

## Capacitive Versus Thermal MEMS for High-Vibration Applications

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Design engineers involved in the development of heavy equipment that operate in high shock and vibration environments need to make some choices regarding the type of accelerometer that is used to measure inclination. In equipment such as tractors, cranes, wood chippers, and construction equipment, designers use accelerometers to measure pitch and roll using two (2D) or three orthogonal (3D) axes.



In most cases, equipment designers have a choice between capacitive -based or thermal MEMS (microelectromechanical) accelerometers. To select the right accelerometer for the application, they need to consider several design variables, including sensor structure, sensor resonance, reliability, stability, bandwidth, and power consumption, together with cost.

Designers also need to understand the key principles of each technology and how these devices measure inclination in high-vibration environments. Here's what designers need to know.

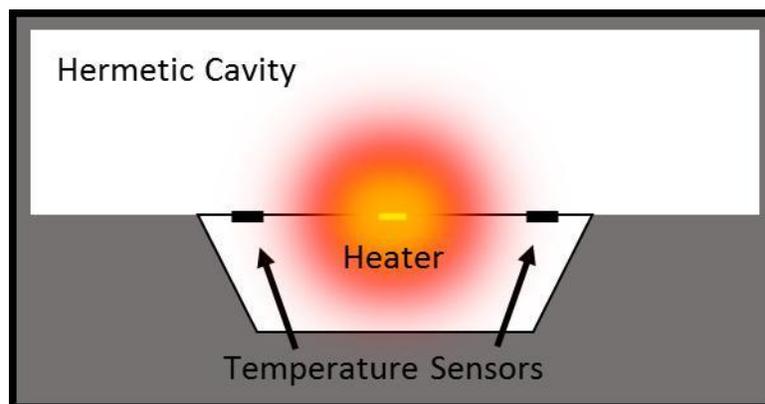
Accelerometers can directly measure the acceleration due to gravity along 1, 2, or 3 orthogonal axes. Inclination is calculated from the amount of acceleration due to gravity being measured on the axes.

A single dual-axis (2D) accelerometer can measure both pitch and roll, and the acceleration measured on the axis being inclined is equal to the sine of the angle. This limits the theoretical usable range to  $0 \pm < 90$  degrees, and in actual implementation to  $0 \pm \sim 70$  degrees, because the sine function starts to flatten out as it approaches 90 degrees. However, a single 2D accelerometer can measure either pitch OR roll for a range of  $0 \pm 180$  degrees.

Three-axis (3D) or two 2D accelerometers are needed for both pitch AND roll over the full range that describes an objects orientation with respect to gravity ( $0 \pm 90$  degrees of pitch and  $0 \pm 180$  degrees of roll). In most cases, two 2D accelerometers are the better choice because many 3D devices have degraded performance on the Z-axis.

A 3D capacitive MEMS accelerometer, using a cantilevered beam structure, calculates acceleration by measuring force on a surface's mass by using capacitive sensing techniques. Acceleration causes the suspended beam structure to change position relative to the two fixed electrodes, which results in a change in capacitance. Force is measured by the change in capacitance between the two fixed electrodes. The change in capacitance is proportional to the acceleration.

A 2D thermal MEMS accelerometer uses a monolithic approach that integrates the sensor and electronics onto the IC which is then hermetically sealed in a package. The silicon die includes a heating element and thermopiles suspended over a cavity etched into the die. Instead of using capacitance to measure force, the thermal sensor uses the movement of the heated gas molecules to detect acceleration. With acceleration, the heated molecules move in the direction of acceleration, and with zero acceleration the heated gas is symmetrical above the heater. These devices have no flexing or moving parts, which make them more durable and delivers very high measurement repeatability.



Thermal accelerometer uses heated gas as "proof mass"



The key differences between the two technologies are directly related to the sensor transducer. Capacitive MEMS accelerometers use a cantilevered beam design (with moving parts). They are inherently wideband transducers (>5 kHz) with a mechanical resonant frequency near 2 kHz for low-g devices used in inclination sensing. When vibration energy is larger than the capability of the sensor transducer or near the resonant frequency of the sensor structure, clipping or sensor resonance can occur in the capacitive accelerometers.

In some cases, the clipping or resonance may cause a massive DC offset shift, particularly on the Z-axis, making the sensor unable to recover the signal in high-vibration environments. DC offset shift in a high-vibration environment is an inherent disadvantage of capacitive accelerometers and requires mitigation techniques to try to isolate the vibration from the accelerometer.

There are a number of approaches to mitigate these effects. However, in some environments, the vibration is too large to mitigate in a capacitive accelerometer.

One approach to try and isolate the accelerometer from the vibration energy is to use a suspension system, consisting of rubber bushings or springs and dampers at the mounting location. Another approach is to use a less sensitive device with stiffer cantilever beams, which, therefore, have a higher resonant frequency and can withstand larger mechanical shocks and vibration. But these techniques add cost, sacrifice performance, and require a longer design time, impacting time to market and product launch deadlines. It also makes the solution less reliable.

If the vibration energy can be mitigated to a level suitable for the capacitive MEMS to function properly, there is still the issue of aliasing that needs to be addressed. The wide bandwidth of the sensor transducer will allow higher frequency vibration to alias (down convert) into the measurement. The solution may require heavy over sampling and more microprocessor horse power – i.e., a more expensive processor -to apply heavy DSP filtering to remove the out-of-band energy and prevent the aliasing.

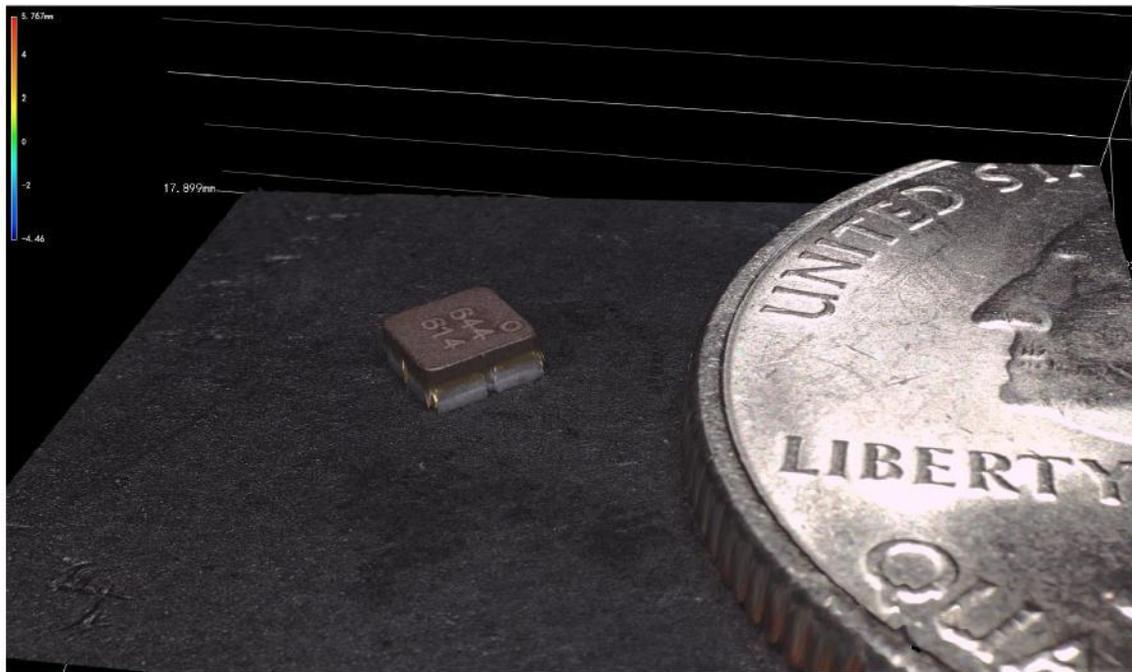
Mechanical shock or impact energy also has an impact on aliasing and sensor resonance in capacitive MEMS accelerometers. A mechanical shock is a high magnitude short duration event and can be modeled as an impulse. Converted to the frequency domain it is seen to have very wide frequency content. If there is enough energy at or near that resonance frequency of the sensor structure, it can go into resonance, and while in resonance it is unable to make any accurate measurements.

Mechanical shock of sufficient magnitude can cause stiction, when the cantilevered beams touch and become stuck together, causing the output to remain constant. In extreme cases the beams can move past their mechanical stops and be damaged.



Another inherent challenge with capacitive MEMS accelerometers is a loss of calibration due to mechanical shock. A high mechanical shock applied to the sensor can slightly change the characteristic of the device. If either the device's zero g bias or sensitivity changes, it makes the customer's calibration invalid. Even a slight change in these characteristics can result in loss of calibration.

In comparison, by using the movement of heat to measure acceleration in a thermal MEMS accelerometer, it acts like a front-end low-pass filter, mitigating the vibration and impact energy adverse effects.



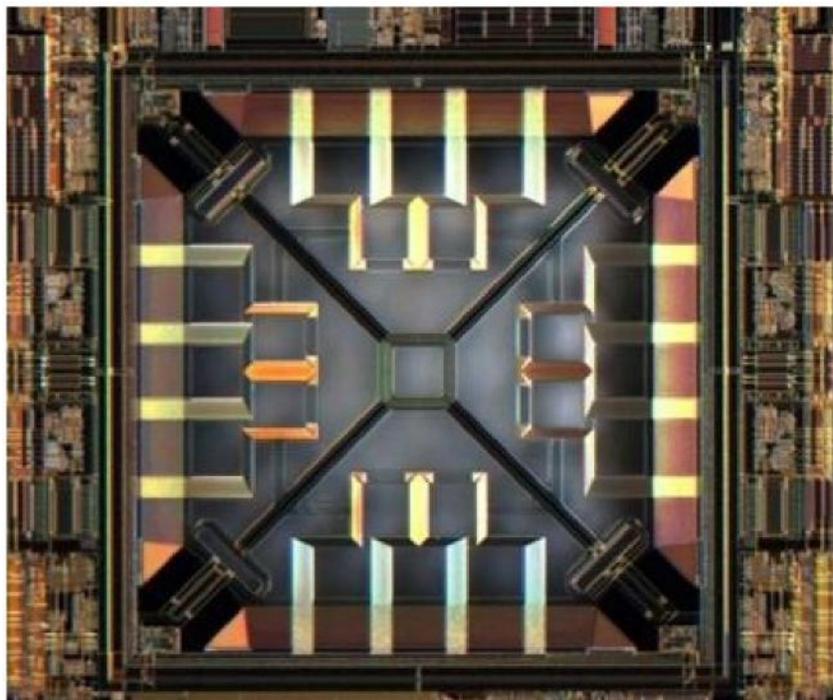
*CAPTION: MEMSIC's MXC6244AU compact - 3x3x1.2mm (L x W x H) - MEMS sensor is immune to vibration and is extremely reliable.*

For example, MEMSIC's MXC6244AU features excellent low-pass filter response thanks to the sensor element (10 Hz/-3 db) and integrated 2<sup>nd</sup> order filtering to further attenuate out-of-band vibration. This results in a more accurate inclination measurement that can be determined without wasting processor cycles by offloading the resources from the processor.

Another factor related to reliability is the structure of the sensors. Capacitance-based accelerometers require a two-die solution – one for the sensor element and the other for the ASIC - to measure inclination in high-vibration environments. In most cases, the sensor element requires a much larger geometry than the ASIC die.



A thermal MEMS sensor integrates the sensor and electronics on a single monolithic IC, resulting in a much smaller and more reliable device. This also translates into lower cost in manufacturing, while simplifying the assembly process. For example, the MEMSIC MXC6244AU includes DSP processing directly on the die compared to capacitance-based structures that require larger geometries.



*Caption: Because thermal MEMS sensors do not have any moving parts, they are very long lived and resistant to shock and vibration.*

Together, the monolithic design and no capacitive cantilever structure of a thermal MEMS accelerometer translates into high shock survivability and best-in-class reliability (repeatability) in demanding environments. With no moving parts, the thermal MEMS device exhibits no variance due to shock and vibration that could impact any stored calibration.

Thermal MEMS devices such as MEMSIC's MXC6244AU also exhibit no measureable resonance, delivering immunity to vibration; no temperature hysteresis, excellent zero-g offset stability, and 50,000g shock tolerance, all contributing to greater reliability.

However, capacitive MEMS accelerometers offer a low-power advantage, particularly for power critical applications such as battery-operated devices. These accelerometers offer an order of magnitude less power than thermal MEMS sensors that typically consume 3 milliwatts of power. Current is required to generate the heat used to measure acceleration in the thermal devices.



Capacitive MEMS accelerometers also excel in the area of bandwidth for higher frequency applications, typically above 100Hz, for high-g sensing applications such as crash detection for airbag deployment. In these cases, the solution needs the wide bandwidth and high-g capability offered by the capacitive MEMS transducer. On the other hand, thermal MEMS accelerometers are well suited for sensing low-g (<10g), low frequency - <30 Hz – accelerations in high-vibration environments because they have no moving parts and no sensor resonance. The devices have an inherent low-pass filter response of <30 Hz.

In comparison, capacitive MEMS at low-g typically have a resonant frequency in the low kHz range. If there is energy at or near the resonant frequency of the MEMS structure in the application it can cause measurement problems, resulting in a bias error and thus an invalid acceleration. Back-end low-pass filtering can't fix the problem if the front-end amplifier of the MEMS device is overloaded.

Thermal MEMS accelerometers eliminate these types of errors in high-vibration environments thanks to no sensor resonance, inherent transducer low pass response and built-in filtering. Inherently, these sensors will not resonate or cause problems in vibration environments.

Summary: Thermal MEMS accelerometers are well-suited for inclination sensing in high vibration environments for several reasons. Their inherent low-pass response and zero resonance makes inclination sensing possible where capacitive MEMS accelerometers fail. In addition, their monolithic design and no capacitive cantilever structure – no moving parts -means high shock survivability and best-in-class reliability in demanding environments.

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