Shock and Vibration Performance Comparison of MEMS and Quartz-based Oscillators

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1 Introduction

All electronic products are subject to shock and vibration during their lifetime. Forces can range from motion experienced by mobile consumer products carried around in pockets or backpacks to high vibration levels for industrial equipment or aerospace applications. Even stationary products in buildings may experience vibration from a nearby fan or other equipment. It is therefore important to consider how electronic components perform in the presence of shock and vibration. Table 1 shows typical levels of acceleration in various environments.

Table 1. Vibration in various field applications [1]

Environment	Acceleration Typical -g level
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
Railroad	0.1 to 1 peak
Ship – rough seas	0.8 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

Shock and vibration can cause physical damage to components and enclosures, lead to solder joint failure in PCB assemblies, and degrade performance of electronic components. Clock oscillators are susceptible to several detrimental effects: damage to the resonators, increased phase noise and jitter from vibration, and frequency spikes from shock.

Crystal resonators in quartz-based oscillators are cantilevered structures that can be especially sensitive to damage from vibration. SiTime MEMS resonators are fundamentally more robust for two reasons. First, they have much smaller mass than quartz resonators, which reduces the force applied to the resonator from the vibration-induced acceleration. Second, the proprietary design of SiTime MEMS oscillators includes very stiff resonator structures that vibrate in-plane in a bulk mode, a geometry that is inherently vibration-resistant, and oscillator circuit design that minimizes frequency shifts under vibration.

2 Test Conditions

Because external forces can vary in direction, duration and intensity, it is important to measure the electrical response of oscillators in a variety of test conditions to fully understand their sensitivity to shock and vibration. SiTime evaluated oscillator response to three different modes of vibration or shock: (1) sinusoidal vibration, (2) random vibration and (3) pulsed shock impact. Tested devices were all commercially available products and included MEMS-based oscillators from SiTime and a competitor, and quartz-based oscillators from several manufacturers. We included quartz oscillators with surface acoustic wave (SAW) crystal resonators, known to have low jitter at high operating frequencies.

Table 2. Oscillator devices under test; Single-ended parts (shaded blue) operate at 26 MHz and differential parts (shaded green) operate at 156.25 MHz

Label	Manufacturer	Part number	Technology	Output
SiTime	**SiTime**	SiT8208AC-22-33E-26.000000	MEMS	LVCMOS
Quartz 1	**TXC**	7Q-26.000MBG-T	TCXO	Clipped sine
Quartz 2	**Kyocera**	KT3225R26000ZAW28TMA	TCXO	Clipped sine
Quartz 3	**NDK**	NT3225SA-26.000000MHZ-G8	TCXO	Clipped sine
SiTime	**SiTime**	SiT9120AC-1D2-33E156.250000	MEMS	LVPECL
Quartz 4	**Epson**	EG-2102CA156.2500M-PHPAL3	SAW	LVPECL
Quartz 5	**TXC**	BB-156.250MBE-T	3rd overtone	LVPECL
Quartz 6	**Conner Winfield**	P123-156.25M	3rd overtone	LVPECL
Quartz 7	**AVX Kyocera**	KC7050T156.250P30E00	SAW	LVPECL
Quartz 8	**SiLab**	590AB-BDG	3rd overtone + PLL	LVPECL
MEMS 2	**Discera**	ASFLMPLP-156.25MHZ-LR-T	MEMS	LVPECL

2.1 Sinusoidal Vibration

The first test measured response to sinusoidal vibration at frequencies ranging from 15 Hz to 2 kHz. The periodic nature of sinusoidal vibration creates frequency modulation, which induces spurs in the phase noise spectrum, at frequencies offset by the vibration frequency. To characterize the oscillator sensitivity to vibration, the vibration-induced phase noise spur in dBc is converted into an equivalent frequency shift in parts per billion (ppb), then normalized by the peak acceleration of the sinusoidal vibration and expressed in ppb/g.

The vibration test setup consists of a controller, power amplifier and shakers, as shown in Figures 1 and 2. Peak acceleration was 4-g for each sinusoidal vibration frequency (15, 30, 60, 100, 300, 600, 1000 and 2000 Hz). Each sweep of the vibration frequency took about 15 to 20 minutes, and the dwell time at each frequency point was about 1 minute. The oscillator response to external force is anisotropic, i.e. it depends on the direction of the vibration. The tests were therefore repeated in the x, y, and z directions with reference to device pin 1 mark on the package and orientations shown in Figure 1. The plots present the data on the worst-case direction for each oscillator.

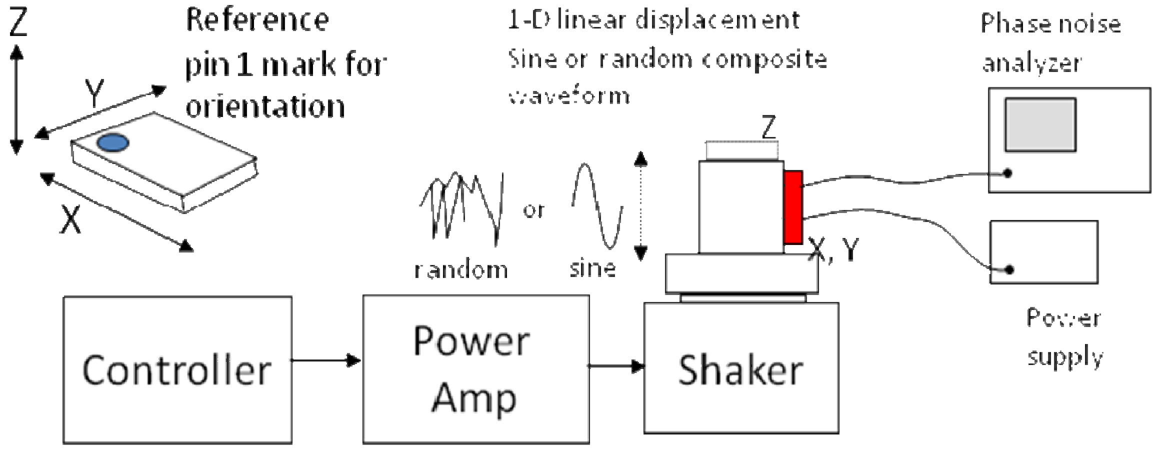
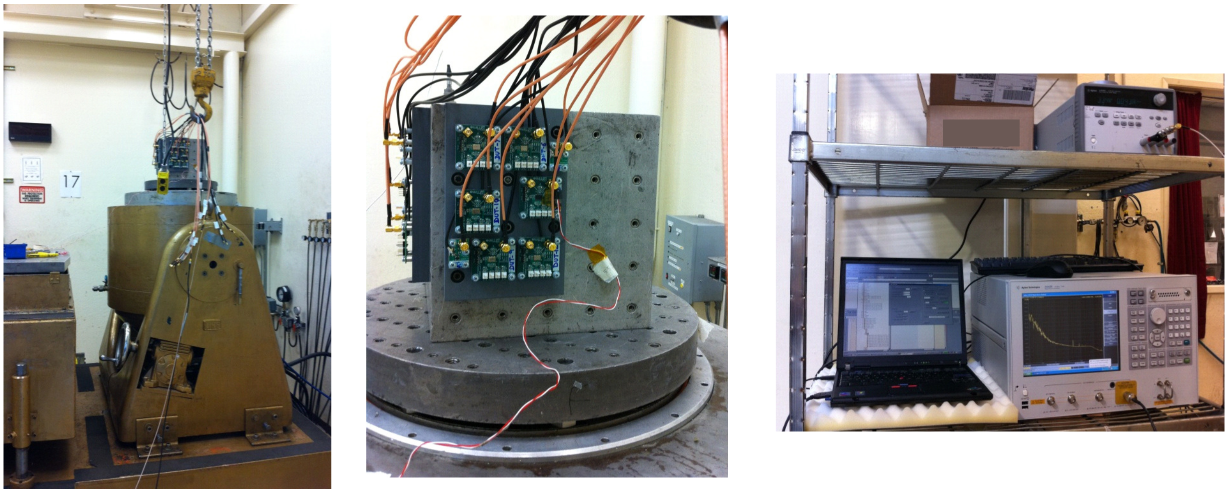


Figure 1. Sinusoidal and random vibration test setup



(a) (b) (c)

Figure 2. Photos of vibration testing equipment:
(a) shaker, (b) device mounting block, (c) phase noise analyzer

2.2 Random Vibration

Oscillators may experience random vibrations during use that have a frequency ranging from a few Hz to a few kHz. These vibrations increase broadband phase noise. Several standards specify test conditions for random vibration profiles that vary with the expected operating environment or type of electronic equipment tested [1]. We conducted tests according to MIL-STD-883H [2], Method 2026, because that standard is most applicable to electronic components. This standard specifies a vibration profile and allows for various intensity levels (see Figure 3). Condition B, with a composite power level of 7.5-g rms, is suitable for a high vibration mobile environment. The controller in the test setup of Figure 1 uses digital signal processing to synthesize random vibration in the specified frequency range, based on the power density level defined in the vibration profile.

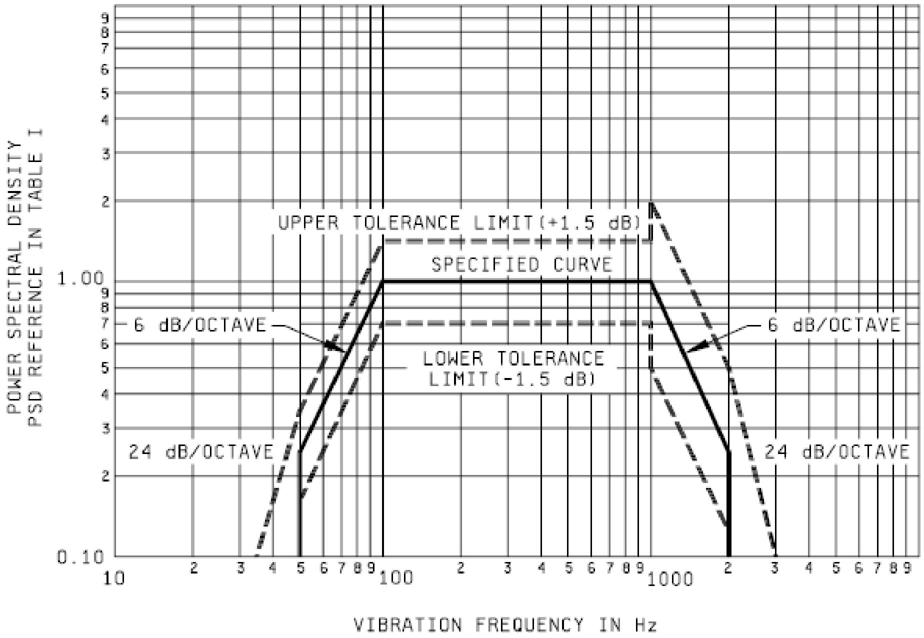


FIGURE 2026-1. Test condition I, random vibration test-curve envelope (see table I).

TABLE I. Values for test condition I. 1/

Characteristics		
Test condition letter	Power spectral density	Overall rms G
A	.02	5.2
B	.04	7.3
C	.06	9.0
D	.1	11.6
E	.2	16.4
F	.3	20.0
G	.4	23.1
H	.6	28.4
J	1.0	36.6
K	1.5	44.8

1/ For duration of test, see 4.

Figure 3. MIL-STD-883H specifications for random vibration testing [2]

Random vibration causes increases in phase noise at offsets corresponding to the vibration frequency. We measured phase noise with and without random vibration for each oscillator and calculated the values of integrated phase jitter from 15 Hz to 10 kHz. The induced jitter can then be derived from the root-mean-square difference between the two values.

2.3 Shock

The third test measured the transient frequency deviation during operation in response to shock impact. This test followed the specifications of MIL-STD-883H [2], Method 2002 and we monitored the transient frequency response to a 1 ms half sine wave shock pulse with an acceleration of 500-g.

The MIL-STD-883H [2], Method 2002 standard is widely adopted for testing quartz crystal oscillator survivability under mechanical shock in non-operational mode. Most of the commercially available quartz crystal oscillators are specified in the environmental qualification tests with levels of 100-g to 1500-g, while SiTime MEMS oscillators have achieved environmental qualification at 10,000-g to 50,000-g of mechanical shock.

The shock test setup is shown in Figures 4 and 5. Similar to the approach for vibration testing, we oriented the oscillators to apply shock in the x, y and z directions and measured the worst case. Frequency measurements taken every 100 µs continuously for 10 seconds provide data on frequency response before, during and after the shock impact.

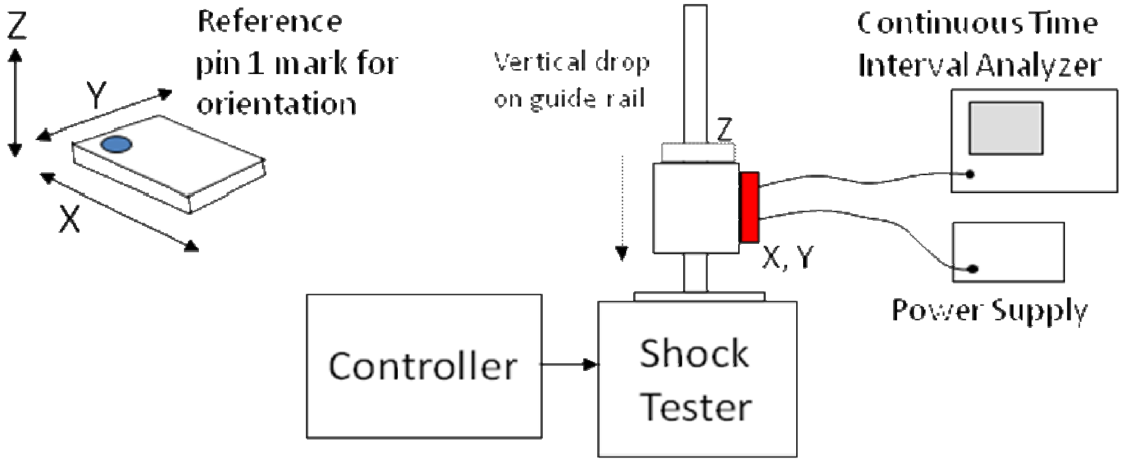


Figure 4. Mechanical shock test setup

(a) (b)

Figure 5. Photos of shock testing equipment: (a) shock tester and (b) mounting block

3 Experimental Results

3.1 Sinusoidal Vibration

Figure 6 presents the vibration sensitivity results for quartz, SAW and MEMS based differential oscillators subjected to sinusoidal vibration. The SiTime MEMS oscillator outperformed the other devices by a factor of 10 to 100. The other MEMS-based oscillator, MEMS 2, with a different resonator design and out-of-plane vibrating mode, showed vibration sensitivity that is similar to the quartz and SAW devices.

Single-ended oscillators are less sensitive to sinusoidal vibration, as shown by the data in Figure 7, and the difference between quartz and MEMS performance is not as dramatic. However, the SiTime device still outperformed the quartz-based oscillators in this study.

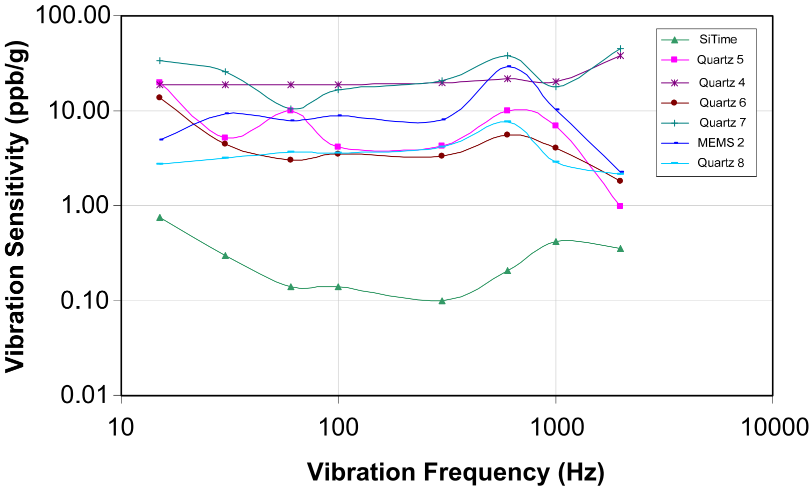


Figure 6. Differential oscillator sensitivity to sinusoidal vibration

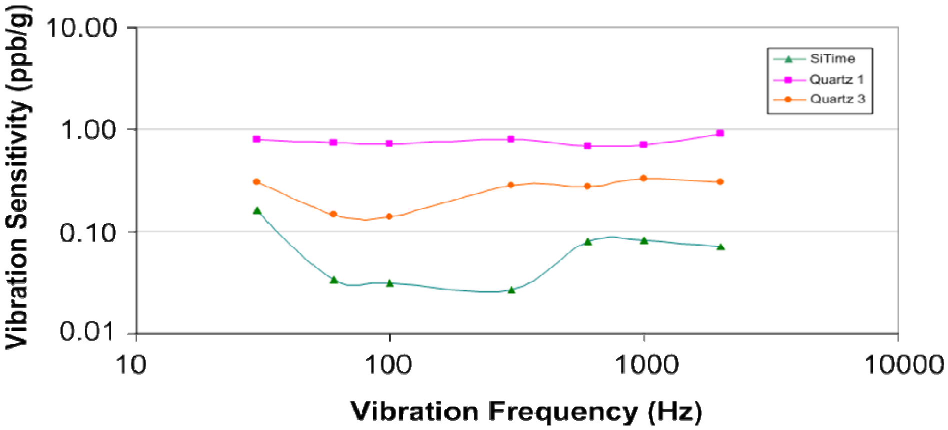


Figure 7. Single-ended oscillator sensitivity to sinusoidal vibration

3.2 Random Vibration

Random vibration induces phase noise at low offsets from the carrier frequency, as shown by the difference between the blue (no vibration) and red (with vibration) curves in Figure 8. Although the SiTime MEMS oscillator exhibits higher close-in phase noise when tested in a quiet environment, adding random vibration does not significantly increase the phase noise. In contrast, both SAW-based devices showed dramatic increase in phase noise under random vibration. This level of degradation can be detrimental to systems sensitive to close-in phase noise and shows how devices in real-world conditions may perform differently from datasheet specifications.

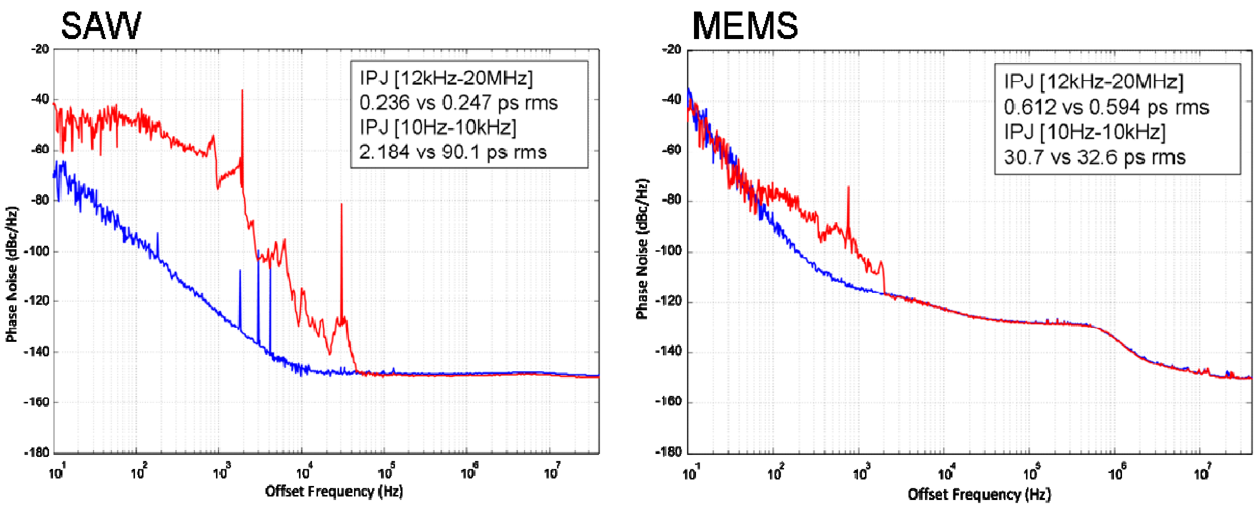


Figure 8. Phase noise under random vibration for SAW and SiTime MEMS oscillators

Results of induced jitter calculations for eight differential oscillators are shown in Figure 9. Even though many of these oscillators exhibit low phase noise when tested in a laboratory setting, it is important to consider the additional jitter induced by random vibration. Most of the oscillators tested exhibit significant increases in jitter, from nearly 20 to over 100 ps rms. In contrast, the SiTime MEMS oscillator is relatively immune to random vibration.

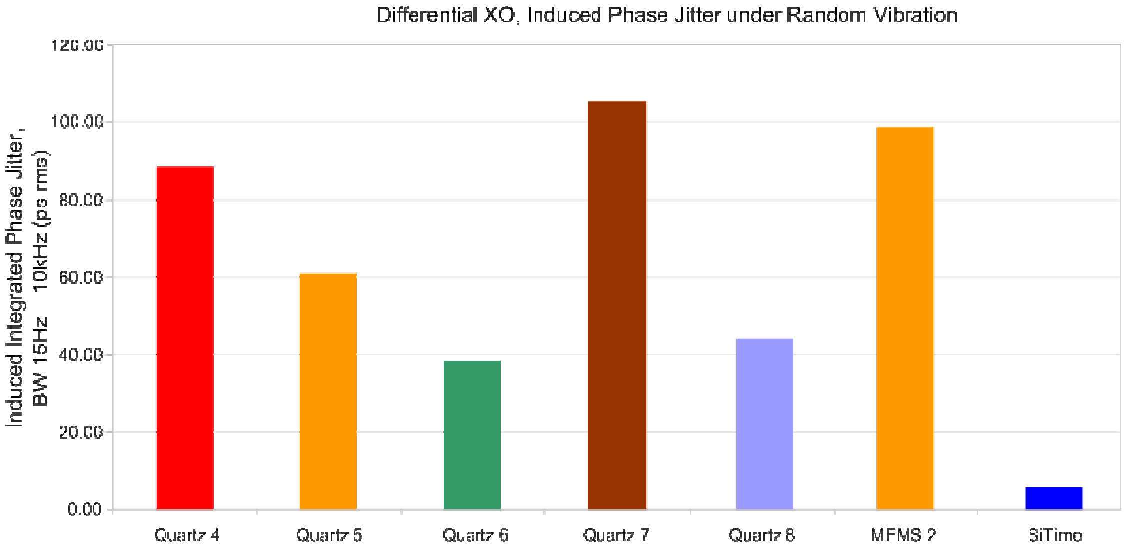


Figure 9. Induced phase jitter in differential oscillators

3.3 Shock

Overall results comparing the maximum transient frequency deviation in response to shock tests on differential oscillators are shown in Figure 10. The SAW devices (Quartz 4 and Quartz 7) are especially sensitive to shock, with over 10 ppm of transient frequency spike. Other quartz devices exhibited 2 to 7 ppm of peak frequency deviation. The only exception is the SiTime device, which demonstrated a transient frequency deviation of less than 1 ppm. Results on single-ended LVCMOS oscillators in Figure 11 confirm the shock resistance of SiTime MEMS oscillators.

The frequency stability vs. time charts recorded in the experiments are shown in Figure 12 for all eight differential devices tested. Traces representing shock pulses applied in the x, y or z directions are superimposed on the same scale to show the effect of direction on shock resistance.

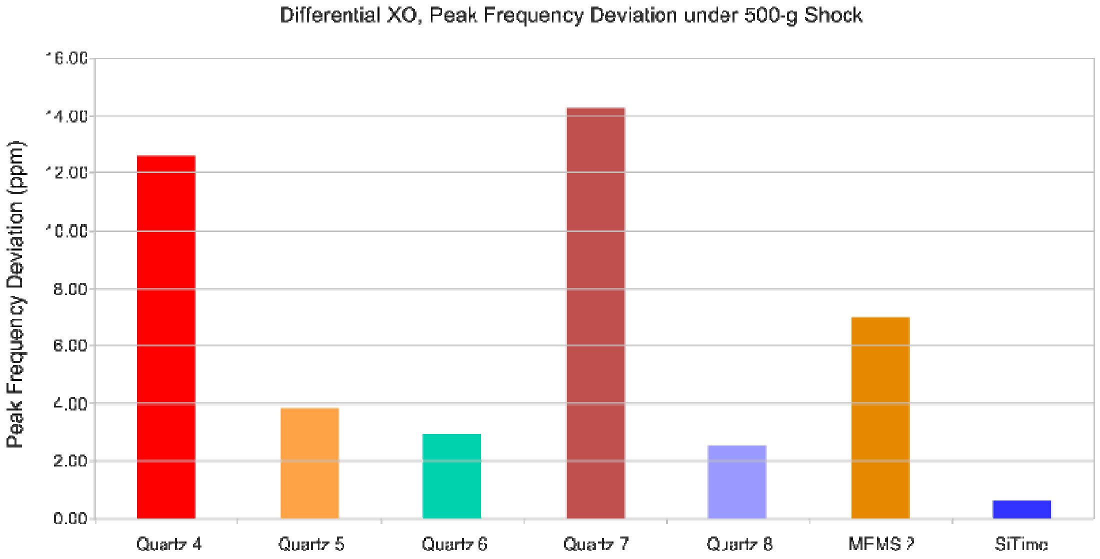


Figure 10. Shock test results for differential oscillators

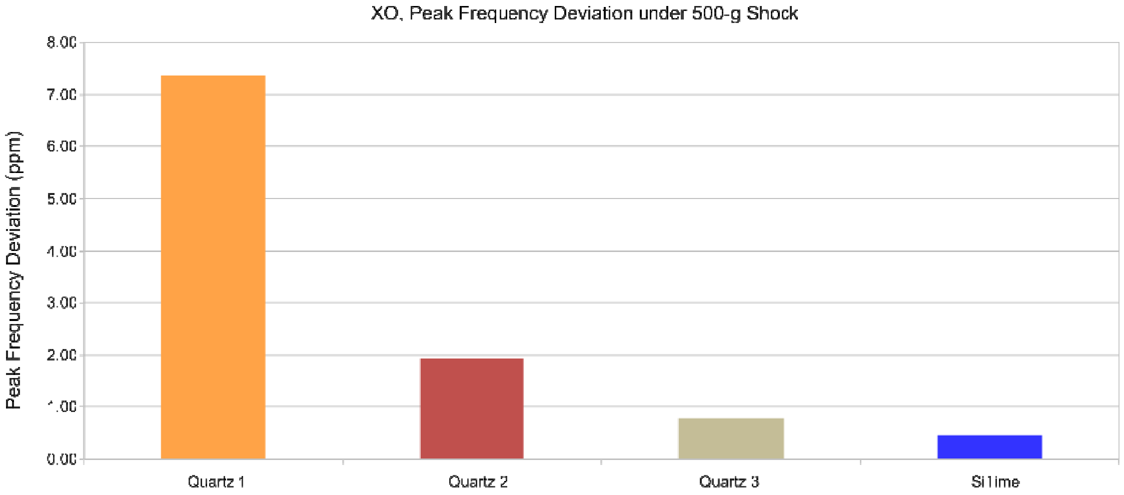


Figure 11. Shock test results for single-ended oscillators

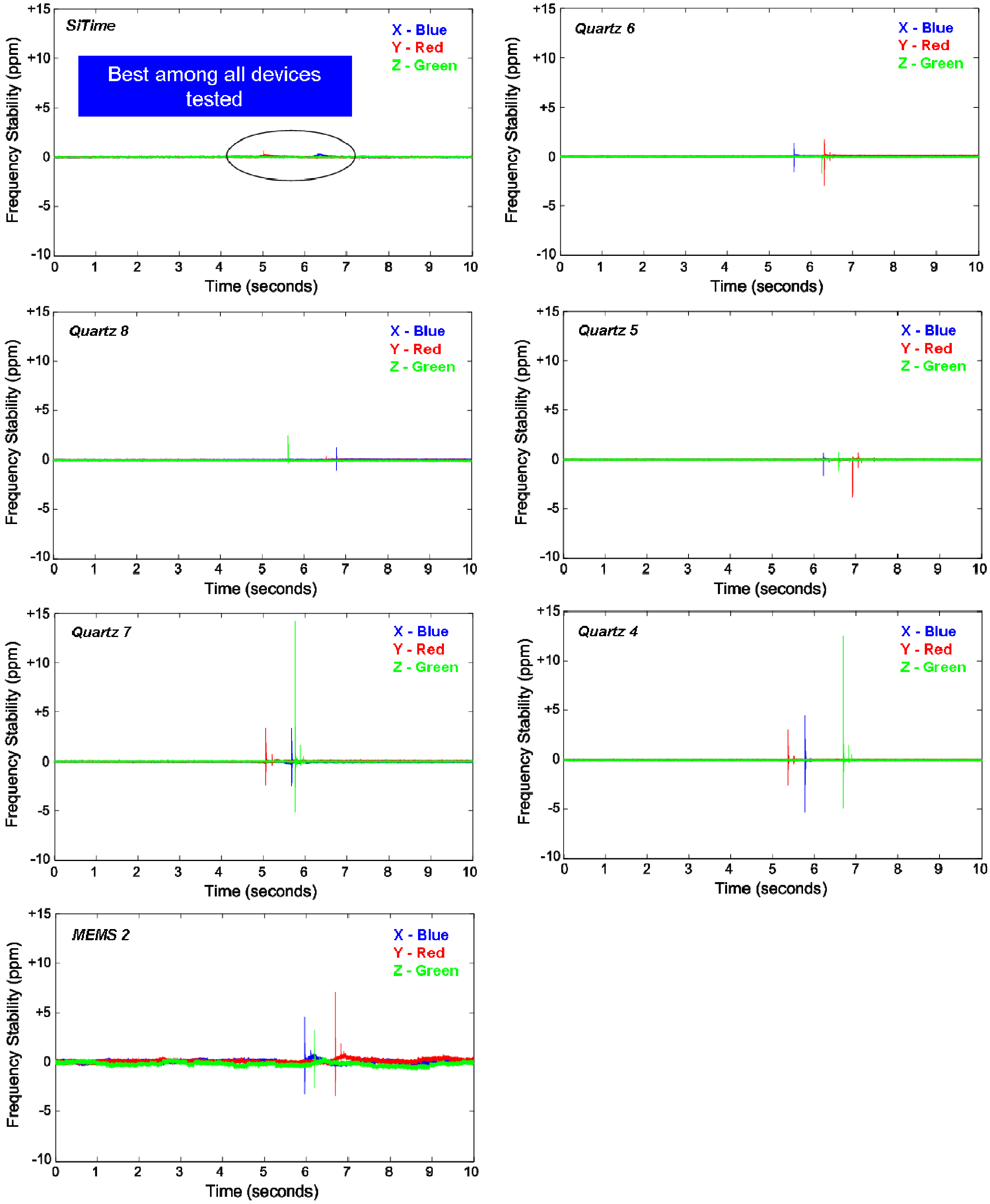


Figure 12. Frequency stability during shock testing of differential oscillators

4 Conclusions

Electronic components that perform well in a laboratory environment may not exhibit the same performance in real-world conditions where shock and vibration are present. SiTime MEMS oscillators have achieved very high quality and environmental reliability ratings on survivability to shock and vibration. Now, experimental data on phase noise and jitters measurement in shock and vibration tests demonstrate that SiTime MEMS oscillators can not only survive but perform extremely well under these conditions. This resistance to mechanical shock and vibration is a result of fundamental advance in MEMS device technologies and SiTime's proprietary design of MEMS resonator and analog circuit for the precision oscillators.

5 References

[1] J. R. Vig, "Chapter 4: Oscillator Stability" in *Quartz Crystal Resonators and Oscillators For Frequency Control and Timing Applications - A Tutorial*, Tech. Rep. SLCET-TR-88-1 Rev. 8.5.2.2, AD-M001251, March 2004.

[2] *Department of Defense Test Method Standard: Microcircuits*, MIL-STD-883H, U.S. Defense Logistics Agency, 2010.

[3] *Environmental Conditions and Test Procedures for Airborne Equipment*, DO-160G, RCTA, Inc. 2010.

[4] *NEBS Requirements: Physical Protection*, GR-63. Telcordia, 2012.

[5] *Payload Vibroacoustic Test Criteria*, NASA-STD-7001, Rev. A, NASA, 2011.

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