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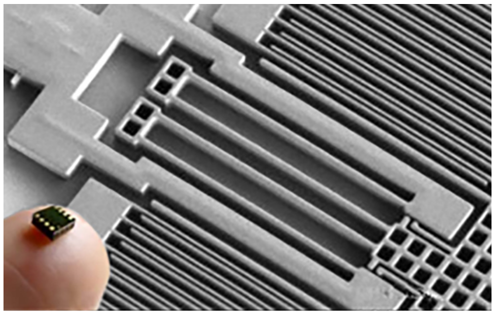
White Paper

Limitations of MEMS Accelerometers for Vibration Monitoring Systems

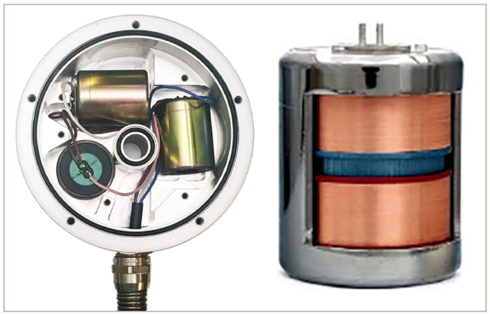
Micro-Electro-Mechanical Systems (MEMS) are appearing in vibration monitoring equipment in numerous industries including industrial, construction and blasting. Instantel recently completed extensive testing comparing current MEMS accelerometers against traditional solenoid geophone sensors.



Close-up of a MEMS accelerometer. Typical case dimensions: 5 mm x 5 mm (0.2 inch x 0.2 inch)

Actual size of MEMS

Close-up of internal view



A solenoid geophone cut-out showing the internal copper winding. Typical dimensions for one of three solenoids in a triaxial geophone: 25 mm x 32 mm (1 inch x 1.25 inches)

Triaxial geophone internal view

Solenoid geophone cut-out view

Our tests confirm that MEMS accelerometers contain significant uncertainty in the validity of their recorded data where vibrations with high frequencies (1,000+ Hz) are dominant. In several of our tests, the MEMS accelerometers registered erroneous amplitudes 19 to 45 times higher than the solenoid geophones (see Figure 1). Sources of high-frequency vibrations include heavy equipment, jackhammers, pile drivers, hoe rams and explosives.

The Major Concerns of MEMS Accelerometers in Vibration Monitoring

1. Vibration Rectification Error (VRE)

- VRE generates a very low-frequency offset in the output data of the MEMS accelerometer.
- VRE is caused by nonlinearities and asymmetries integral to the MEMS fabrication processes.
- VRE is unpredictable in applications where frequency and amplitude vary.
- Test results showed that MEMS accelerometers reported extreme velocity amplitudes on all channels and invalid data before they recovered.

2. High Frequencies and MEMS Operational Limits

- MEMS accelerometers are more susceptible to high frequencies than solenoid geophones. This can cause them to exceed their operational limits and respond with erroneous data.
- Measurement errors occur that are intrinsic to the internal architecture of MEMS accelerometers and are therefore unpreventable.

3. Aliasing

- MEMS accelerometers are more susceptible to aliasing than solenoid geophones.
- MEMS accelerometers must be sampled at a much higher rate, or be more aggressivley filtered, to provide the same data integrity as solenoid geophones.

4. Noise and the Noise Floor

- MEMS accelerometers are inherently more susceptible to their internally generated noise.
- MEMS accelerometers can randomly generate false triggers when low trigger levels are required.

5. Regulatory Compliance

- MEMS accelerometers must measure acceleration reliably up to 40.7 g to be ISEE compliant.
- Vibration monitors that only use 2, 4, or 8 g MEMS cannot meet the ISEE performance specification.

1. Vibration Rectification Error (VRE)

Nonlinearities and asymmetries integral to the MEMS fabrication processes lead to a phenomenon well documented in literature[1], known as Vibration Rectification Error (VRE). VRE generates a very low-frequency offset (data no longer centered) in the output data of the MEMS accelerometer. As the amplitude of the higher frequency Root Mean Square (RMS) envelope increases so does the magnitude of the offset. As the frequency and amplitude content changes from one location and application to another so does the VRE, making it inconsistent and unpredictable. Any offset in acceleration data creates an error in the resulting velocity signal. This error appears as an increasing ramp for positive offsets and a decreasing ramp for negative offsets. As most vibration standards are specified in velocity, this error can have a dramatic impact on the results. This can be clearly seen in Figure 1. which displays the results of the same vibration event as recorded by MEMS accelerometers and solenoid geophones. In addition, any offset will also reduce the amplitude range of the MEMS and may cause "clipping" (data not recorded) of the signal's peak amplitude.

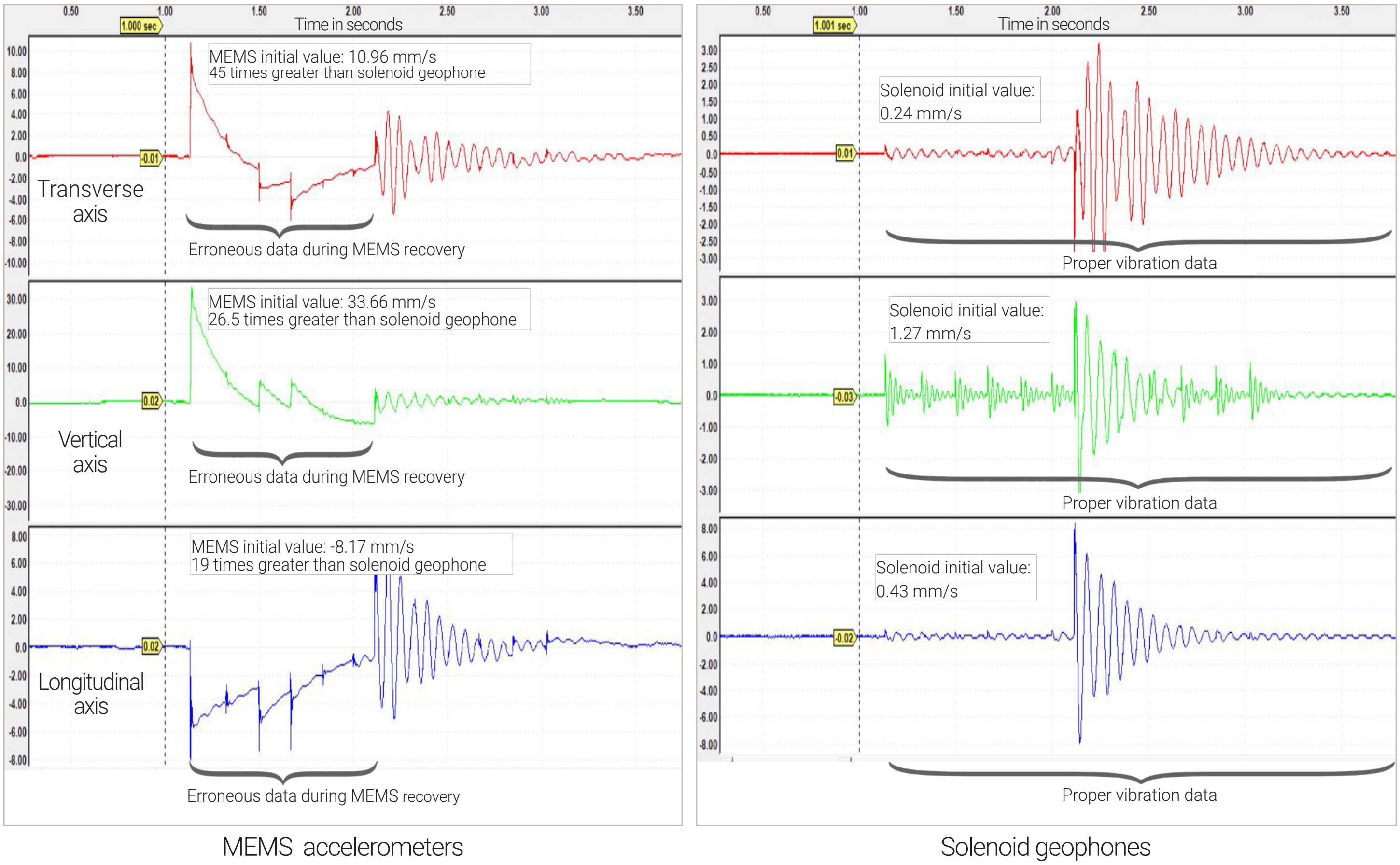


Figure 1. VRE affecting velocity results of MEMS accelerometers compared to the same vibration event as recorded by solenoid geophones

Observational Conclusion:

The MEMS accelerometers reported extreme amplitudes on all channels and invalid data before they recovered. The solenoid geophones recorded the signal data reliably and did not lose any data.

2. High Frequencies and MEMS Operational Limits

The main vibration sources in industrial and construction applications are heavy equipment, as well as impact tools like jackhammers, pile drivers, hoe rams and explosives. These vibrations can be individual or a sequence of impulses with frequencies of several kHz. MEMS accelerometers are inherently more susceptible to these higher frequencies when compared to solenoid geophones and can respond with erroneous data.

Frequencies above 500 Hz are outside the limits of most vibration standards and should be ignored to prevent them from contributing to the final vibration results. Solenoid geophones and standard filter designs can easily remove 500+ Hz signals. Whereas, with MEMS accelerometers, vibrations with frequencies above the monitoring frequency can introduce interference and measurement errors. The causes are primarily from converting acceleration to velocity amplitude (integration), self-resonant frequency and inadequate filter roll-off to attenuate the high-frequency content. Some errors are intrinsic to the internal architecture of a MEMS accelerometer and are therefore unpreventable.

Sources that generate these higher frequencies can cause the MEMS accelerometer to exceed its operating limits. When this happens it consistently produces unreliable data. Once the vibration source returns within the operating limits of the MEMS accelerometer, it can then take several seconds for the velocity output to stabilize and fully recover due to the filter characteristics specified by the monitoring standards (see Figure 2a).

Unfortunately, during this time, none of the MEMS data is valid. As vibrations from jackhammering, pile driving, hoe ramming, blasting and other similar vibration sources are often less than one or two seconds, the majority of their vibration data can be inaccurately reported or missed altogether. To simulate such high frequencies in our lab, we attached a MEMS accelerometer and a solenoid geophone to a precast concrete form and using a fixed hammering jig, induced a signal comparable in frequency to an industrial jackhammer or hoe ram on bedrock. Figure 2a shows the resultant event data that exceeded the MEMS' amplitude range. The MEMS accelerometer required four seconds to recover. During this four second period, data was recorded, but that data was not valid. Essentially, four seconds of the event data was lost. Figure 2b shows the same event data as recorded by the solenoid geophone which accurately recorded event data throughout the entire event time period.

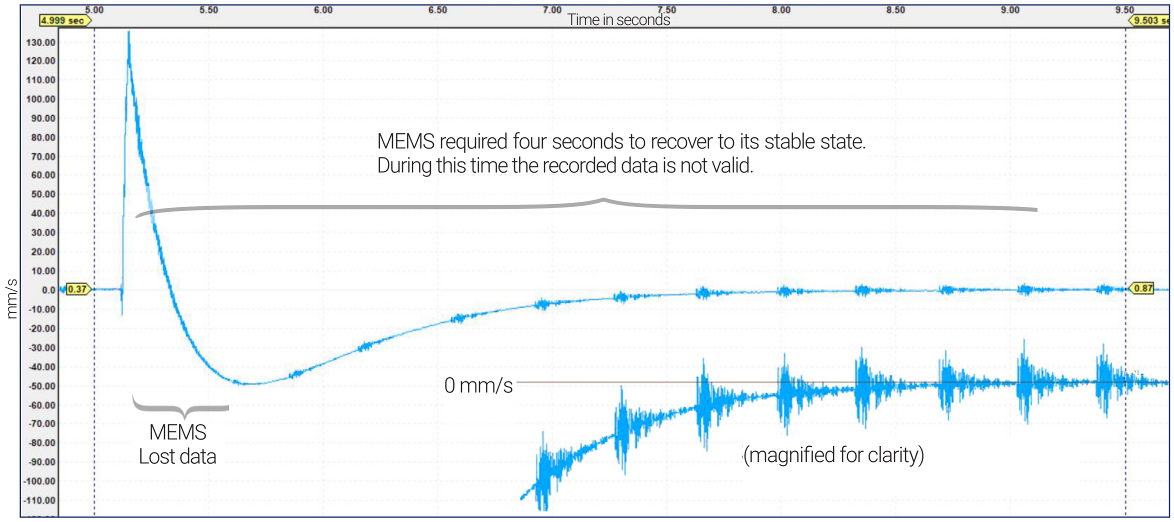


Figure 2a. Typical result when the amplitude of a MEMS accelerometer is exceeded

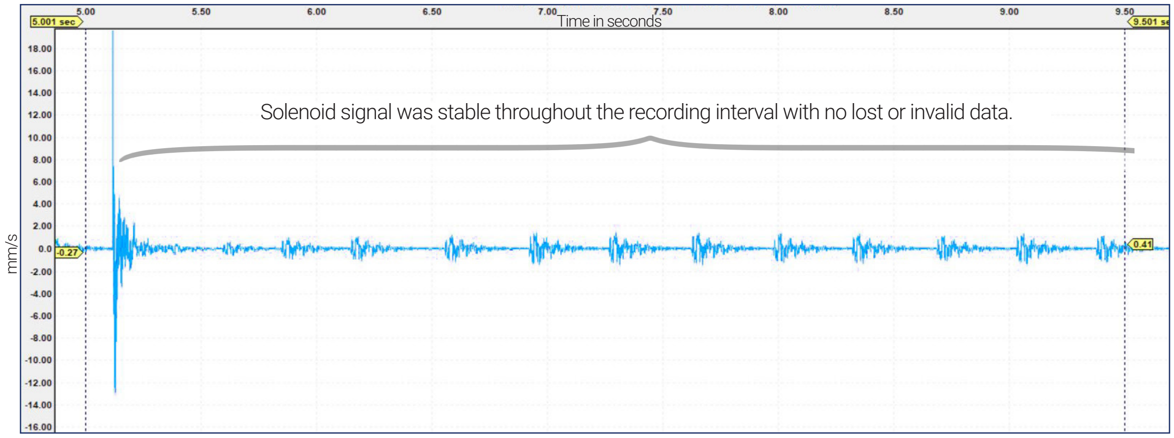


Figure 2b. Typical result of the same vibration event as recorded by a solenoid geophone

Observational Conclusion:

The MEMS based system did not record the vibration waveforms accurately and distorted data during its recovery phase.

The solenoid geophone recorded the vibration waveforms accurately throughout the observation window with no lost data.

3. Aliasing

Aliasing is a phenomenon that can cause different signals to become indistinguishable from one another. Aliasing can occur when unwanted high frequencies distort the frequencies of interest, compromising the collected data. In particular, aliasing can occur when high frequencies are not sampled fast enough. In both MEMS accelerometers and solenoid geophones, aliasing can occur, however, solenoids inherently produce lower amplitudes at high frequencies than MEMS for the same ground motion. This renders MEMS accelerometers far more susceptible to high frequency-induced distortion and the design of monitoring equipment needs to take this into consideration. MEMS accelerometers would need to be sampled at a much higher rate to provide the same data integrity as a solenoid geophone.

4. Noise and the Noise Floor

Noise floor is an important element when monitoring vibration signals. It can be described as the value below which an actual signal is indistinguishable from no signal. One compromise of MEMS accelerometers is that they are inherently more susceptible to their internally generated noise due to their small mass. Another factor is that MEMS accelerometers are active components with integrated electronics while solenoid geophones are passive components. In our lab we measured a MEMS' low frequency component that "wandered" in the time domain. Looking at the standard deviation and averaging the value as a root-mean-square (RMS) level revealed that the probability of the noise signal exceeding the vibration threshold was unacceptably high. This means that noise, which is generated by the inherent design of the MEMS accelerometer and which is not truly part of the event, can randomly generate false triggers when low trigger levels are required. The design of solenoid geophones significantly reduces the potential for the noise floor to generate false triggers, making them more reliable.

5. Regulatory Compliance

Vibration monitoring devices validate compliance to regulatory standards and vibration limits. These limits protect people, structures and assets. Recording and reporting data accurately is paramount for both contractors and property owners ensuring that it stands up to legal scrutiny.

In most projects, a consultant, municipality, state, or federal government will specify the frequency range to be monitored with vibration limits that must not be exceeded. They will also specify specific standards that the measuring equipment must meet. Two of these standards relating to equipment performance are the International Society of Explosives Engineers Performance Specifications for Blasting Seismographs[2] (ISEE-2017) and the Deutsches Institut für Normung (DIN 45669)[3]. Declaring compliance to these standards implies all aspects of the standard including the amplitude range, a frequency range, the maximum internal noise allowed, the linearity, the phase response and calibration requirements are met.

As an example, the ISEE performance specification requires an amplitude range of up to 254 mm/second (10 inches/second) and a frequency response of 2 to 250 Hz. To meet the ISEE performance specification, this would require a MEMS accelerometer capable of measuring acceleration reliably up to 40.7 g. Vibration monitors that only use 2, 4, or 8 g MEMS accelerometers are simply not capable of meeting the ISEE performance specification.

Conclusion

Our testing and analysis shows that MEMS accelerometers can create erroneous data directly related to the frequency and amplitude content of the vibrations being recorded.

High frequencies can affect the accuracy of vibration levels reported by MEMS accelerometers. As it is impossible to predict the exact frequency and amplitude content that a project will produce, this uncertainty jeopardizes the ability to record data accurately and reliably. Our lab observed a strong correlation of high frequencies being a source of data inaccuracy when MEMS accelerometers were used.

While MEMS accelerometers are alluring for their installation flexibility, they clearly do not match the reliability of solenoid geophones. In our opinion, the benefits do not outweigh the risks of recording inaccurate or false data which could result in fines, project delays or shutdowns, or litigation for not adhering to vibration standards or regulatory limits.

Vibration equipment manufacturers must be able to provide proof that their equipment meets compliance standards. We highly recommend that contractors and property owners request these proofs and review them prior to selecting a vibration monitoring system.

Instantel will continue to monitor MEMS technology for advancements that address the above issues.

1. E.g., Zaiss, C. and Spiewak, S.: "Vibration Rectification and Thermal Disturbances in Ultra Precision Inertial Sensors," ASME 2011, International Mechanical Engineering Congress and Exposition, November 11-17, 2011. https://doi.org/10.1115/IMECE2011-65518
2. https://www.isee.org/digital-downloads/461-isee-performance-specifications-for-blasting-seismographs-2017/file , accessed 20 April 2020.
3. DIN 45669-1:2019-09 Measurement of vibration immissions [sic] - Part 1: Vibration meters - Requirements and tests, available at https://www.beuth.de/en/standard/din-45669-1/309978751vvvv

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