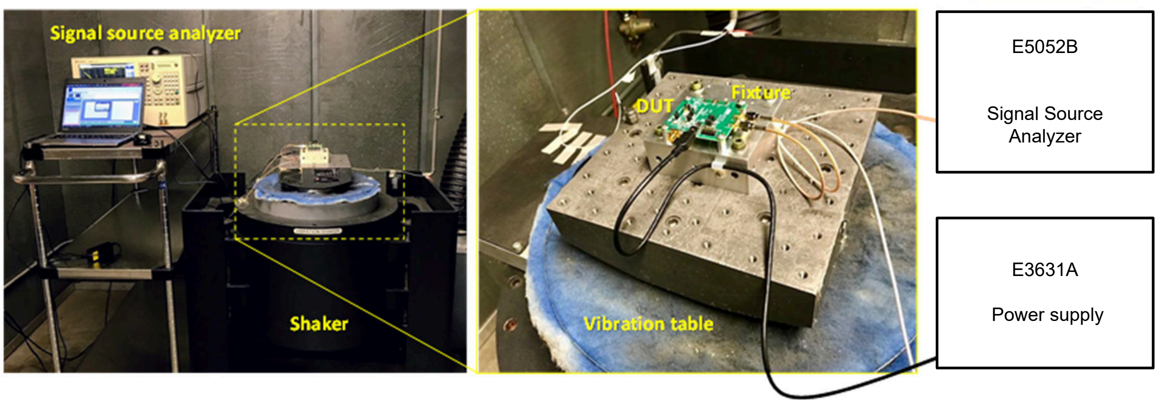

Figure 4-1. Vibration Test Lab Setup Diagram

Random vibrations also increase oscillator phase noise. The test hardware generates random vibration over the specified frequency range, based on the power spectral density level in the MIL-STD-883H. Since the random vibration is spread over a range of frequencies, there is an overall increase in the phase noise of the output clock from the DUT rather than just spurs at specific frequency offsets which is generally observed in sinusoidal vibration tests. The integrated RMS phase jitter values are measured over an integration band from 12-kHz to 20-MHz range. Measurements are taken with and without the vibrations present and the RMS jitter difference between the two cases are calculated to determine the jitter induced by the vibration for each DUT.

4.2 Comparison Test Results

Dynamic phase noise measurement of the BAW oscillator along with the counterpart crystal oscillators under random vibration test results are shown below. From the following plots, the BAW oscillator shows better immunity than crystal oscillators and lower RMS jitter (12-kHz to 20-MHz).

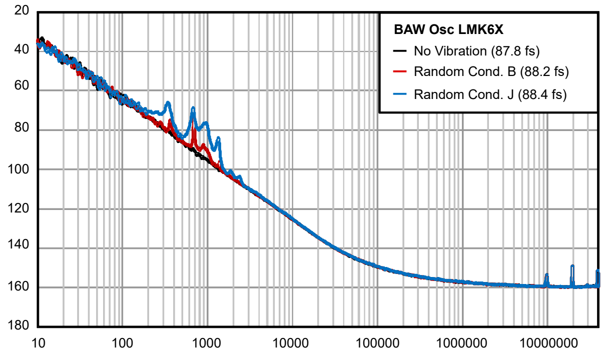

Figure 4-2. BAW Phase Noise Plot for Random Vibration Test

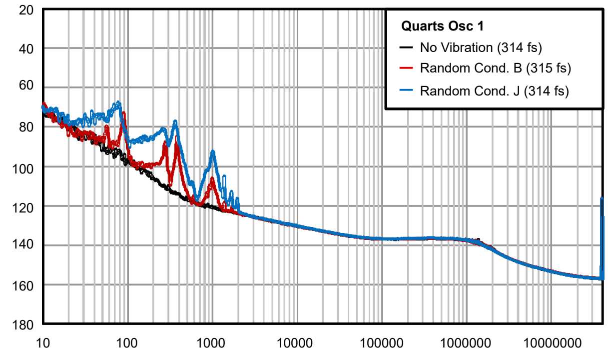

Figure 4-3. Crystal Oscillator 1 Phase Noise Plot for Random Vibration Test

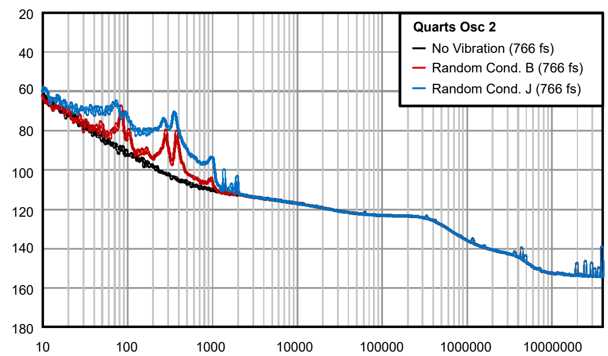

Figure 4-4. Crystal Oscillator 2 Phase Noise Plot for Random Vibration Test

5 Summary

Based on the sinusoidal, random vibration and Mechanical Shock tests and the test results shown in this application note, the following are key observations.

- BAW oscillators are not damaged and work normally during and after sinusoidal, random vibration, and mechanical shock tests.
- Based on the sinusoidal vibration test, the vibration sensitivity for the BAW oscillators is less the 2 ppb/g across all type of packages, as well as single-ended and differential-ended output types.
- Based on the random vibration test, the jitter is not degraded and the device performance has no significant variations before, during, and after the test.
- Based on the mechanical shock test, the ppm variation during the 1500 g acceleration test is less than 0.5 ppm.

These results show that BAW oscillators are robust and highly reliable and immune to the vibration and mechanical shock.

6 References

1. John R. Vig. (2004). *Quartz Crystal Resonators and Oscillators*, US Army Communications-Electronics Research, Development & Engineering Center.
2. Texas Instruments, *Exploring IoT wireless connectivity in mechanical shock and vibration environments*, white paper
3. Texas Instruments, *Vibration and Shock Sensitivity: A Comparative Study of Oscillators*, application report