
Resilience and Reliability of Silicon MEMS Oscillators

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1 Introduction

Oscillators have historically been made from quartz crystal resonators connected to an analog sustaining circuit that drives the resonator to vibrate at a specific frequency. Now, there is an alternative – Silicon MEMS oscillators – and these devices outperform quartz oscillators in noisy environments. The drive toward higher speed telecom and mobile applications places greater demands on the clock source. Additionally, more complex electronics and higher clock frequencies necessitate that the clock device continue to perform well in noisy environments. This paper shows results of comparative experiments that were conducted on quartz and Silicon MEMS oscillators. The data demonstrate that MEMS oscillators outperform quartz in realistic environmental conditions.

Oscillator vendors provide data sheets for each product stating performance parameters such as frequency stability, jitter, and phase noise. While data sheets are a good indicator for selection of timing devices, the user must also evaluate how these devices perform in real-life environmental conditions. Testing under conditions that mimic those seen in the real operating environment provides valuable information about true component performance. The performance of oscillators subjected to environmental stressors, such as electromagnetic interference (EMI), vibration, and noise from power supplies or other system components, will degrade as compared to oscillators in ideal conditions. Ultimately, environmental stressors may reduce the reliability and lifetime of a device. It is important to consider the performance of oscillators under realistic, noisy, harsh conditions when selecting a timing device.

2 Silicon MEMS Advantages

Silicon MEMS oscillators have some inherent advantages over quartz oscillators that allow them to perform reliably in a variety of environments. SiTime developed the MEMSFirst™ process, in which resonators are fully encapsulated in silicon and enclosed within a micro-vacuum chamber [1]. The combination of very small mass of the resonator and its stiff silicon crystal structure makes them durable and extremely resistant to external stresses such as shock and vibration. Additionally, optimally designed analog circuits in the oscillator deliver high performance in electrically noisy conditions.

The schematic of MEMS oscillator architecture in figure 1 shows the key components that contribute to performance and reliability, including a finely tuned silicon MEMS resonator, oscillator sustaining circuit, high precision fractional-N phase locked loop (PLL), and drivers with fully differential circuits.

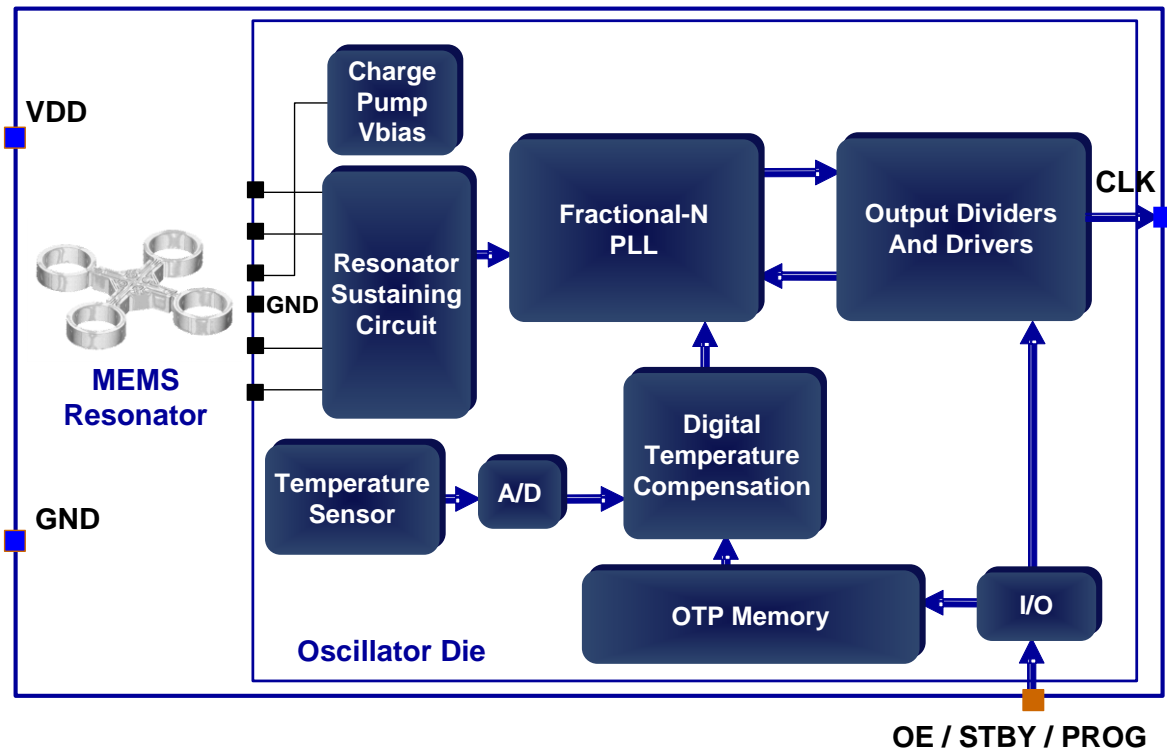


Figure 1. SiTime MEMS oscillator architecture

Most quartz oscillator vendors are experts in manufacturing resonators, but not necessarily in circuit design. They usually outsource the analog circuit and must purchase die that are designed to work with a variety of crystals rather than being optimized for the specific resonator. In contrast, SiTime has a world-class team of analog designers who design all the circuits that are used with SiTime's MEMS oscillators. Since 2006, this team has made dramatic improvements in performance and resilience of SiTime's oscillator products with the result that SiTime's MEMS oscillators are more resilient than quartz devices in noisy environmental conditions.

3 Environmental Stressors

Several factors in the operating environment can negatively impact oscillator performance, degrading phase noise and jitter. Taking each in turn, this paper will compare the effect of environmental conditions on the performance of oscillators produced by SiTime and competing manufacturers.

3.1 Power Supply Noise

One major source of noise in any system comes from power supplies. Most of this noise is filtered out by passive filters and decoupling capacitors that are placed on the power supply input of the oscillator. However, some noise remains, which may increase the jitter on the output clock, and can negatively impact system timing margins. This noise is amplified not only when the power supply itself is switched on, but when other devices on the board turn on or off during system operation. On-board issues, such as inadequate power supply filtering or ground bounce, also affect noise and jitter. The Power Supply Rejection Ratio (PSRR) is a specific parameter that is used in the design of analog circuits and provides an indication of how robust a circuit is to noise from the power supply. Unlike PSRR which is a SNR related parameter expressed in dB, oscillator performance under noisy power supply conditions is expressed by the Power Supply Noise Sensitivity (PSNS) metric. PSNS is quantified in terms of the induced phase jitter exhibited by the oscillator when subjected to a controlled peak-to-peak noise injection at specific frequencies in the range of 20 kHz to 20 MHz.

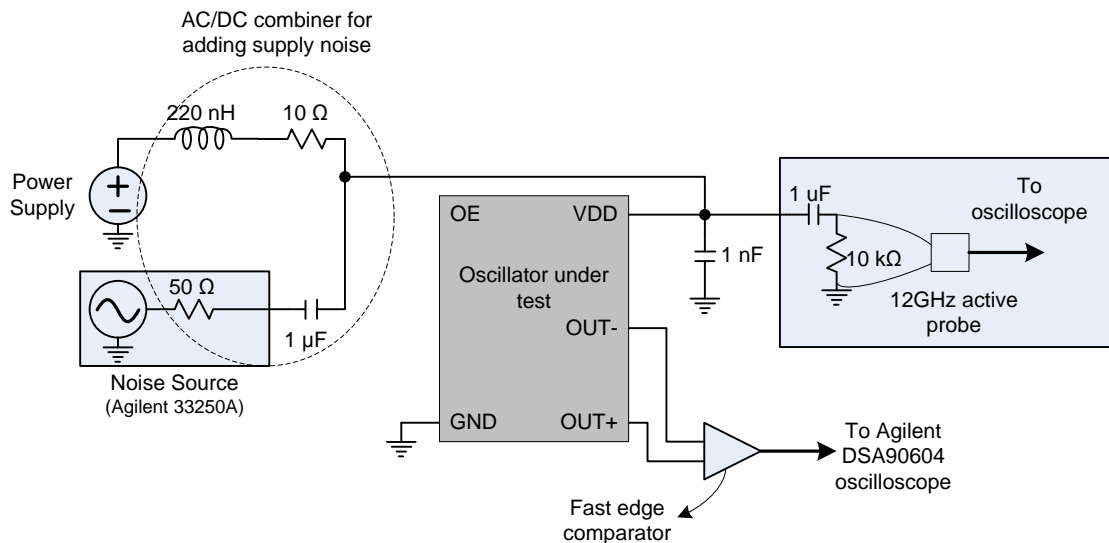


Figure 2. Block diagram for power supply noise rejection test set-up

A test setup that includes a power supply and waveform generator, as shown in figure 2, is a controlled test method to evaluate the PSNS performance of oscillators. The waveform generator adds system noise at a specified voltage and frequency to measure the effect of power supply noise on the oscillator jitter. The plot in Figure 3 shows integrated phase jitter as a function of power supply switching noise frequency for 50mV of peak-peak power supply

noise, comparing results across various quartz oscillators with those of a SiTime MEMS oscillator for LVCMOS outputs. As the plots indicate, SiTime's MEMS oscillator jitter is lower across all noise frequencies. The reason for this is noise-reducing circuits built into SiTime's oscillator circuitry to protect the oscillator from power supply-induced jitter.

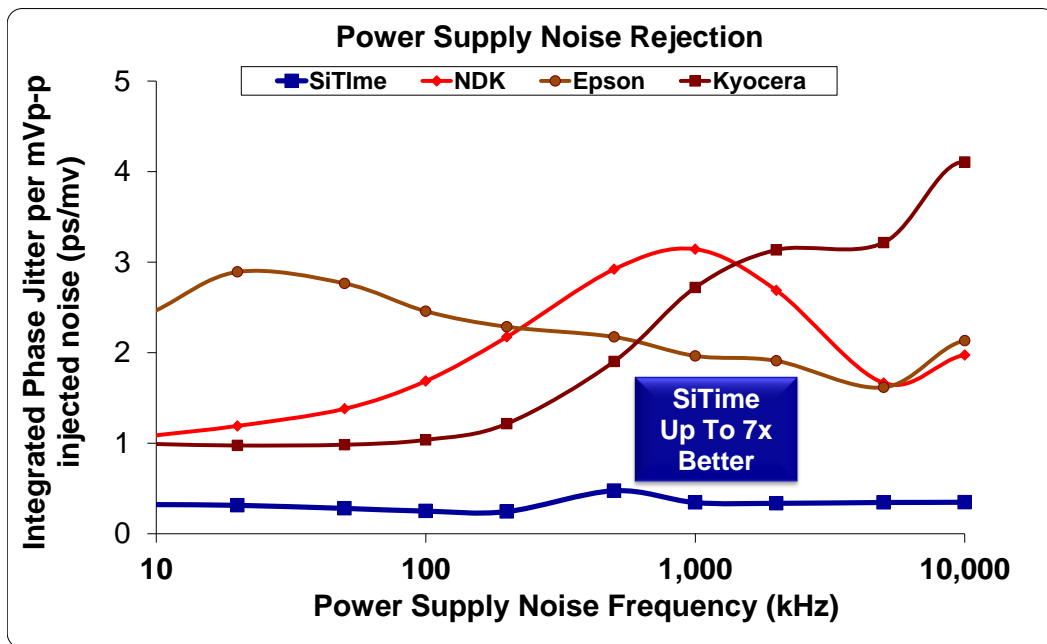


Figure 3. Phase jitter in the presence of 50 mV power supply noise for SiTime MEMS and Epson SAW oscillators as a function of power supply switching noise frequency

3.2 External EMI Noise

Another important noise source to consider is externally generated EMI noise that impacts the oscillator performance (as opposed to EMI signals that are emitted by a clock source). Power supplies, power lines, lightning, computer equipment, and electronic components are all potential sources of externally generated EMI, which can be coupled into the system through radiation. EMI is a major concern in applications such as passive optical networks (PON), cellular base stations and many products that are used in outdoor environments where large electromagnetic sources are present. EMI is also a concern in dense electronic boards with multiple switching power supplies, since oscillator components can be placed close to these power supplies. Inbound EMI can change the clock jitter and, in catastrophic cases, even the operating frequency of clock devices, negatively impacting the functioning of any system that

depends on the clock signal for reliable performance. Phase jitter and phase noise increase significantly in the presence of incoming EMI, and attempts to filter out the noise reaching the oscillator are not always successful. Another approach is to design clock devices that successfully reject EMI. Electromagnetic susceptibility, or EMS, quantifies the detrimental impact of EMI on electronic circuits such as oscillators.

EMS can be measured by following the procedure specified in EMC standard IEC EN61000-4.3. This standard specifies a radiated electromagnetic (EM) field of 3V/m across a frequency range of 80 MHz to 1 GHz in 1% incremental steps. The device under test is located in a calibrated anechoic chamber and positioned so that it is aligned with the axis of the vertically polarized antenna, as shown in figure 4. The phase noise analyzer and high precision, low noise digital signal analyzer capture the oscillator phase noise. The electromagnetic field induces noise spurs, and the average power of the spurs provides a measure of the EMS of the oscillator.

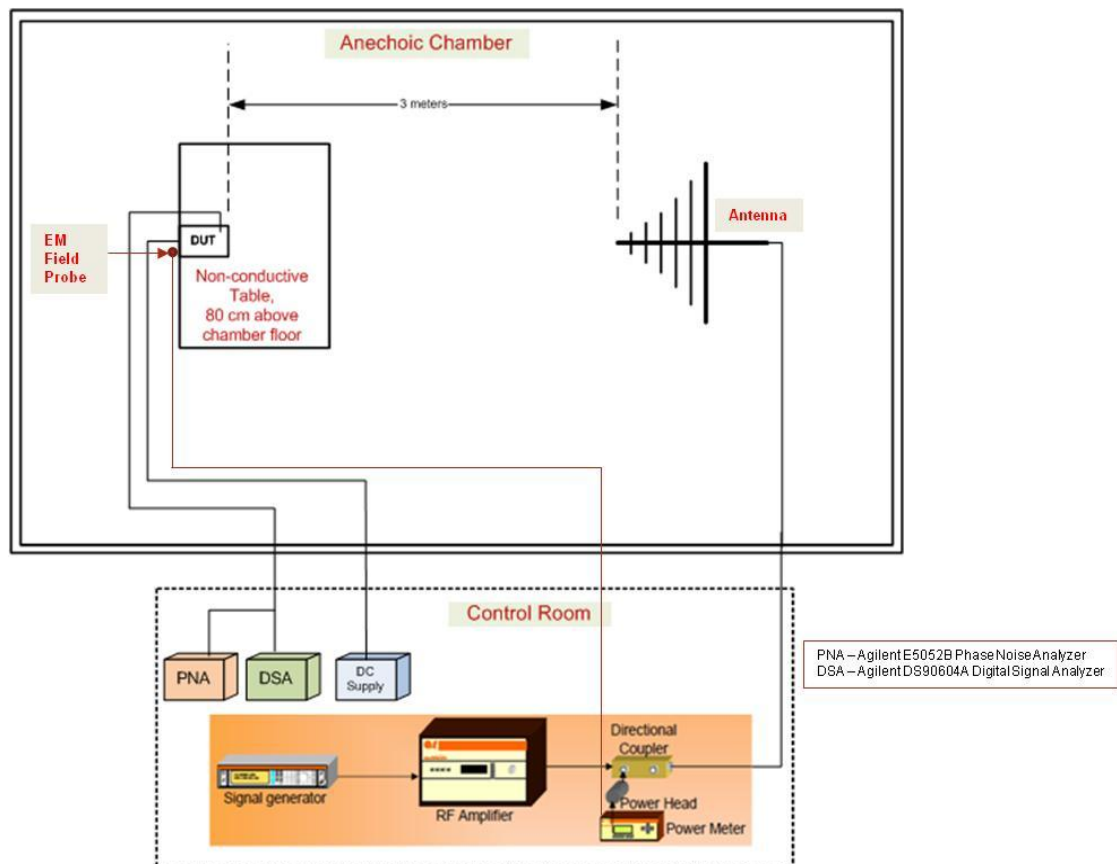


Figure 4. Setup for EMS Testing

Data on multiple quartz and MEMS oscillators illustrate the effect of EMI on both differential and single-ended oscillators (Figures 5 and 6). SiTime MEMS oscillators outperform competing quartz- and MEMS-based oscillators by a considerable margin. These results emphasize the importance of understanding the relationship between performance and operating environment.

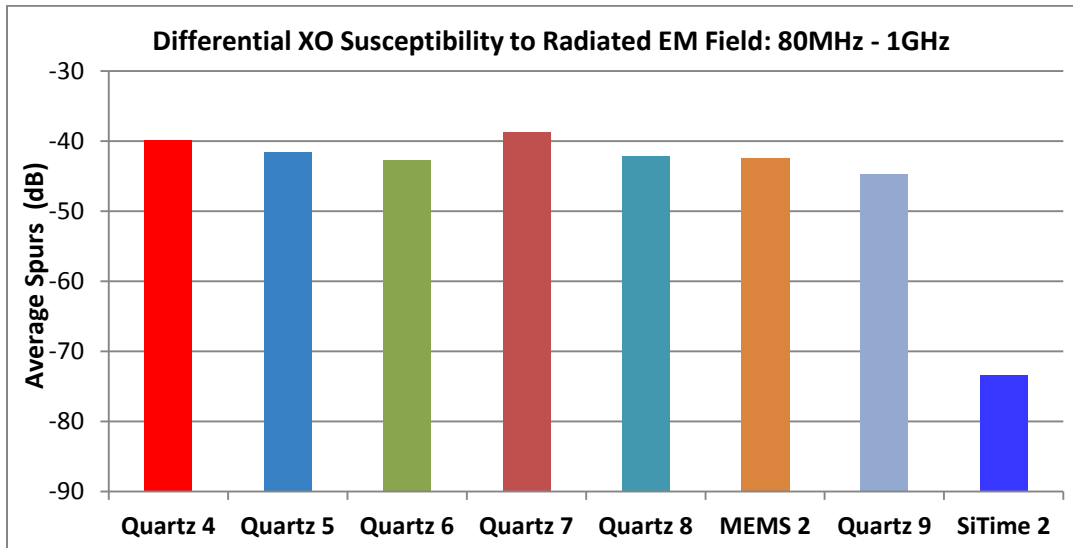


Figure 5. Average level of EMI-induced phase noise spurs on 156.25MHz LVPECL differential clock oscillators

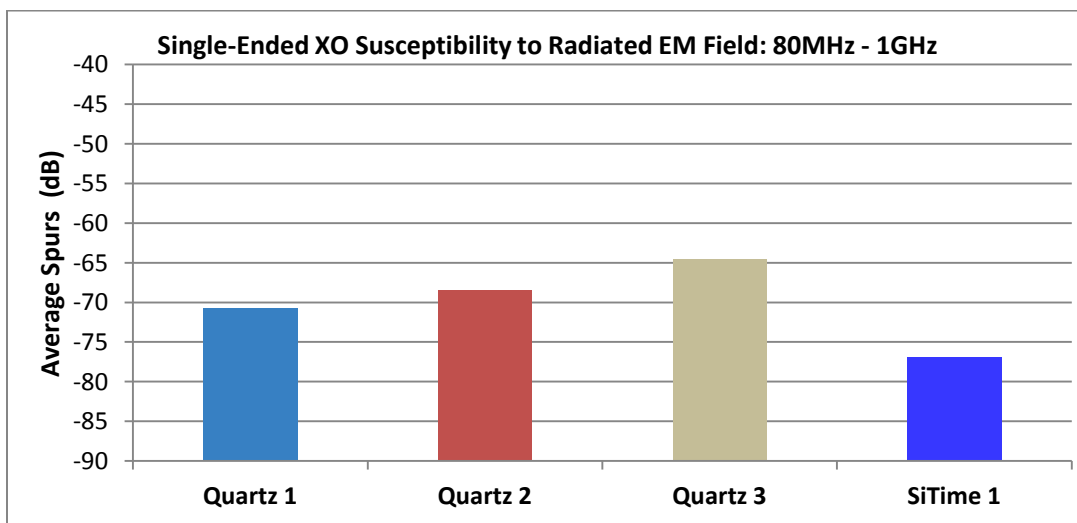


Figure 6. Average level of EMI-induced phase noise spurs on 26 MHz single-ended oscillators

3.3 Shock and Vibration

Many electronic products are subjected to substantial vibrational forces during use. This is especially true of mobile, portable devices carried around in pockets or backpacks. Electronics in mobile GPS units, industrial equipment, or aerospace applications may undergo higher levels of vibration. Even stationary products may experience vibration from a nearby fan or other equipment.

Quartz oscillators may show significant sensitivity to vibration because of the mechanical assembly and packaging used. SiTime's MEMS First™ technology [1] produces MEMS resonators that are inherently more resistant to vibration-induced performance degradation for two reasons. First, the moving section of the silicon resonator has much smaller mass than a quartz resonator. This reduces the force applied to the resonator from the vibration-induced acceleration. Second, the silicon MEMS resonators are very stiff structures that vibrate in-plane and are therefore resistant to movement caused by vibration forces.

Vibration can degrade oscillator performance by inducing an electrical signature at the same frequency as the mechanical vibration, causing frequency spikes or increased phase jitter or broadband noise. Mechanical forces may also damage the physical resonator structure. Because oscillator response depends on the direction, severity and frequency of external mechanical forces, looking at results from several different types of tests gives the most complete picture of the resiliency of an oscillator.

The first test is evaluating the response to sinusoidal vibration by observing spurious phase noise, or noise spurs, occurring at a specific frequency. This phase noise is translated into a frequency modulated (FM) noise and normalized to the carrier frequency for 1g vibration acceleration. The result is expressed in part-per-billion/g (ppb/g) as a function of vibration frequency. The measurement setup includes a controller, power amplifier and shakers.

Sinusoidal vibration tests included vibration frequencies ranging from 15 Hz to 2 kHz with a peak acceleration of 4g, representative of vibration forces that oscillators would experience in the field. Oscillators were subjected to vibration in the x, y and z axes, and results reported are the highest observed noise response for the three directions.

Figure 7 presents vibration sensitivity results for quartz-, SAW- and MEMS-based differential oscillators. MEMS1, which is an in-plane vibrating oscillator from SiTime, outperformed the other devices by a factor of 10 to 100. The other MEMS-based oscillator, MEMS2, vibrates out-of-plane, which probably explains why its sensitivity was similar to the quartz and SAW devices.

Single-ended oscillators are less sensitive to sinusoidal vibration, as shown by the data in figure 8, and the difference between quartz and MEMS performance is not as dramatic. SiTime's device outperformed the competing quartz-based oscillators.

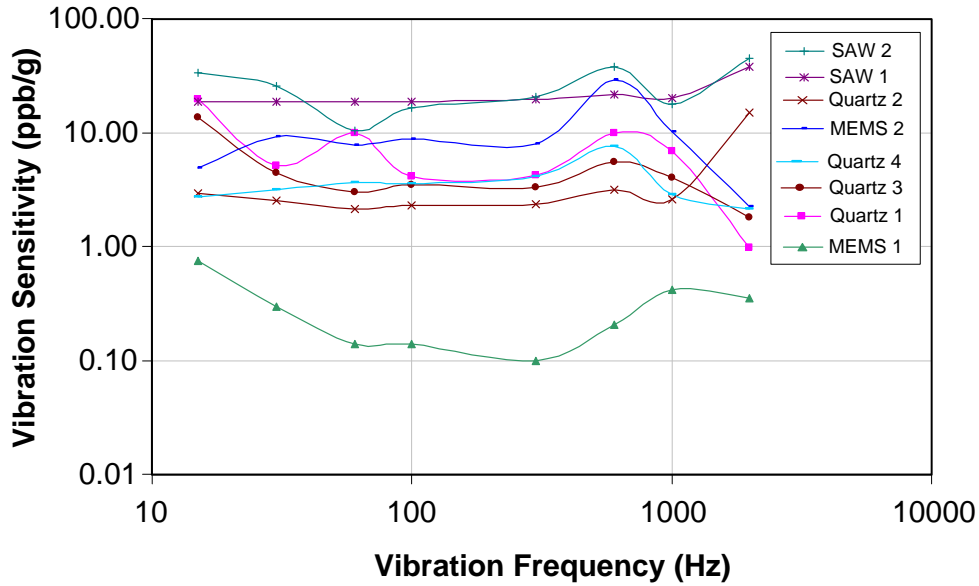


Figure 7. Differential XO maximum vibration sensitivity vs. frequency under 4g peak acceleration sinusoidal vibration in X, Y, or Z axis n

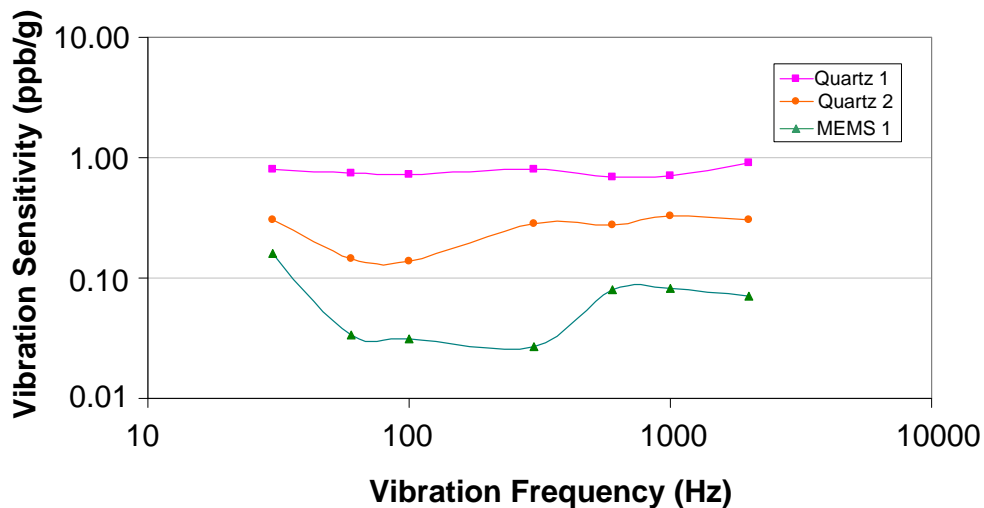


Figure 8. Single-ended XO maximum vibration sensitivity vs. frequency under 4g peak acceleration sinusoidal vibration in X, Y, or Z axis

The second vibration test generates random vibration at an acceleration of 7.5-g rms, as defined by MIL-STD 883F, which simulates a harsh operating environment. Results are reported in terms of induced phase jitter in the time domain, calculated by integrating the induced phase noise over 15 Hz to 10 kHz offset frequency. The data (see figure 9) show a wide range of responses. The SiTime MEMS oscillator outperforms all the other devices, showing that it is relatively immune to random vibration.

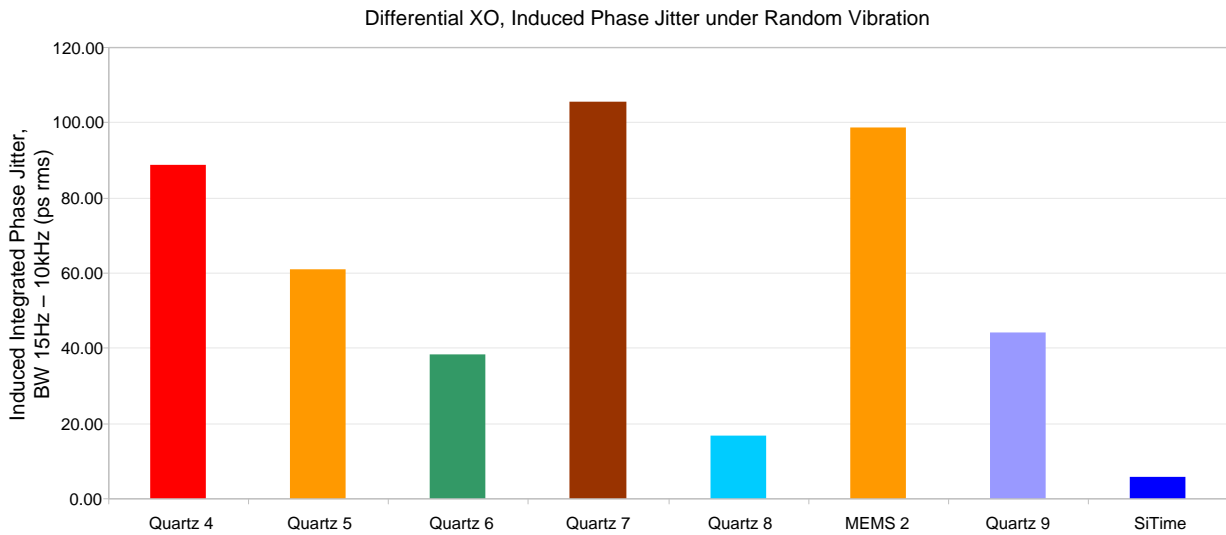


Figure 9. Differential oscillator phase jitter induced by random vibration

SiTime MEMS oscillators are also insensitive to shock impact, the third test of resistance to mechanical force. Sudden shock tends to cause transient deviations in oscillator frequency. SiTime measured the response of quartz- and MEMS-based oscillators to a 1 ms half sine wave shock pulse with an acceleration of 500 g. Results in figure 10 show that while most devices exhibit significant frequency deviation, the frequency of the SiTime MEMS deviates by less than 1 ppm.

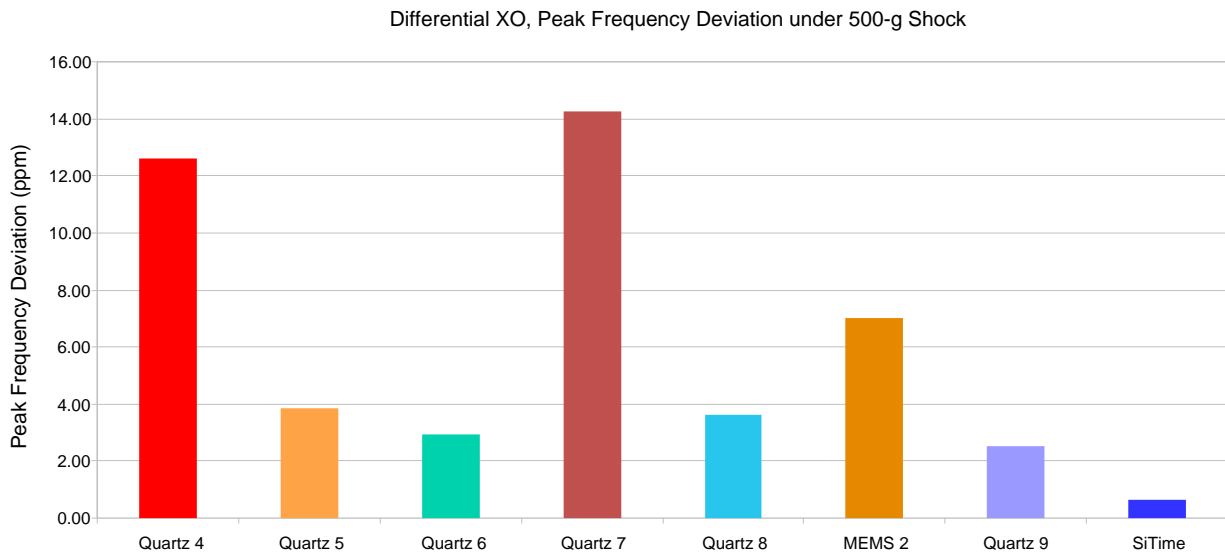


Figure 10. Response of differential oscillators to 500-g shock

4 Reliability

One method of quantifying the reliability of a component is predicting mean time between failure (MTBF). For semiconductor components, this is the inverse of the failures in time (FIT) rate, expressed as the number of failures statistically expected after 1 billion operating hours. The higher the MTBF, the longer the expected lifetime of the device and therefore the more reliable the device. Low values of FIT rate indicate a low number of expected failures and high reliability.

SiTime calculates FIT by subjecting oscillators to stress testing at elevated temperature and voltage for an extended period of time. Stressing thousands of oscillators for cumulative test time of over two million device hours resulted in no failures. Based on these results, SiTime's MEMS oscillators have a calculated reliability rate of less than 2 FIT, corresponding to a MTBF of at least 500 million hours. For details on methods to calculate FIT rate and MTBF, see "[Reliability Calculations for SiTime Oscillators.](#)"

Figure 11 includes reported MTBF for oscillators from various manufacturers, showing that semiconductor-based oscillators as a class are more reliable than quartz oscillators and that SiTime's products are a factor of two more reliable than the nearest competitor and over 10 times better than the most reliable quartz oscillators.

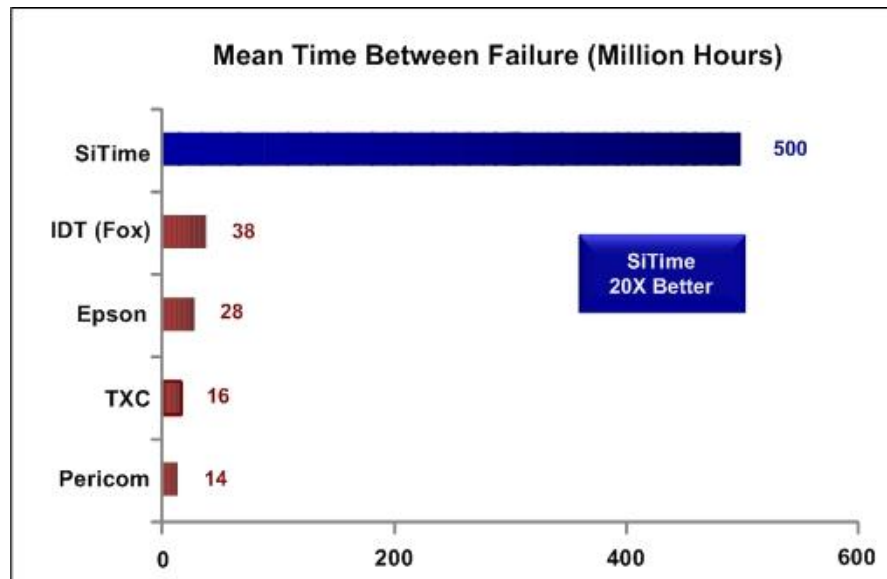


Figure 11. Reliability of quartz- and semiconductor-based oscillators in terms of MTBF

5 Summary

It is important to consider oscillator performance in real-world conditions in order to truly understand device capabilities. Actual operating conditions often include the presence of power supply noise, external EMI, vibration and shock. Testing under these conditions demonstrates the advantages of SiTime MEMS oscillators as compared to competing quartz and semiconductor-based devices. SiTime outperforms the competition in all four categories considered.

- Power supply noise: SiTime 7x better than quartz
- Susceptibility to EMI noise: SiTime up to 50x better than competitors
- Vibration: up to 40x better than quartz
- Reliability: 2x better than MEMS competitors, up to 40x better than quartz

Environmental stresses such as external sources of noise and vibration can adversely affect the resilience, performance and reliability of clock devices. The silicon MEMS oscillators produced by SiTime are resilient in the face of environmental conditions ranging from typical to extremely challenging, maintaining phase noise and jitter specifications and exhibiting long-term reliability in a variety of operating environments.

6 References

- [1] SiTime Corp., “*SiTime’s MEMS First Process*”, Application Note 20001,
http://www.sitime.com/support2/documents/AN20001_MEMS_First_Process.pdf.
- [2] SiTime Corp., “*Reliability Calculations for SiTime Oscillators*”, Application Note 10025,
<http://www.sitime.com/images/stories/applications/SiTime-Reliability-AN10025-Rev1.0.pdf>

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