Application Note

Standalone BAW Oscillators Advantages Over Quartz Oscillators

TEXAS INSTRUMENTS

Clock and Timing Solutions

ABSTRACT

This application report details TI's BAW technology, the integration of a BAW resonator with oscillator circuitry to make a standalone oscillator, and the advantages of using a BAW oscillator over a quartz oscillator. The key advantages of the BAW oscillator over a quartz oscillator include: increased flexibility, improved temperature stability, improved jitter performance, increased power supply noise immunity, significantly better vibration stability, and significantly better shock performance.

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1 Introduction

Quartz crystal oscillators (XOs) have dominated the timing reference market for over a century since the invention in the 1920s. These crystal oscillators have found utility in a wide range of products from low-end (real-time clock) to high-end (complex radio, GPS, and military/aero) applications. In the past few decades, mobile communication and the emerging internet-of-things (IoT) markets have driven the search for new resonator technologies that consume lower power, with smaller form factor, for ease of integration, while maintaining similar or better performances than quartz crystals. A few standalone oscillator products utilizing different types of micro-resonator technologies have been released to the consumer market in the past decade. Texas Instruments started the development of its own bulk acoustic wave (BAW) resonator technology aiming for advanced timing applications since 2012 and has released a few system products including industry's best performance jitter cleaner (LMK05318 family) and world's first commercialized crystal-less BLE radio (CC2652RB family) since 2018. Using the mass production experience of these devices, TI is now launching the BAW-based standalone oscillator products.

2 BAW Technology Overview

TI's BAW resonator technology utilizes piezoelectric transduction to generate high-Q resonance at 2.5 GHz. The resonator is defined by the quadrilateral area overlaid by top and bottom electrodes. Alternating high- and low-acoustic impedance layers form acoustic mirrors beneath the resonant body to prevent acoustic energy leakage into the substrate. Furthermore, these acoustic mirrors are also placed on top of the resonator stack to protect the device from contamination and minimize energy leakage into the package materials. This unique dual-Bragg acoustic resonator (DBAR) allows efficient excitation without the need of costly vacuum cavities around the resonator. As a result, TI's BAW resonator is immune to frequency drift caused by adsorption of surface contaminants and can be directly placed in a non-hermetic plastic package with the oscillator circuitry in standard oscillator footprints (3.2 mm × 2.5 mm and 2.5 mm × 2.0 mm).

3 BAW Oscillator Integration

The LMK6C/D/P/H contains a BAW resonator, Fractional Output Divider (FOD), and output driver, which together generate a pre-programmed output frequency. Temperature variations of oscillation frequency are continuously monitored by an internal precision temperature sensor and is provided as an input to the Frequency Control Logic block. Using this Frequency Control Logic block, frequency corrections are performed internally for maintaining the output frequency within ±25 ppm across temperature range and aging. The output driver is capable of providing both single-ended LVCMOS and differential LVPECL, LVDS, and HCSL output formats. The device also contains an internal LDO which reduces the power supply noise, resulting in low noise clock output.

Figure 3-1 shows the pre-mold integration of the BAW oscillator. The BAW oscillator contains a base die which includes the additional IC circuitry such as the FOD, LDO, and temperature sensor and the BAW resonator die. The WLP (wafer-level package) is utilized to increase device reliability in terms of vibration and shock immunity as well as further stress isolation.

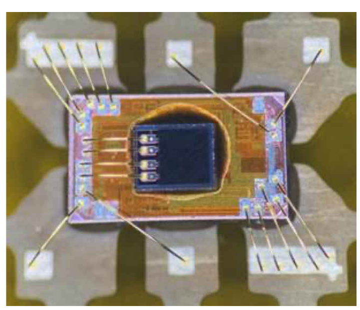

Figure 3-1. BAW and Base Die Integration

The results are a simple 4 pin (single ended LVCMOS) or 6 pin (differential, LVPECL, LVDS, HCSL) industry standard 3.2 mm × 2.5 mm or 2.5 mm × 2.0 mm packages that are pin to pin compatible to the alternatives allowing for drop in replacement.

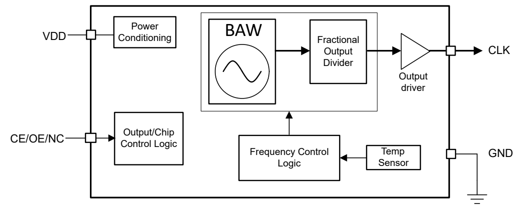

Figure 3-2. LMK6C/D/P/H BAW Oscillator Block Diagram

4 Crystal Oscillators

Quartz resonators are integrated in two different manners to make a standalone oscillator device; with each method presenting their own benefits and disadvantages. The first method, is to combine the crystal resonator with the oscillation circuitry and simply add the output driver to support different output types – this is usually called an SPXO, simple packaged oscillator.

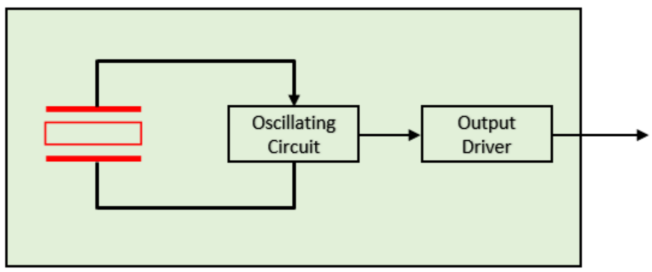

Figure 4-1. SPXO Crystal Oscillator Block Diagram

While this can be an elegant solution and present simplicity, small package, and quick start up time (as there is no calibration), it is very limited in frequencies it can support. The frequency support is purely dependent on the quartz crystal that is used. To support a different output frequency, a different crystal needs to have been assembled in the package as there is no capability to changed that post assembly. Furthermore, as the crystal resonator frequency is inversely proportional to the thickness of the crystal, that makes a crystal resonator operating at the fundamental frequency above ~50 MHz rare as they are extremely difficult to handle and manufacture. A more likely solution is to operate at an odd overtone of the fundamental, for example third-order overtone, meaning it’s operating at 3 times the fundamental frequency. When a crystal operates at the 3rd overtone, its resistance is about 3 times that of the fundamental, while it’s capacitance its almost nine times less – both changes which greatly impact the Q and the ability to tune the crystal.

Another method for crystal integration, is to use the crystal as the reference to a PLL loop with a VCO operating at a much higher frequency (usually in GHz). From this GHz frequency then a simple divider and output driver can provide the specific output frequency needed at the specific output type. A fractional engine can be added, either in the PLL or the output divider, to increase the number of frequencies supported with single IC. These crystal oscillators will have some communication protocol (I2C or SPI) for simple register programming.

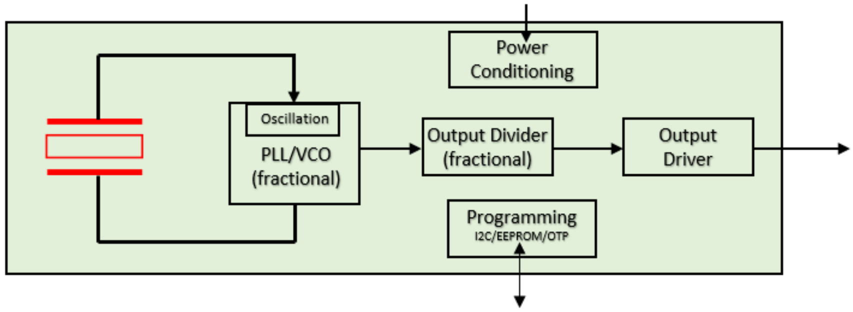

Figure 4-2. Crystal Oscillator with PLL Block Diagram

While this is a more robust and flexible solution with one silicon having capability to support all frequencies, it has some drawbacks. Generally speaking because more core blocks are required (PLL, divider, etc.) this will lead to a larger package size (5 mm × 3.2mm, 7mm × 5mm) and higher current consumption (100+ mA). Lastly, the PLL calibration and lock will cause a slower start up time usually at or above 10 ms.

The cost of de-risking supply constraints, one silicon supporting all potential frequencies through different programming, is clear when it comes to size, power, and startup time.

5 Summary Comparison Between LMK6C/D/P/H BAW Oscillator and Quartz Oscillator

Table 5-1. LMK6C/D/P/H BAW Oscillator Key Specification Comparison to Quartz Oscillators

Parameter	LMK6C/D/P/H BAW Oscillator Specifications and Details	Quartz Oscillator Specifications and Details	BAW Benefits Over Quartz	Advantage
Flexibility	One BAW die + One base die (Singe IC solution to support any frequency, voltage supply, pin to pin compatible)	Frequency limitations	Alleviates supply constraints, single IC supports all frequencies	BAW Oscillator
Temperature Stability	±10 ppm (Maintains temperature stability irrelevant of temperature range)	As temperature increases so does ppm stability	Tighter stability at extended temperature	BAW Oscillator
Jitter **BW 12 kHz–20 MHz**	125 fs max (LVDS, LVPECL, HCSL) 500 fs max (LVCMOS)	High end performs similar to BAW	BAW matches well with top end of the Quartz market	Similar
Power Supply Noise Immunity	-70 dBc (Peak spur due to 50 mV injection on 3.3 V power supply from 50 kHz to 1 MHz) (**Integrated LDO**)	Typically has no integrated LDO	No external LDO or DC/DC converter required to optimize performance	BAW Oscillator
Vibration	MIL_STD_883F Method 2002 Condition A (In addition to MIL standard, the BAW oscillator has a typical vibration stability of ~1 ppb/g. This results in minimal phase noise impact due to vibration.)	Typically does not pass MIL-STD. Can be as high as 10+ ppb/g.	Minimal impact from environmental effects	BAW Oscillator
Shock	MIL_STD_883F Method 2007 Condition B (In addition to MIL standard, can withstand much higher shock levels)	Typically does not pass MIL-STD. Can fail at 2,000g.	Minimal impact from environmental effects	BAW Oscillator

5.1 Flexibility

The LMK6C/D/P/H BAW oscillator is a single IC (single BAW die + single base die) solution which can generate any output frequency from 1 MHz to 400 MHz – much like a PLL/VCO based quartz oscillator – however at the specs much closer to an SPXO. BAW oscillator has fast start up time (<5 ms), comes in industry standard smallest package (3.2 mm × 2.5 mm, 2.5 mm × 2.0 mm), and has a typical current consumption of 50 mA. It can operate at 1.8 V, 2.5 V or 3.3 V supply and is pin to pin compatible with all oscillator competitors. The BAW oscillator also supports all standard output types including LVPECL, LVDS, and HCSL for differential and LVCMOS for single ended.

5.2 Temperature Stability

Crystal tend to have a high dependability on temperature, with the frequency varying significantly as temperature increases. Supporting a 25-ppm part at extended industrial grade (115°C LVCMOS/105°C differential), is not possible without adding some temperature compensation circuitry. LMK6C/D/P/H BAW oscillator meets ±10 ppm budget across full temperature range.

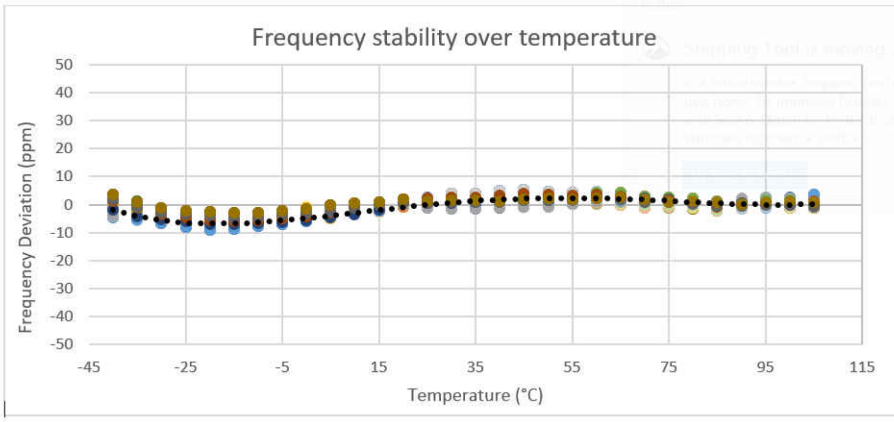

Figure 5-1. BAW Oscillator Frequency Stability Over Temperature

5.3 Phase Noise Performance

Jitter is key performance spec which all clock products are judged against. The LMK6P/D/H BAW oscillator offers great jitter performance meeting **100 fs typical** for differential outputs:

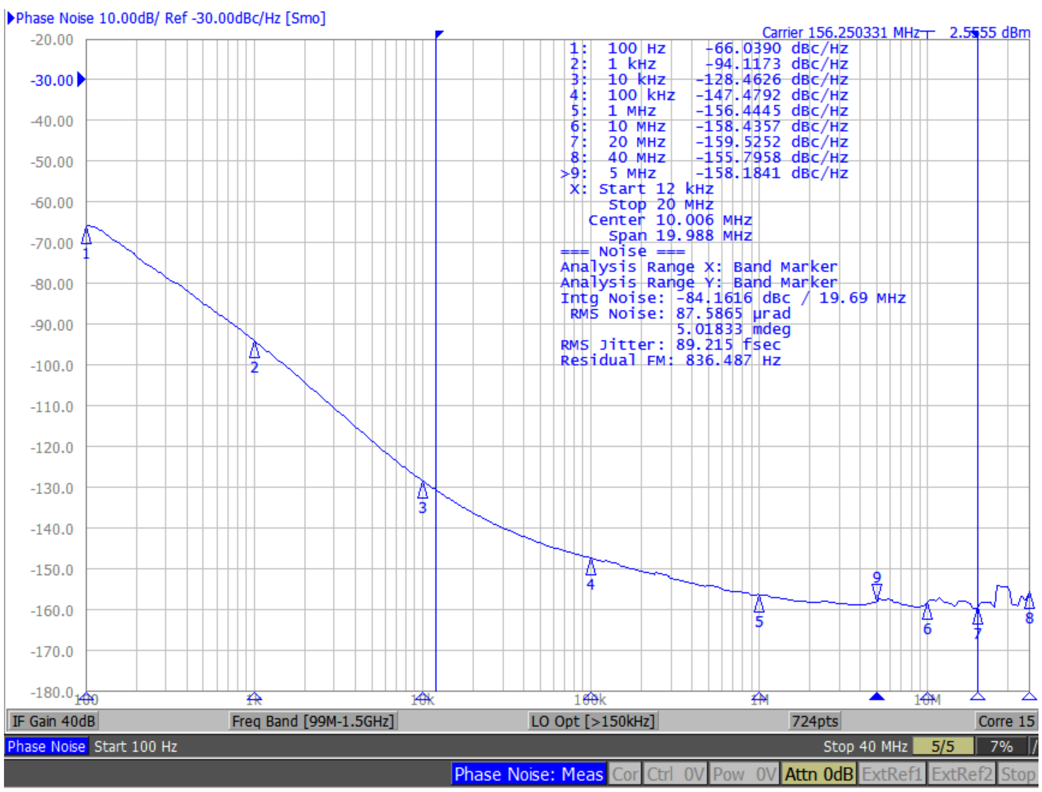

Figure 5-2. LMK6P/D/H BAW Oscillator Differential Phase Noise Performance (Normalized)

The single ended version has best in class jitter performance with typicals below < 300 fs:

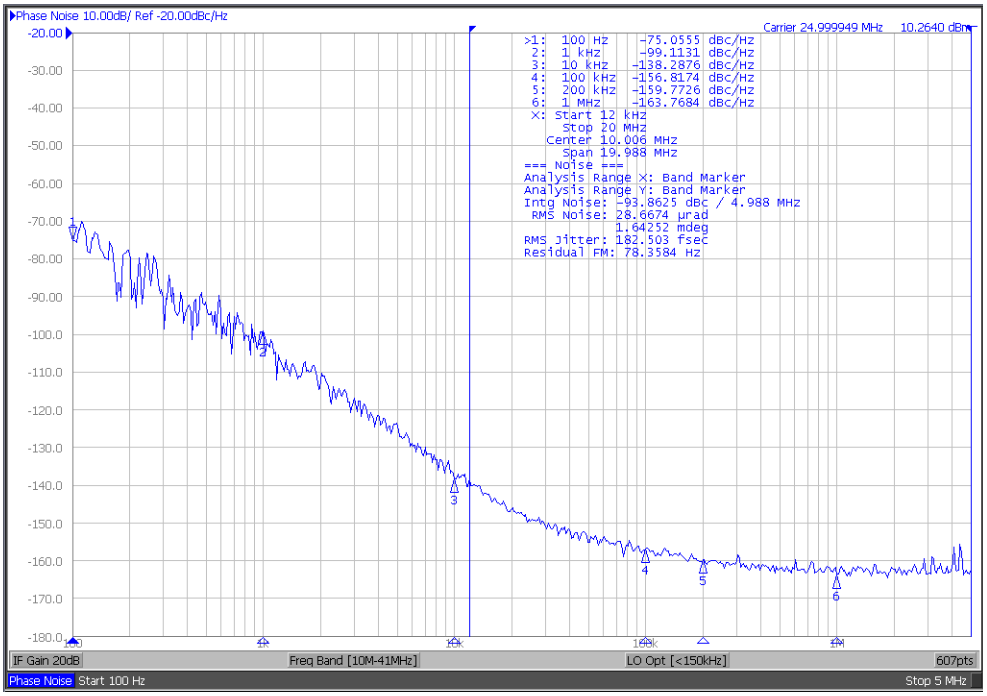

Figure 5-3. LMK6C BAW Oscillator Single-ended Phase Noise Performance (Normalized)

5.4 Power Supply Noise Immunity

The LMK6C/D/P/H BAW oscillator integrates internal LDOs which provide the output clock with protection against ripples on the power supply. This adds the benefit of no external LDO or DC/DC converter being needed on the supply to get the best performance out of the oscillator. With a simple bypass capacitor on the supply pin, a majority of the ripple is rejected and does not induce noise on the output.

5.5 Mechanical Robustness

For oscillators, vibration and shock are common causes for increased phase noise and jitter, frequency shift and spikes, or even physical damages to the resonator and its package. Compared to quartz crystals, the LMK6C/D/P/H is more resilient to vibration and shock due to its orders of magnitude smaller mass and higher frequency – force applied to the device from acceleration is much smaller due to the smaller mass. The LMK6C/D/P/H BAW oscillator meets both MIL_STD_883F Method 2002, Condition A (vibration) and MIL_STD_883F Method 2007 Condition B for shock, with no performance degradation, (jitter, stability, general device performance) post vibration and shock event.

In addition to Military Standards testing, the LMK6C/D/P/H BAW oscillator is tested while under stress for multiple conditions. Not only does the BAW oscillator observe minimal frequency shift due to shock while under stress, it also recovers post event to previous levels:

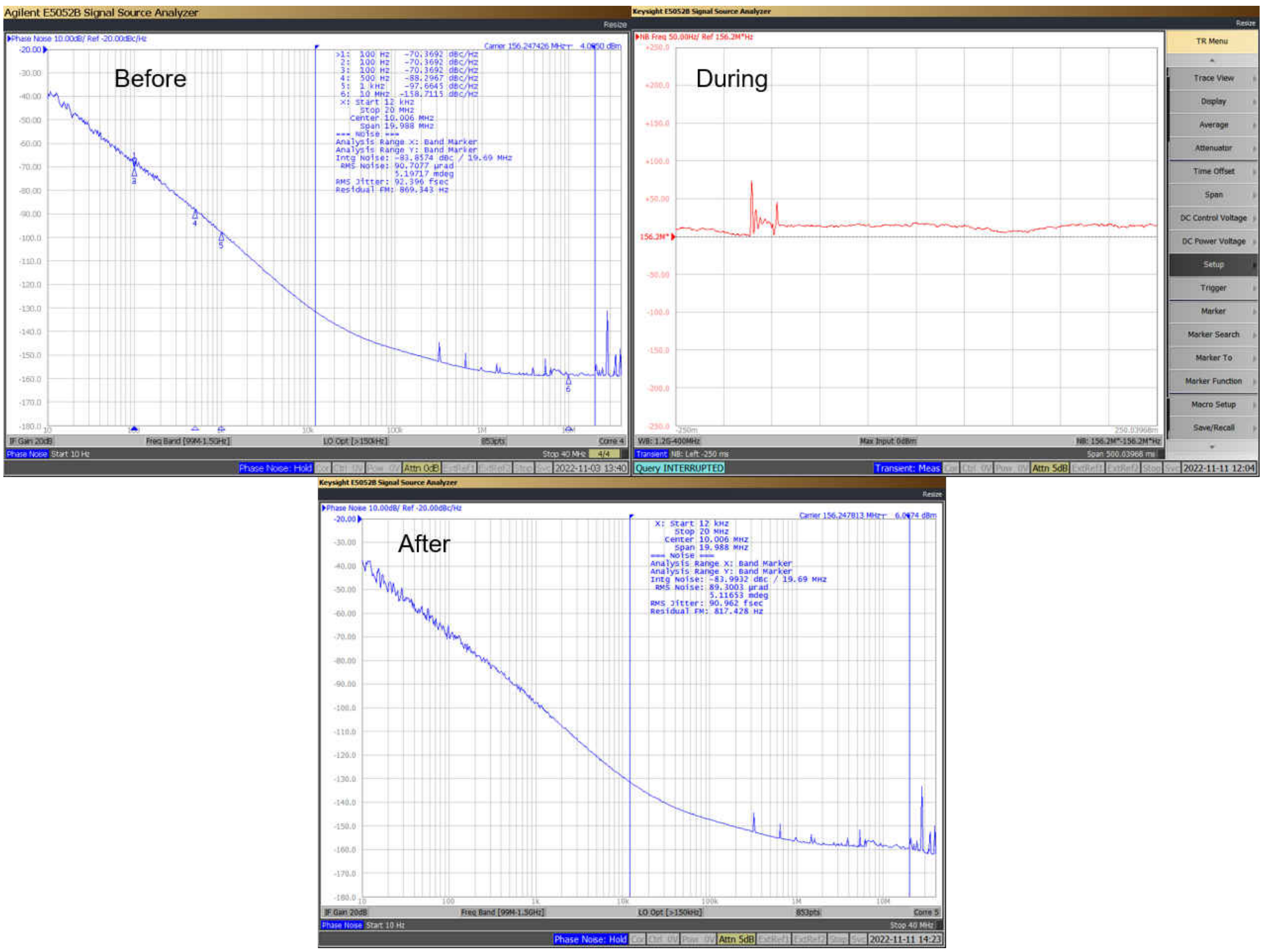

Figure 5-4. LMKD/P/H Shock Effect at 1500 g

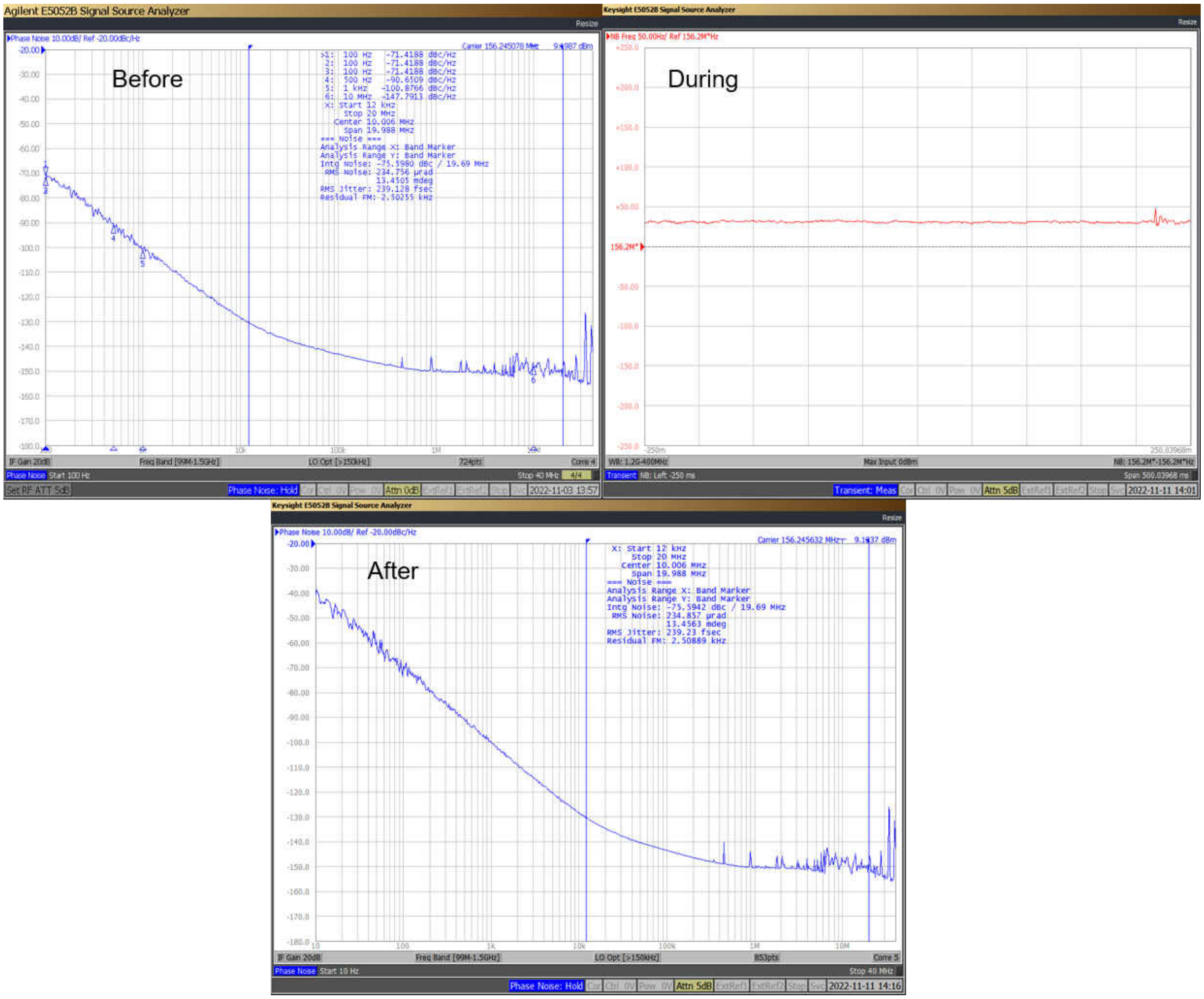

Figure 5-5. LMK6C Shock Effect at 1500 g

With regards to vibration, BAW oscillator exhibits minimal frequency deviation due to vibration to the tune of about 1 ppb/g. This is close to an order of magnitude improvement from crystal oscillator solutions.

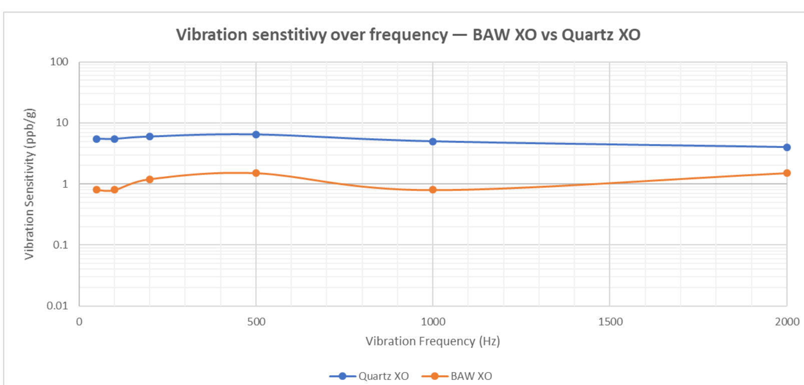

Figure 5-6. LMK6C/D/P/H BAW Oscillator vs Quartz Oscillator Vibration Sensitivity

The LMK6C/D/P/H BAW oscillator guarantees a ± 25 ppm all inclusive frequency stability with 10 year aging. Figure 5-7 and Figure 5-8 show the aging trends for the LMK6P/D/H differential and LMK6C single-ended BAW oscillator.

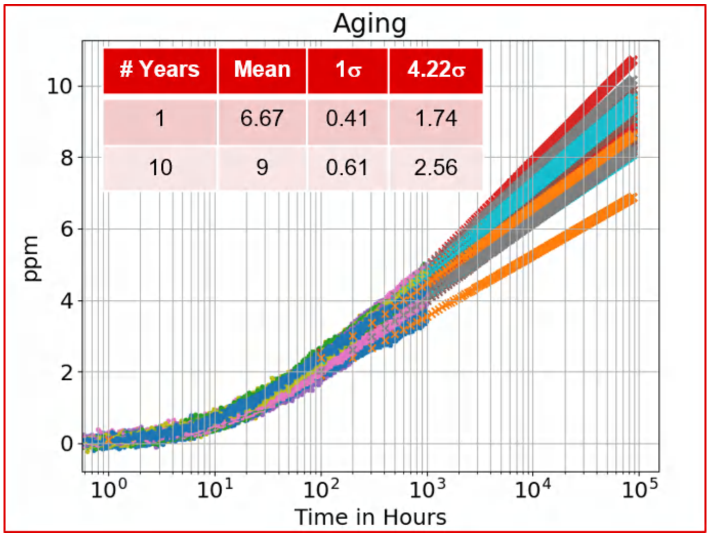

Figure 5-7. LMK6P/D/H Differential Aging

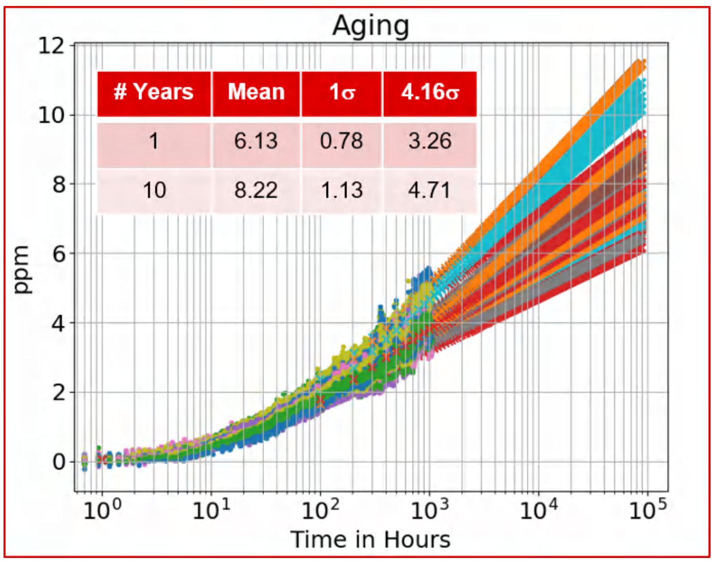

Figure 5-8. LMK6C Single-ended Aging

6 Conclusion

The LMK6C/D/P/H BAW oscillator presents superior alternative options to crystal oscillators with many performance advantages as highlighted in this document. In addition to that, the BAW oscillator does not have the same supply constraints that exist in the quartz crystal oscillator market, as it is a fabricated process fully controlled and designed by TI producing large volumes of material with just a single wafer run.