White Paper

Why We Pulled Our MEMS Vibration Sensor Off The Market

In March of 2017, Instantel launched the SmartGeo, a MEMS-based vibration sensor. We were excited. We felt we would be migrating from traditional solenoid sensors to MEMS.

Solenoid sensors are about the size of a spool of thread. A geophone requires three solenoid sensors to account for the transverse, vertical and longitudinal planes. For decades, solenoid sensors have been the standard in our industry.

Micro-Electro-Mechanical Systems, or MEMS sensors, are smaller than a fingernail. There were some great advantages to our MEMS-based SmartGeo vibration sensor. It worked in most orientations, making installation easier because of greater level tolerances, a real convenience when installed on rock, tunnel walls, or when buried in hard ground. It could be mounted horizontally (on a floor) or vertically (on a wall).

This paper presents the scientific reasons why Instantel concluded that we *could not trust* certain MEMS* (hereinafter referred to as MEMS) vibration sensors for applications in our industry.

1.2 Million Reasons

We invested more than $1.2M USD in our MEMS technology.

We had 1.2 million reasons not to pull it off the market.

There was one compelling reason to pull the product:

We couldn't trust it.

Many people who depend on vibration monitoring data may not have a scientific understanding about how solenoid and MEMS vibration sensors operate. Yet, as one accountable for protecting the structural health of buildings, homes, tunnels, and the environment, you depend on these sensors to be reliable and accurate.

Our concern with MEMS started when we received a jobsite video from a customer, complete with vibration recordings. The video showed an operating jackhammer with our MEMS vibration sensor and also our solenoid geophone mounted side-by-side on a nearby wall.

The MEMS was recording readings up to ten times that of the solenoid geophone. Which one was accurate? If it was the MEMS, it was a good case to shut down the work. What if this was not just one jackhammer? What if it were a pile driver, or a tunnel boring machine, or equipment on a large construction site? You can imagine the implications of jobsite shutdowns, project delays, escalating costs, and even potential fines and litigation.

* Tested MEMS vibration sensors included ADXL355 and ADXL357 only.

What does all this mean?

You will need to decide for yourself. For us at Instantel, rigorous testing proved we could not trust certain MEMS* sensors for applications in our industry. For that one reason, we pulled them off the market.

MEMS:

- unreliable and inconsistent
- prone to vibration rectification error (VRE)**
- susceptible to inclusion of false data
- potential to generate higher than actual readings, which results in false data
- experienced data loss

Solenoid sensors produced reliable and consistent readings across multiple tests.

A jobsite could be shut down, cost delays could be incurred, and fines might be levied if vibration readings are higher than actual levels.

In a court of law, if we were asked to validate the accuracy of vibration data generated by a MEMS vibration sensor, knowing what we know, we would need to reassess the data.

If we used any measurement device—a deli counter weigh scale, a doctor's thermometer, an engineer's oscilloscope, or a vibration geophone—and if we knew the device was not always reliable, we would not use it.

If we owned a home next to a construction site, or if we were a city official responsible for the structural health of historic buildings, subway tunnels, or bridges, we would not be confident in protecting our assets with MEMS devices.

** See "Addendum" on page 31

We tested and re-tested, comparing readings from MEMS to those of solenoid sensors. At first, we thought the MEMS was so sensitive that it was detecting vibrations levels not possible with solenoids. **Extensive** testing proved that not to be the case.

At times we found that MEMS and solenoid readings were consistent within industry tolerance levels. At other times the MEMS sensors produced dramatically higher readings as well as irregular waveform patterns. Testing continued but results did not change.

Solenoid Sensors:

- ***produced reliable and consistent readings across multiple tests***

MEMS:

- ***unreliable and inconsistent***
- ***prone to vibration rectification error***
- ***susceptible to inclusion of false data***
- ***potential to generate higher than actual readings, which results in false data***
- ***experienced data loss***

Since the initial concern was raised, we have continued testing MEMS technology. Remember, we have 1.2 million reasons why we want it to work. We undertook additional testing and development, adding more MEMS sensors to our device and programming complex algorithms to filter out the erroneous readings, all with hopes that errors generated by one internal process could be corrected by another. They were not.

New MEMS vibration sensors were appearing in the industry. You might think that was discouraging to us, but it was the opposite. Maybe MEMS was working differently now. We tested a current model MEMS vibration sensor. That device uses part numbers ADXL355 and ADXL357; the same chips we had designed into our MEMS sensor. We found the same kind of results that we observed in our prior tests. We needed to be absolutely certain, so we retested. Each of the twenty-three test scenarios resulted in data loss and false data.

Committed to our reputation for integrity

Instantel's slogan, one we really do believe in, is **"The World's Most Trusted."**

Test after test proved we could not trust the MEMS sensors.

For that one reason, we pulled our MEMS vibration sensor off the market.

The data analysis is complex, but the tests are easy to understand. Take a concrete frame, something that replicates building material. Mount a solenoid geophone onto it. Mount a MEMS vibration sensor beside that. Take a round heavy object – we used a shot put – and in a controlled manner, drop it onto the concrete (because it's round, with no corners or flat surfaces, it impacts the concrete in a consistent manner at each drop). Drop it again and again, in the same place, and then from varied distances from the sensors, multiple times. Logical expectations are that if you dropped the weight at point 'A' multiple times, the vibration readings should be statistically consistent each time. (The readings would not be exactly equal, because not all micro properties can be controlled.) The solenoid readings were reliable and consistent across multiple drop tests. With MEMS, readings were inconsistent, in some instances over ten times higher, prone to rectification error, inclusion of false data, and data loss – **generally, unreliable.**

We conducted similar tests with a jackhammer, equipment commonly found on jobsites. The results were similar. Again, solenoid sensors provided reliable and statistically consistent readings where MEMS did not.

Then we tested on a jobsite that involved use of heavy equipment, a hydraulic hoe ram breaking through bedrock to create a basement, in an urban setting, with adjacent buildings. Again, we mounted a MEMS device side by side to a solenoid geophone, this time near the wall of the adjacent building. The nature of the construction work did not produce regulatory exceedances. The vibration levels were actually quite low over the course of four weeks of monitoring. However, data analysis once again showed anomalies in the MEMS waveform where the solenoid signals were statistically consistent. Though these were low levels and not frequently observed, it again left us questioning our trust in the device. What if those anomalies occurred when it really mattered, when vibrations were approaching exceedances? What if neighbors had launched complaints, or what if legal action was being taken? Under those circumstances, when it mattered the most, we felt we simply **could not trust MEMS**.

The above represents a simplified explanation of why we do not trust the accuracy of MEMS and why we pulled our MEMS product off the market. **It was a simple matter of reliability, accuracy, and trust.**

Instantel is continuing to evaluate MEMS technology. At some point, we may develop and launch a new MEMS sensor, but that will not happen until thorough scientific testing and analysis proves we can trust the technology when used in the applications of our industry. Currently, we do not feel we can.

The following outlines our technical and scientific analysis which formed the basis for our conclusions. If you have any questions or concerns, please feel welcome to reach out to us.

Overview

Instantel compared vibration measurements from our solenoid-based geophone with those from a MEMS-based accelerometer device. We selected three methods to cover a range of applications commonly found in our industry: drop test, jackhammer, and heavy equipment applications, more specifically:

1. **Multiple controlled drop tests of a metal sphere (shot put) onto a concrete frame.**
2. **Jack hammering on a concrete frame.**
3. **Urban construction site with heavy equipment, hydraulic rock breaker (hoe ram).**

Results

- Across multiple drop tests of a shot put onto a concrete frame, solenoid geophones provided consistent vibration readings where MEMS did not.
- Across multiple jack hammer tests done on a concrete frame, solenoid geophones provided consistent vibration readings where MEMS did not.
- Though vibration levels at a construction site deploying a hydraulic rock breaker (hoe ram) were low, vibration waveform patterns for the solenoid geophone were consistent and as expected, where MEMS produced irregularities.

These new test results are consistent with similar tests that Instantel previously conducted in 2017.

Conclusion

Due to the inconsistencies and irregularities found across multiple scenarios in the recorded data provided by the tested MEMS device, Instantel does not have confidence or trust that the MEMS data is reliable and accurate over time.

Solenoid based vibrations sensors, used for decades in the industry, remain a reliable and accurate measurement technology.

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On-site Test Conditions

- Both devices were hard-mounted to a concrete test frame as per their mounting instructions (see Figure 1. and Figure 2.).
- The devices were mounted side by side to limit measurement variations and to ensure that both devices would capture the same data to allow correlation of results.
- Both devices were configured to automatically record events greater than 0.2 inches/s.
- Both devices were calibrated within the last six months of testing.
- Events were separated by a one-minute interval to isolate the events.
- Both devices were configured to the ISEE-2017 Performance Specification for Blasting Seismographs.
- 'X' = Longitudinal, 'Y' = Transverse, and 'Z' = Vertical.

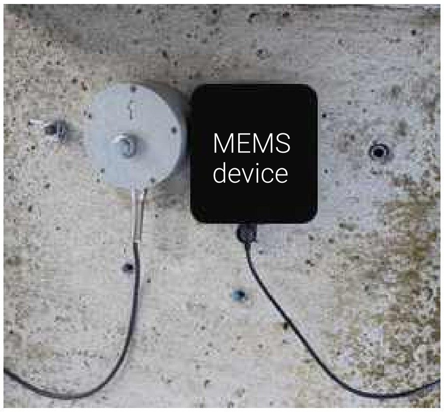


Figure 1. Solenoid and MEMS devices mounted on a concrete test frame.

Two Vibration Types Varying Height and Distances

1. Weight drop, 11.8 pounds from various heights.

Purpose: To provide a repeatable, low to medium-level impact to assess the devices' ability to report consistent data between events.

2. Jackhammering applied to the base through a metal plate.

Purpose: To evaluate performance with a continuous vibration source.

The concrete test frame (Figure 2) measured 108" x 39" x 24" (L x W x H). The walls of the frame were 3.5" thick. Both devices were installed on the inner right wall of the frame, 16" from the surface of the base.

The solenoid device was installed 21" from the back edge. The MEMS device was installed 15.5" from the same wall.

The controlled weight drop occurred at various distances from the edge and at various heights.

Test 1: Distance: 85", Height 47.25"

Test 2: Distance: 52.5", Height 48"

Test 3: Distance: 26.5", Height 48.5"

Test 4: Distance: 30", Height 24"

Test 5: Distance: 85", Height 25"

Two jackhammer tests were conducted at the base of the concrete frame.

Test 6: Event J1: Distance: 75"

Test 6: Event J2: Distance: 48"

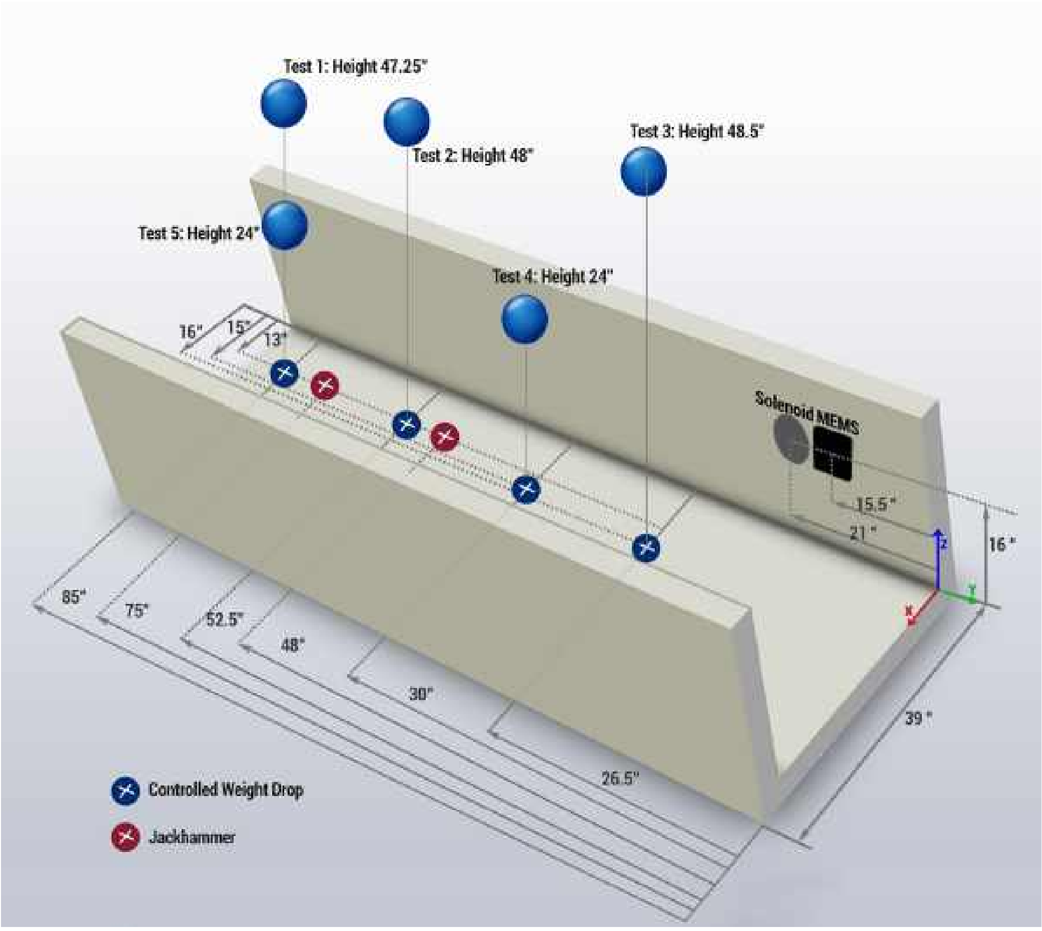


Figure 2. Test locations on the concrete frame used to test the solenoid and MEMS devices.

Test Results

Controlled Weight Drop - Test 1

An 11.8 pound spherical metal weight was suspended 47.25 inches above the base of the concrete frame at a distance of 85 inches from the edge of the structure (see Figure 2) and dropped four separate times. When released, the weight created an impact event that could be repeatable in intensity and position. Upon impact, the weight exhibited the characteristics of a diminishing bounce. These vibrations are visible in the data as lower-level impacts spread over a few hundred milliseconds. The peak values and dominant frequencies were recorded on both devices. These values are presented in Table 1. along with a visual representation in Figure 3. To demonstrate recording consistency, the standard deviations per channel were also calculated.

Standard deviation is a statistical measure of how spread out a set of data is from the mean or average value. It measures the amount of variability or dispersion of a data set relative to its mean. A higher standard deviation value indicates that the variation in the data is higher. For our tests, the lower the standard deviation, the better.

Observations

			Solenoid		MEMS	
	Weight Drop	Axis	Peak (inches/s)	Dominant Frequency (Hz)	Peak (inches/s)	Dominant Frequency (Hz)
Test 1 Drop Height: 47.25", Distance: 85"	Event 1	Z	0.123	32.5	1.460	0.5
		X	0.387	125.2	1.390	0.5
		Y	0.388	2	0.639	0.5
	Event 2	Z	0.118	32	1.140	0.5
		X	0.381	126.2	0.728	0.5
		Y	0.380	1.8	0.461	1
	Event 3	Z	0.115	32.2	1.370	0.5
		X	0.382	124.8	1.060	1
		Y	0.388	1.8	0.630	0.5
	Event 4	Z	0.142	44.8	1.383	0.5
		X	0.380	127.2	0.958	0.5
		Y	0.356	2	0.683	0.5

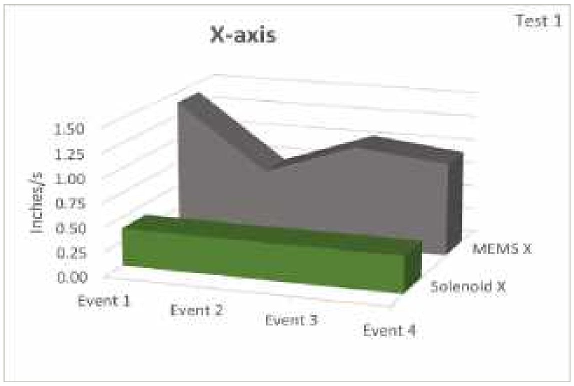
Table 1. Peak levels and dominant frequencies for each fixed-height weight drop.

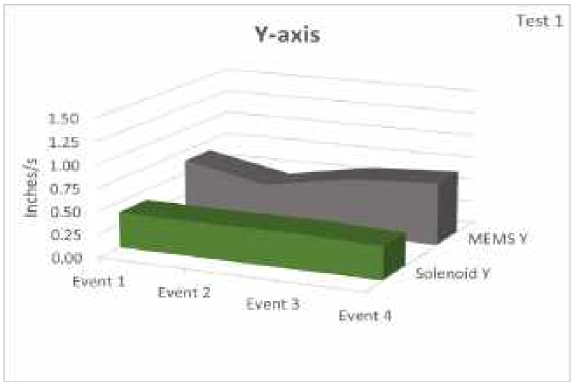
The MEMS data shows extreme variation in peak levels (91% variation between events 1 and 2 on X). The MEMS device struggled to provide repeatable data between the different events, despite the impact consistency between events, as shown by the solenoid data. These results indicate incredibly poor performance.

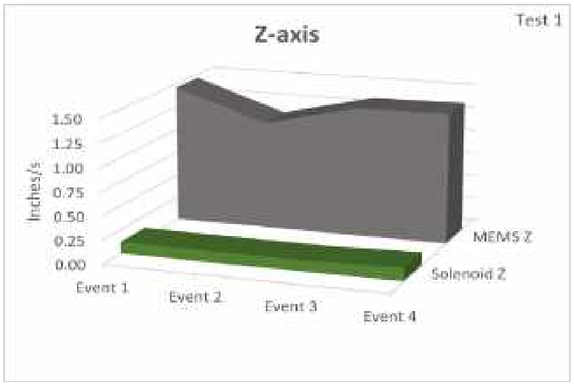
The solenoid data have comparable peak values well within the environmental variations between tests and show a very high level of repeatability across multiple impacts.

Test Results

Controlled Weight Drop - Test 1







Standard Deviations

Solenoid	MEMS
X-axis: 0.08	X-axis: 6.98
Y-axis: 0.39	Y-axis: 2.49
Z-axis: 0.31	Z-axis: 3.50
	(Up to 91% variation between events.)

MEMS vs. Solenoid
(recorded peak value variations)
X-axis = 259% variation (Event 1)
Y-axis = 92% variation (Event 4)
Z-axis = 1087% variation (Event 1)

Figure 3. Comparing MEMS versus solenoid peak levels of four weight drops Test 1.

Comparing peak-level data reveals that solenoids and MEMS do not correlate well. The reported dominant frequencies in Table 1. and the four frequency domain plots (Figure 8., Figure 9., Figure 10., Figure 11.) reveals that large vibration rectification error (VRE)* spikes recorded by the MEMS at the 0.5 Hz to 1 Hz range mask the true data as recorded by the solenoid sensor. Due to these VRE spikes the frequency data is lost and unrecoverable by the MEMS vibration sensor.

Observational Conclusion

MEMS data shows extreme variation in peak levels between events where solenoid data remained highly consistent. Relatively low-impact hits caused the MEMS device to report erroneous peak frequencies at 0.5 Hz to 1 Hz.

* See "Addendum" on page 31.

Time Domain Plots
Test 1 Event 1

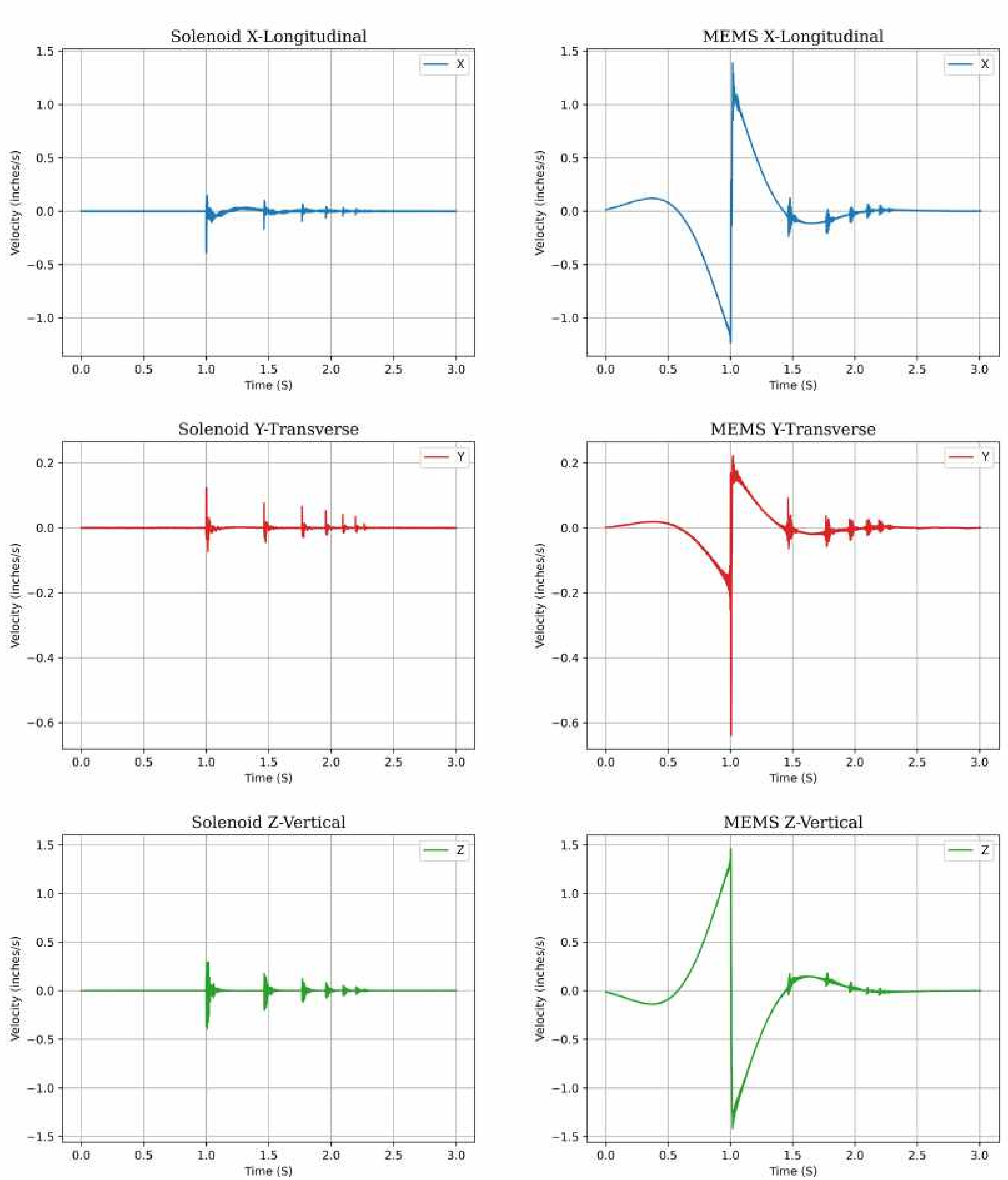


Figure 4. Time domain plots for Test 1, Event 1.

Observational Conclusion

The MEMS vibration sensor experienced a large discontinuity at the moment of impact, with drifting data for the first 0.5 seconds before inverting, and then drifting for another 0.5 seconds before settling. This is a clear indication of VRE causing the MEMS vibration sensor to output false data and the unit's algorithm struggling to make sense of it.

Time Domain Plots

Test 1 Event 2

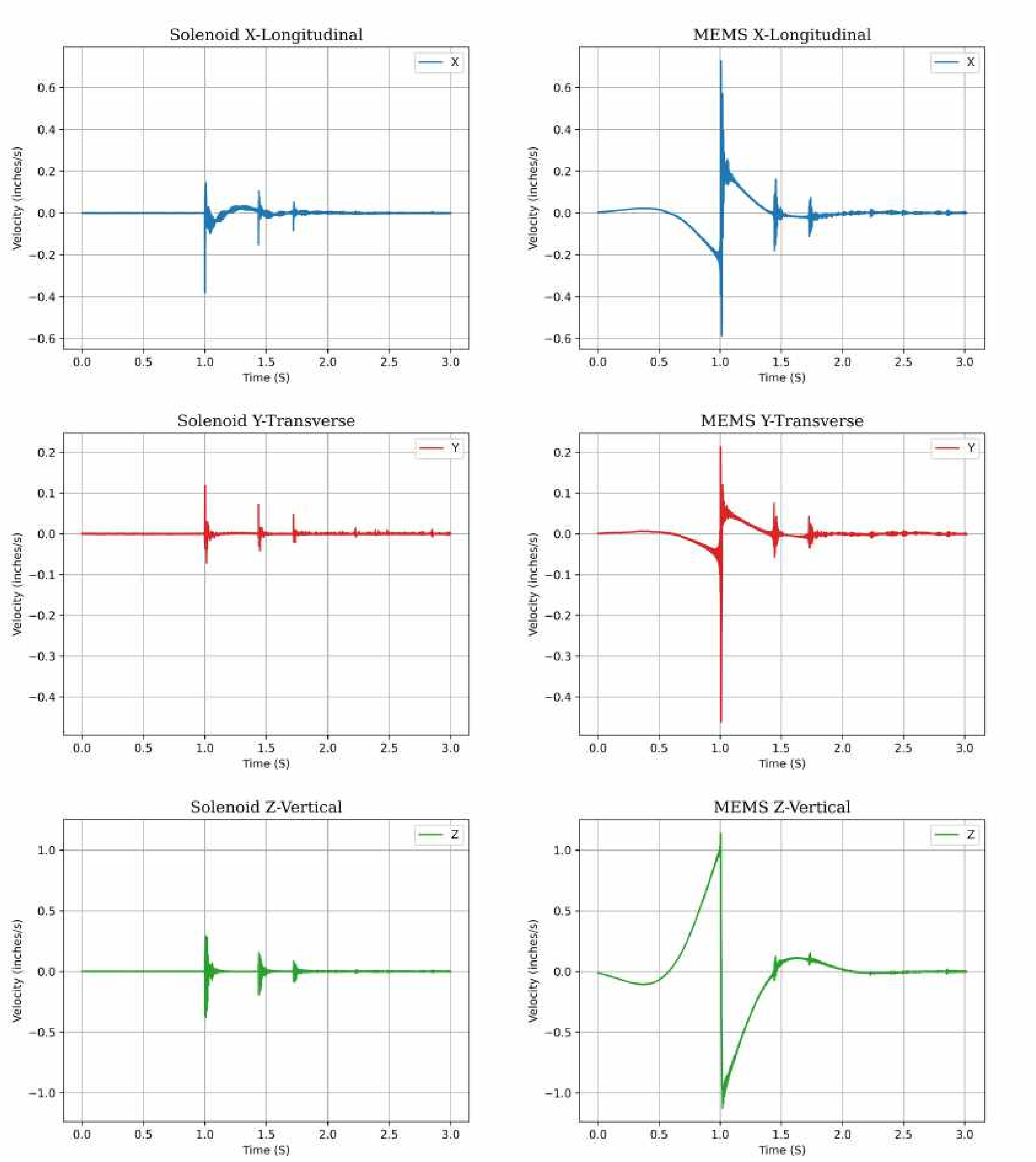


Figure 5. Time domain plots for Test 1, Event 2.

Observational Conclusion

Similarly to Event 1, we again see a large discontinuity in the MEMS vibration sensor that obscures the true impact data. Of particular interest is the Z-Vertical axis, where the peak values of the bounces are significantly less than the solenoid sensor. This indicates that the discontinuity is causing the actual data to be attenuated.

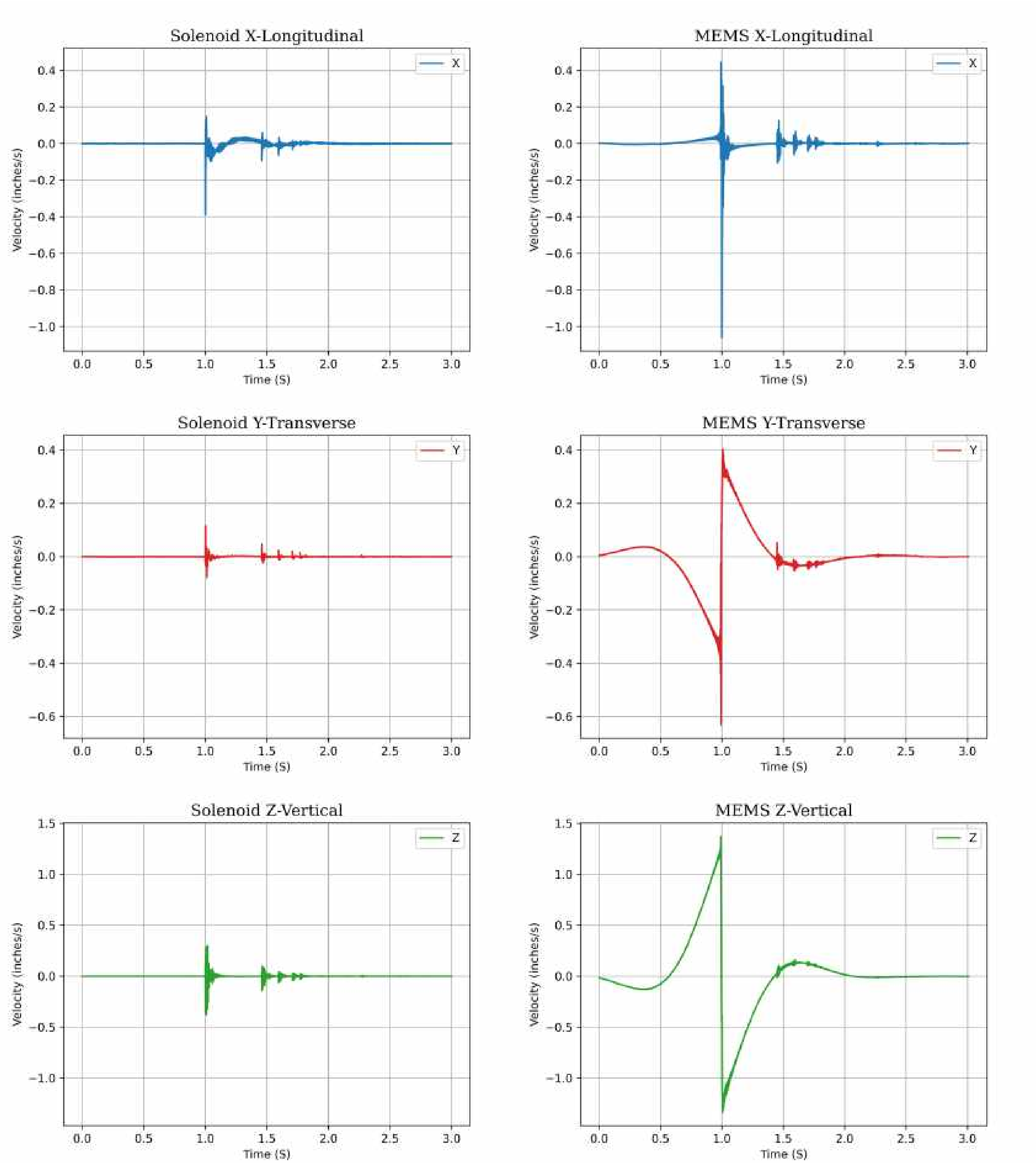


Figure 6. Time domain plots for Test 1, Event 3.

Observational Conclusion

Similar results to Event 1 and Event 2. The peak values at the discontinuity are very high and obscure the true data. The MEMS bounce data on the Z-Vertical axis is again significantly attenuated. The DC offset caused by the VRE appears to be causing an overflow in the MEMS algorithm when converting from acceleration to velocity.

Time Domain Plots — Test 1 Event 4

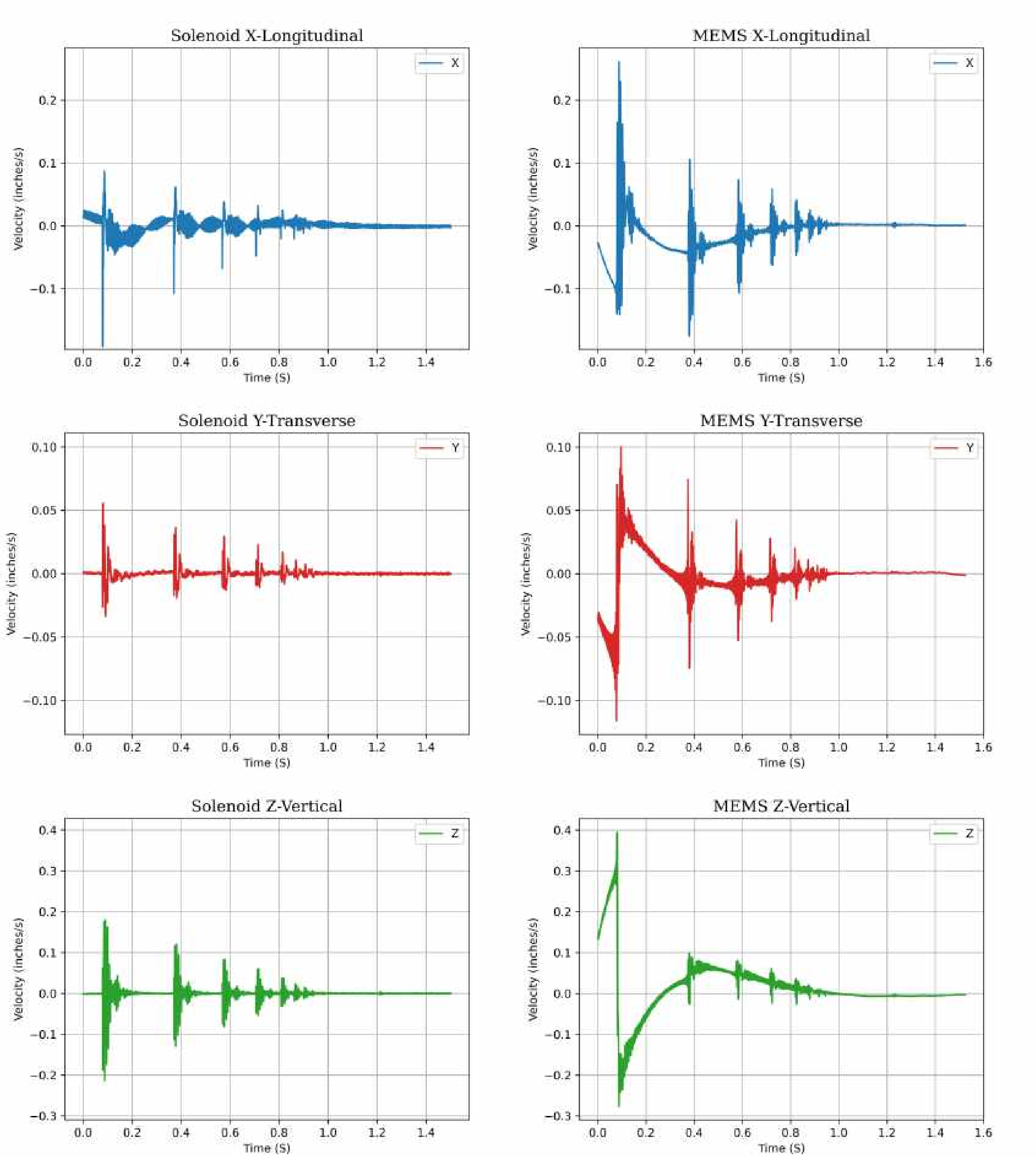


Figure 7. Time domain plots for Test 1, Event 4.

Observational Conclusion

Similar results to Event 1, Event 2 and Event 3. Discontinuities and incorrect levels. In all four events, the MEMS vibration sensor's peak displacement occurs one second after the sensor initially detects the impact. This is seen as an increasing offset in the data before the discontinuity. The MEMS vibration sensor reports the impact time incorrectly.

Frequency Domain Plots Test 1 Event 1

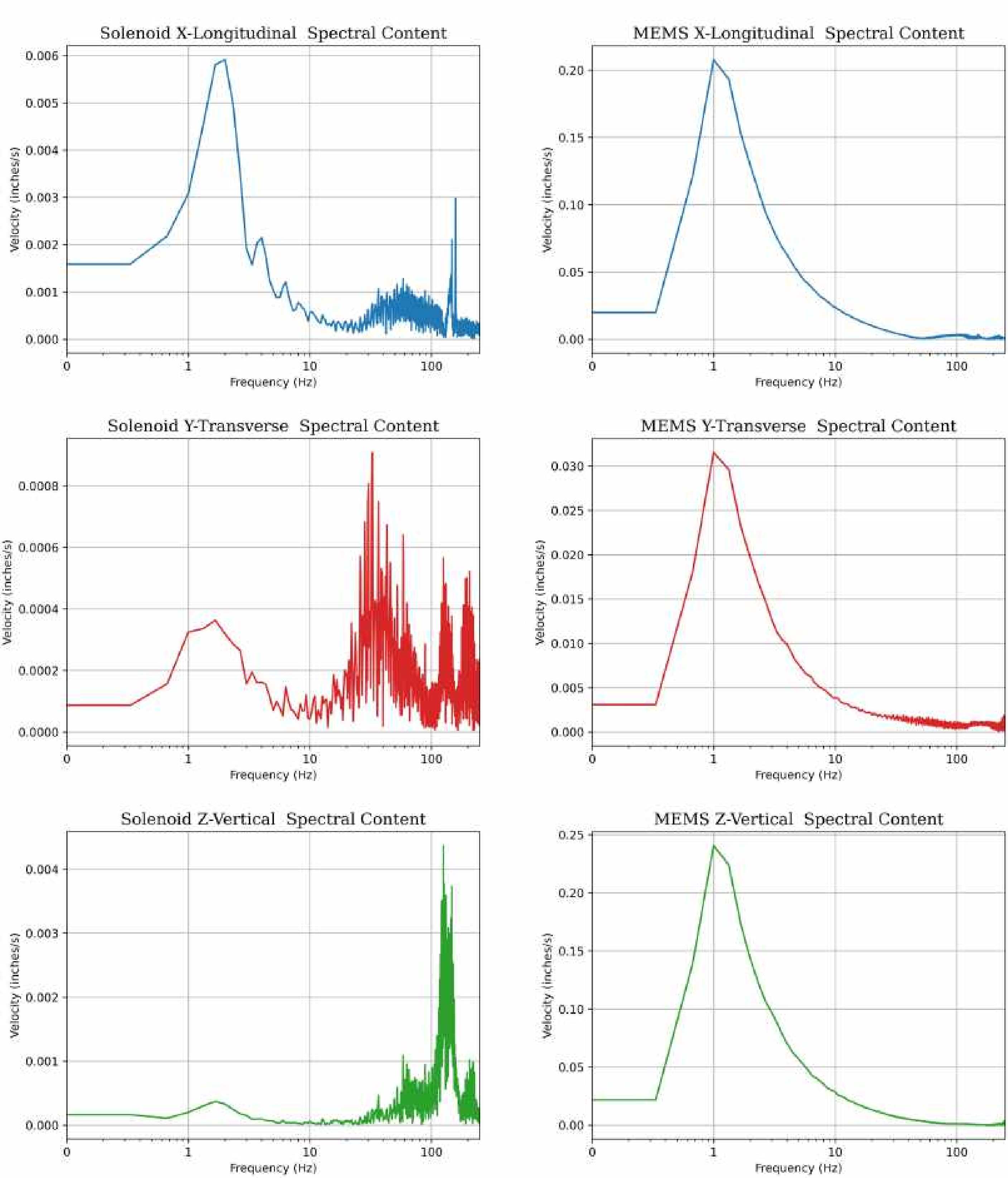


Figure 8. Frequency domain plots for Test 1, Event 1.

Observational Conclusion

The sensors' frequency domain plots reveal that the majority of the frequency data is lost in the MEMS vibration sensor due to the VRE caused by the event. The VRE causes an offset in the data which appears as an extremely large low-frequency signal, obscuring the true frequency data.

Frequency Domain Plots

Test 1 Event 2

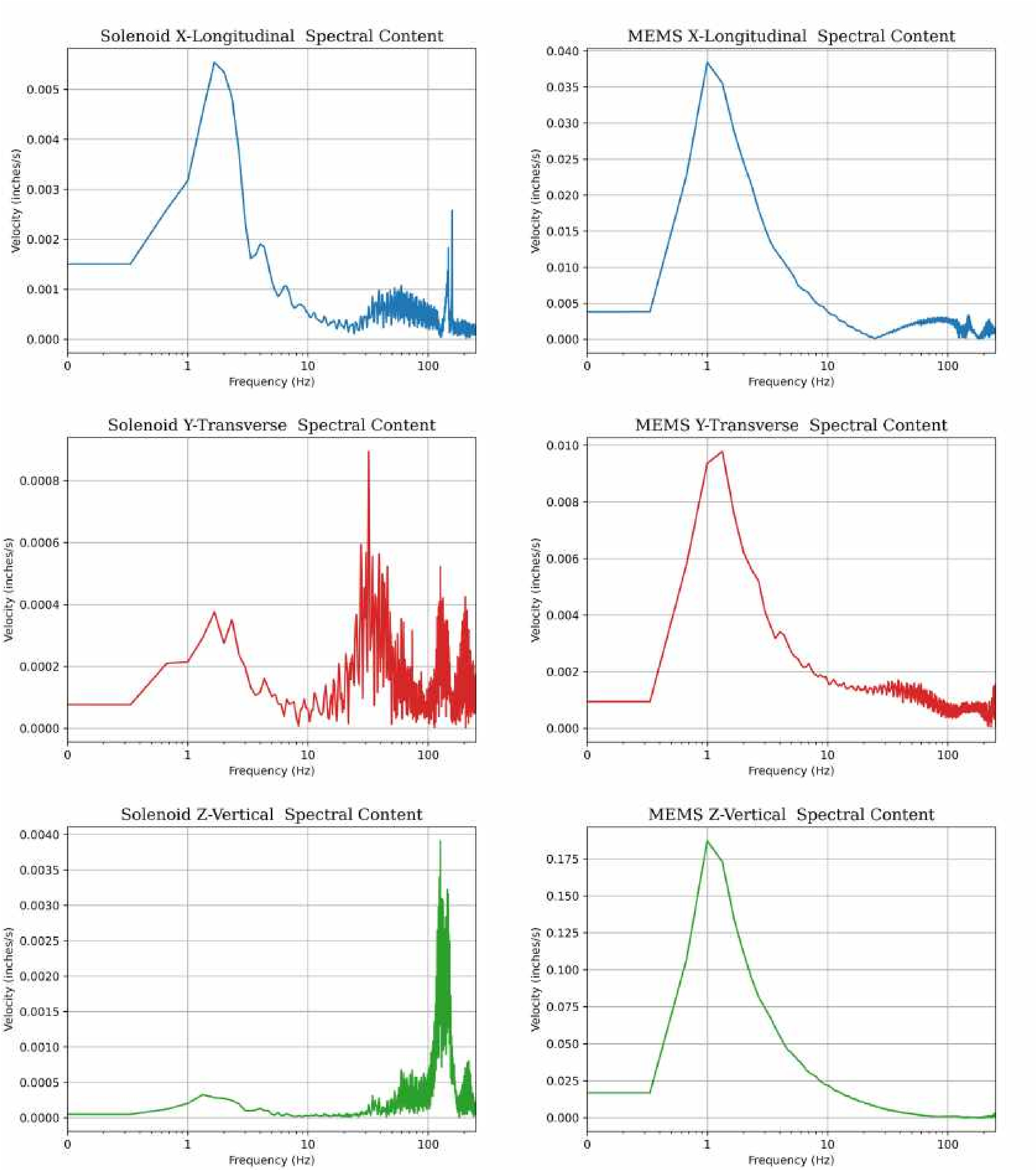


Figure 9. Frequency domain plots for Test 1, Event 2.

Observational Conclusion

Similar to Event 1, the VRE causes an offset in the acceleration data which appears as a false large low-frequency signal in the frequency domain. This spectral content is unusable.

Frequency Domain Plots

Test 1 Event 3

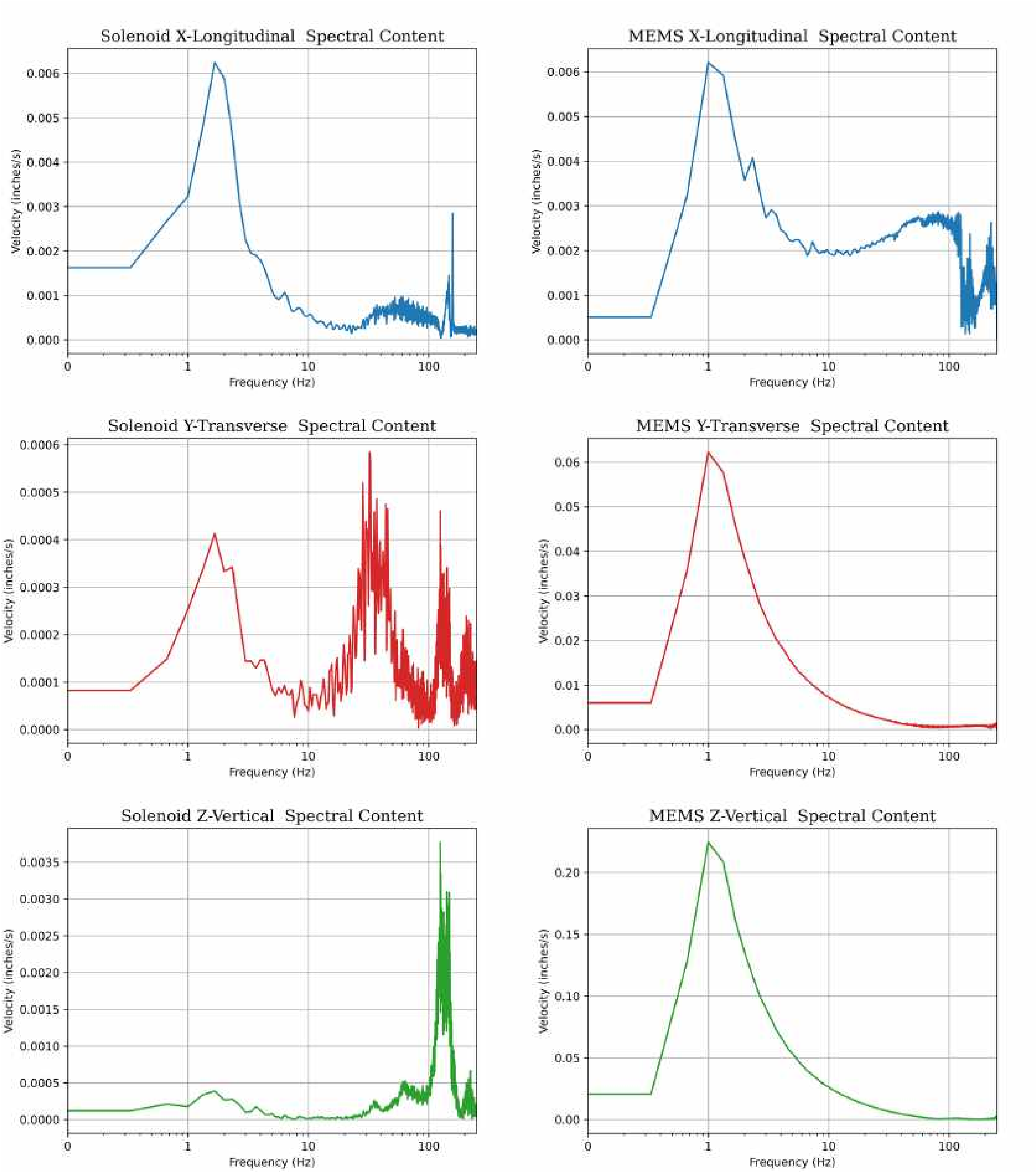


Figure 10. Frequency domain plots for Test 1, Event 3.

Observational Conclusion

Again, a repeat of Event 1 and Event 2 where the true frequency data is lost due to the false low-frequency signal of the VRE. This causes incorrect peak frequencies to be reported.

Frequency Domain Plots

Test 1 Event 4

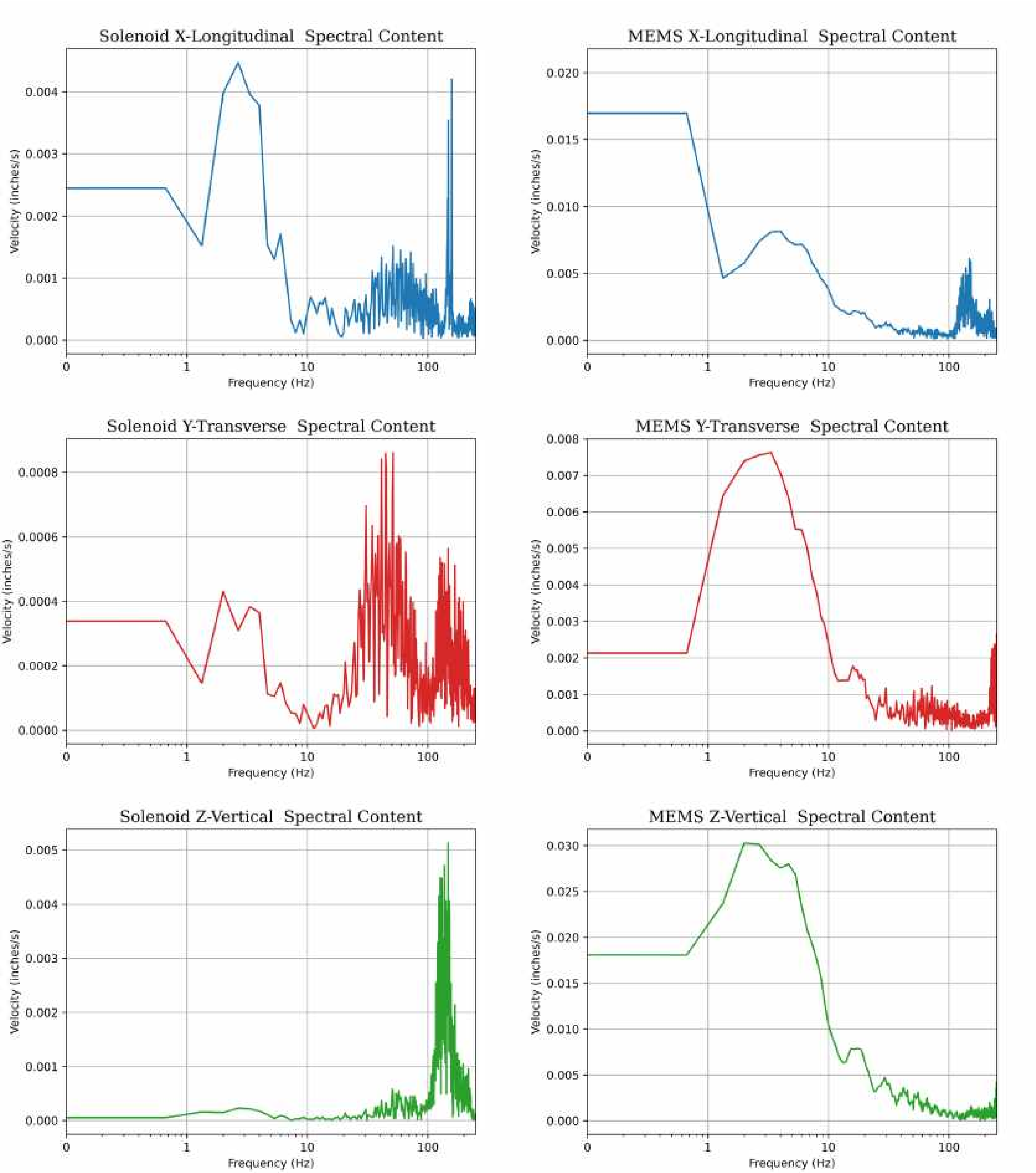


Figure 11. Frequency domain plots for Test 1, Event 4.

Observational Conclusion

As with Event 1, Event 2 and Event 3, the true frequency data is obscured and the peak frequency is misreported. The MEMS vibration sensor is unable to recover the actual event data due to the VRE induced in the sensor itself.

Time Domain and Frequency Domain Analysis of an Event

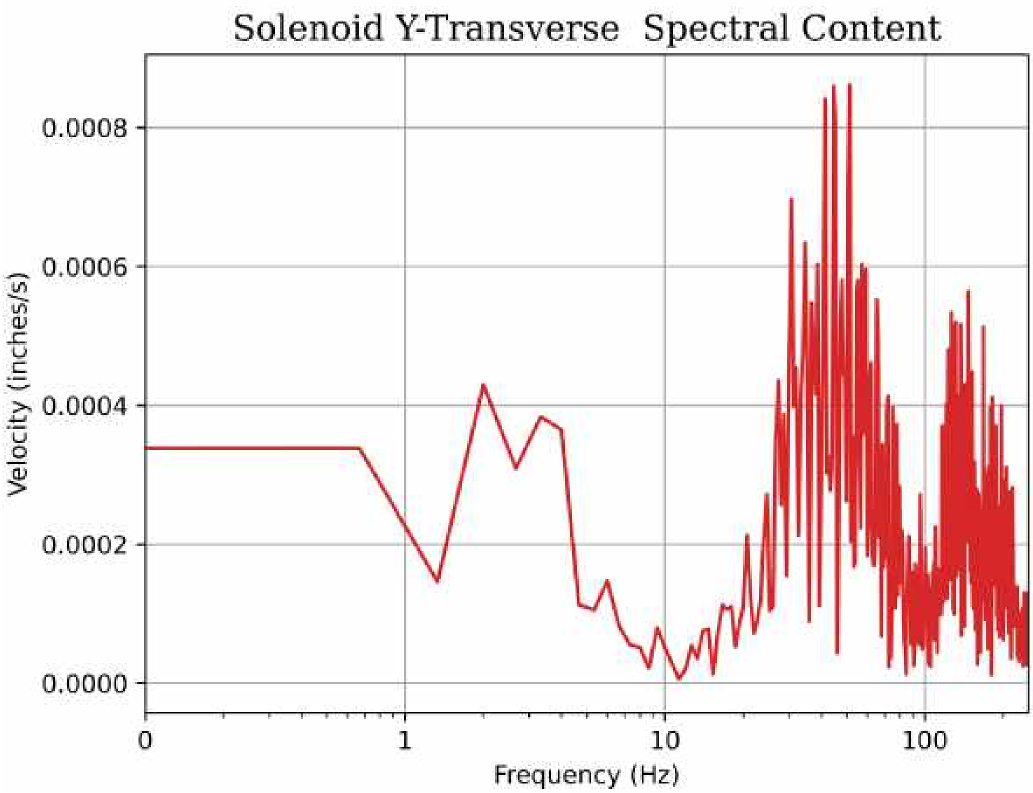
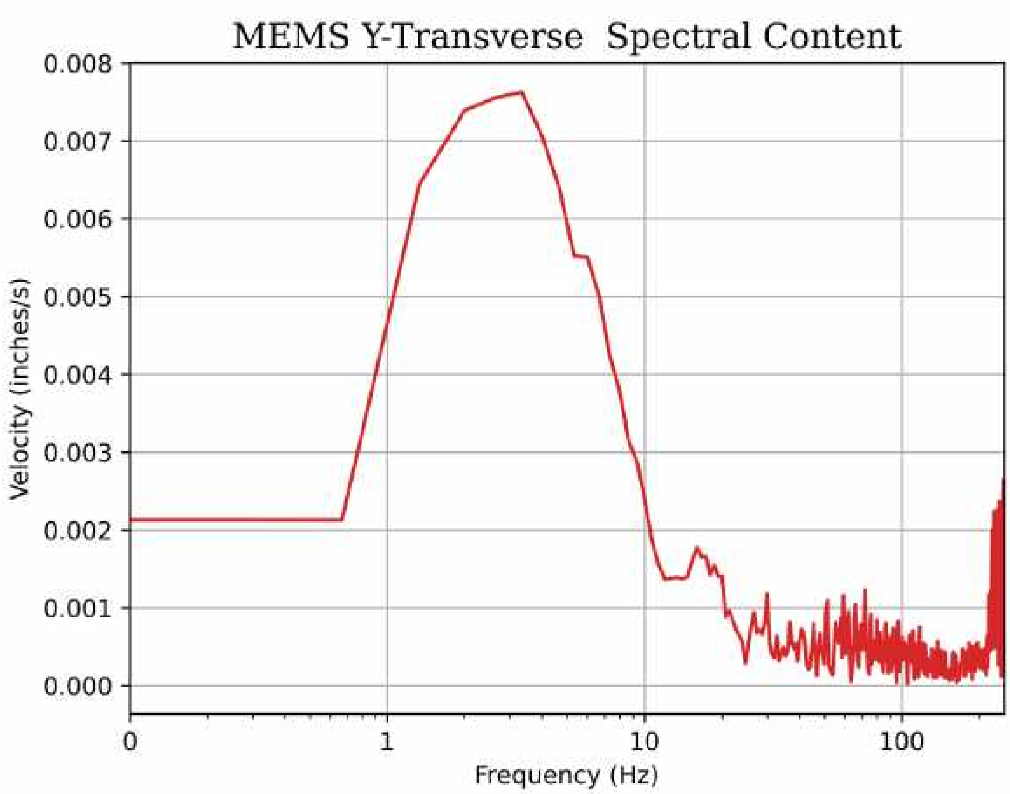


Figure 12. The frequency content of the initial impact and successive bounces as recorded by the solenoid device.

When comparing the results for Test 1 Event 4, Y (Transverse), the frequency domain graphs for the solenoid show a fundamental peak in the 10 Hz to 100 Hz range depending on the axis and a well-distributed set of signals across the band.



The spectral content on the MEMS device is dominated by the VRE at roughly 3 Hz. This impact caused the MEMS to inject a low-frequency offset into the data. Once this occurs, the spectral content is unrecoverable, and the peak values are incorrectly high, resulting in the incorrect frequency being reported and the true event data being lost.

Observational Conclusion

Relatively low-impact hits can cause the MEMS device to report erroneous peak frequencies.

Time Domain and Frequency Domain Analysis of an Event

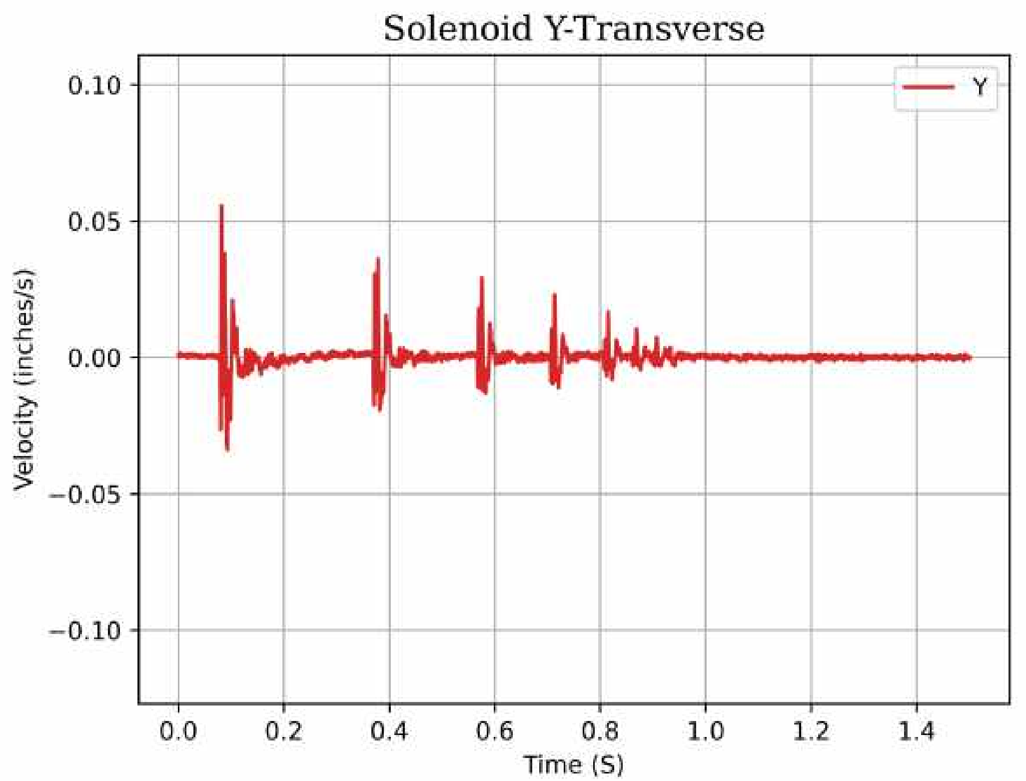


Figure 14. Successive bounces are recorded with diminishing peaks as recorded by the solenoid device.

When comparing the time domain results for Test 1 Event 4, Y (Transverse) we see the initial weight drop occurs just before 0.1 seconds. The repeated and diminishing vibrations represent the weight bouncing off the surface with successive impacts before coming to a complete stop. Each bounce coincides with a lower peak level than the previous one with decreasing time intervals between bounces.

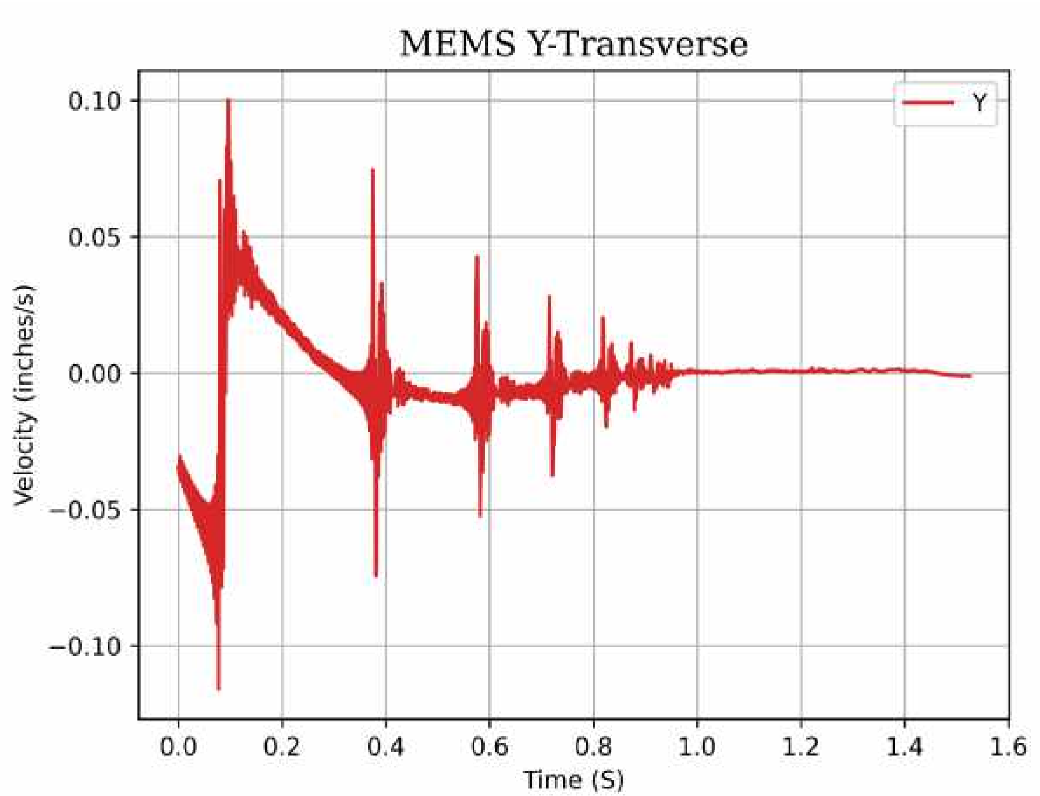


Figure 15. MEMS device exhibiting a VRE discontinuity.

The initial impact causes the MEMS device to exhibit vibration rectification error. This error appears as a constant value at the output of the MEMS internal sensing device and the integration process used to calculate velocity from acceleration quickly 'ramps' the error up to erroneously high values. The discontinuity caused by vibration rectification error is then slowly averaged out. As can be observed at around 0.9 seconds and beyond, it takes the MEMS almost a full second to recover from the vibration error discontinuity and report signals and levels that are closer to expected values as reported by the solenoid device.

Observational Conclusion

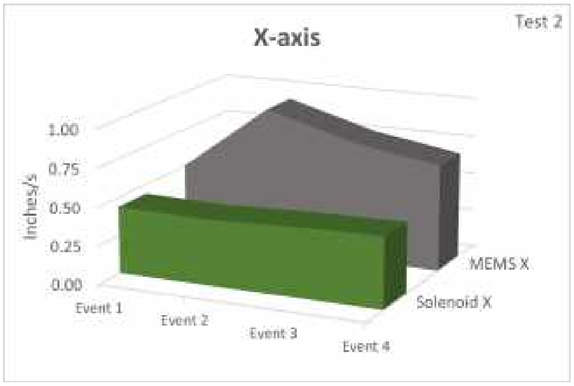
Relatively low-impact hits can cause the MEMS device to report erroneous peak frequencies.

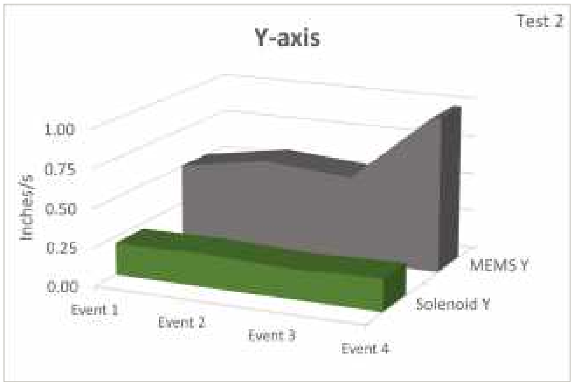
Test Results for Controlled Weight Drop - Test 2

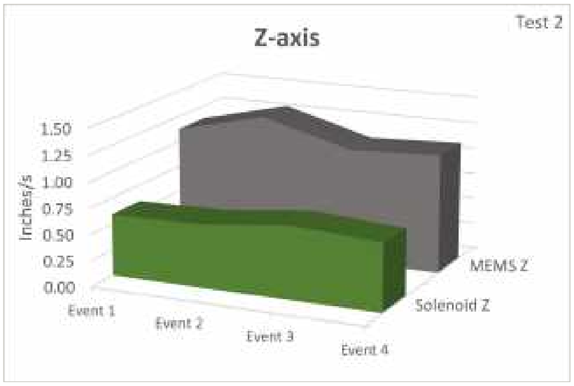
The following data sets represent test variations in height and distance from the solenoid and MEMS devices.

	Weight Drop	Axis	Solenoid Peak (inches/s)	Solenoid Dominant Frequency (Hz)	MEMS Peak (inches/s)	MEMS Dominant Frequency (Hz)
Test 2 Height: 48", Distance from edge: 52.5", Distance from wall: 13"	Event 1	Z	0.593	59.8	1.124	0.5
		X	0.439	123.5	1.171	0.5
		Y	0.208	1.8	0.505	0.5
	Event 2	Z	0.608	1.8	1.330	0.5
		X	0.430	124.0	0.942	0.5
		Y	0.214	2.0	0.598	0.5
	Event 3	Z	0.703	54.2	1.099	1.5
		X	0.452	146.5	0.785	0.5
		Y	0.192	1.8	0.553	1.0
	Event 4	Z	0.646	57.8	1.140	0.5
		X	0.462	121.5	0.693	0.5
		Y	0.209	1.8	1.044	0.5

Table 2. Peak levels and dominant frequencies for controlled weight drop, Test 2.







Standard Deviations

Solenoid	MEMS
X-axis: 0.35	X-axis: 5.32
Y-axis: 0.23	Y-axis: 6.32
Z-axis: 1.24	Z-axis: 2.68

(Up to 107% variation between events.)

MEMS vs. Solenoid
(recorded peak value variations)
X-axis = 167%
Y-axis = 400%
Z-axis = 119%

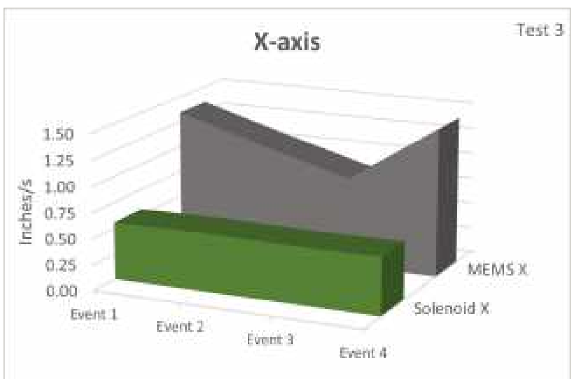
Figure 16. Comparing MEMS versus solenoid peak levels of four weight drops Test 2.

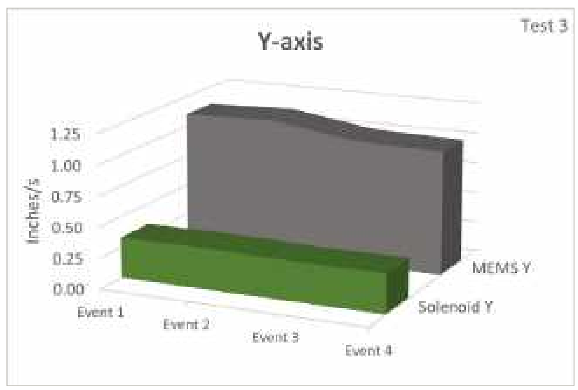
Test Results for Controlled Weight Drop - Test 3

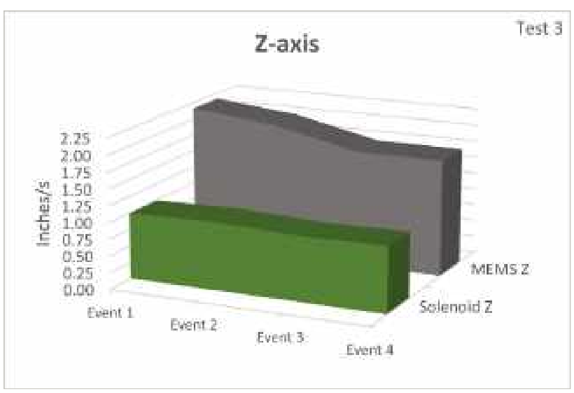
The following data sets represent test variations in height and distance from the solenoid and MEMS devices.

			Solenoid		MEMS	
	Weight Drop	Axis	Peak (inches/s)	Dominant Frequency (Hz)	Peak (inches/s)	Dominant Frequency (Hz)
Test 3 Height: 48.5", Distance from edge: 26.5", Distance from wall: 16"	Event 1	Z	0.995	61.2	2.161	1.5
		X	0.557	147.2	1.342	1.0
		Y	0.330	2.0	1.103	0.5
	Event 2	Z	1.023	59.8	2.030	1.0
		X	0.566	148.2	1.097	1.5
		Y	0.336	2.0	1.129	0.5
	Event 3	Z	0.972	54.5	1.755	0.5
		X	0.552	149.5	0.866	0.5
		Y	0.321	1.8	1.027	0.5
	Event 4	Z	0.990	56.8	1.755	1.5
		X	0.558	148.8	1.436	1.5
		Y	0.324	1.8	1.013	0.5

Table 3. Peak levels and dominant frequencies for each controlled weight drop, Test 3.







Standard Deviations

Solenoid
X-axis: 0.15
Y-axis: 0.18
Z-axis: 0.54

MEMS
X-axis: 6.52
Y-axis: 1.44
Z-axis: 5.18
(Up to 66% variation between events.)

MEMS vs. Solenoid
(recorded peak value variations)
X-axis = 157%
Y-axis = 236%
Z-axis = 117%

Figure 17. Comparing solenoid versus MEMS peak levels of four weight drops Test 3.

Test Results for Controlled Weight Drop - Test 4

The following data sets represent test variations in height and distance from the solenoid and MEMS devices.

			Solenoid		MEMS	
	Weight Drop	Axis	Peak (inches/s)	Dominant Frequency (Hz)	Peak (inches/s)	Dominant Frequency (Hz)
Test 4 Height= 24", Distance from edge: 15", Distance from wall: 13"	Event 1	Z	0.621	61.8	1.769	1.0
		X	0.391	149.0	0.886	0.5
		Y	0.205	1.2	0.248	0.5
	Event 2	Z	0.601	61.0	1.456	0.5
		X	0.384	150.2	0.916	0.5
		Y	0.202	1.5	0.457	0.5
	Event 3	Z	0.630	2.2	1.786	1.0
		X	0.393	151.5	0.849	0.5
		Y	0.210	1.5	0.257	0.5
	Event 4	Z	0.630	2.0	1.730	0.5
		X	0.395	151.8	0.935	0.5
		Y	0.210	2.2	no data reported*	no data reported*

Table 4. Peak levels and dominant frequencies for each controlled weight drop, Test 4.

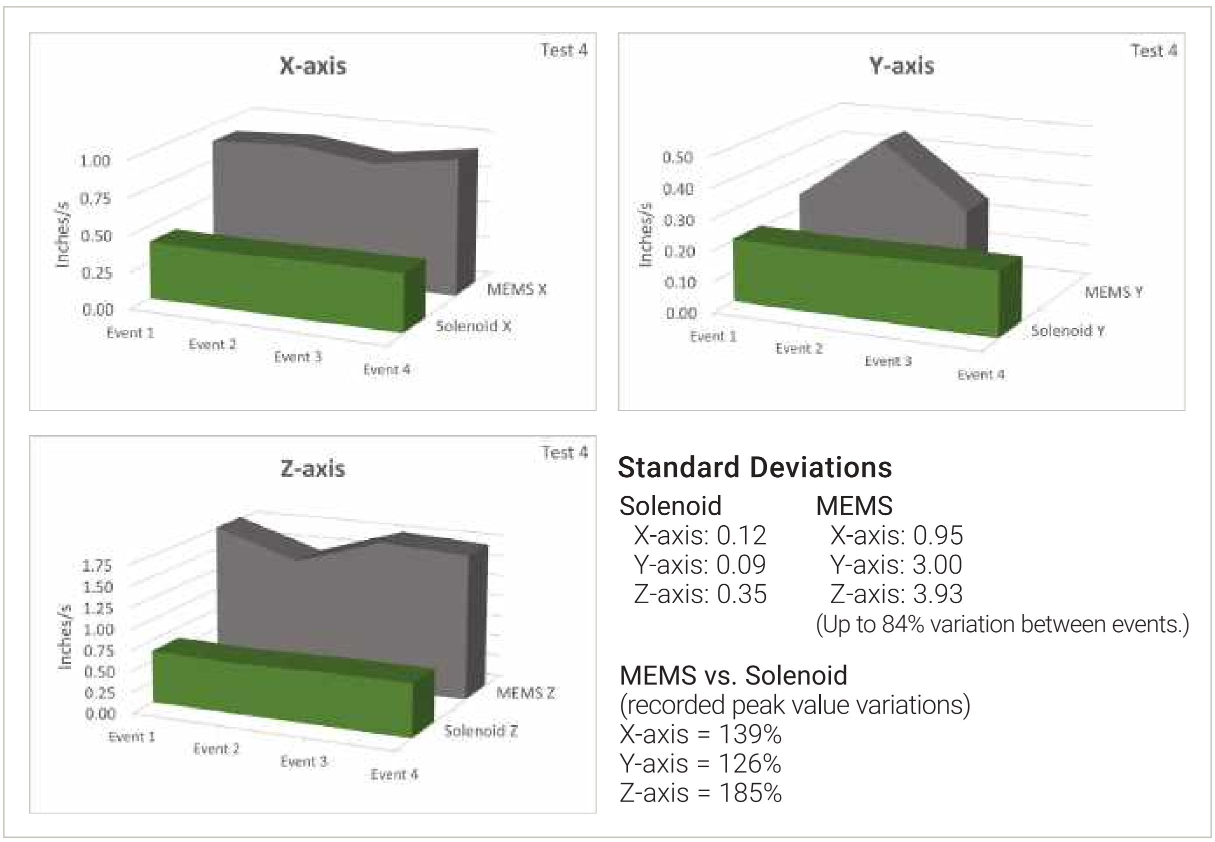


Figure 18. Comparing solenoid versus MEMS peak levels of four weight drops Test 4.

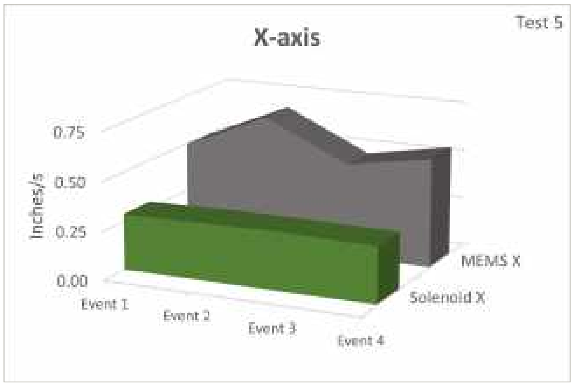
* The device under test did not report any data for this event on this channel, and the cause for this remains unknown.

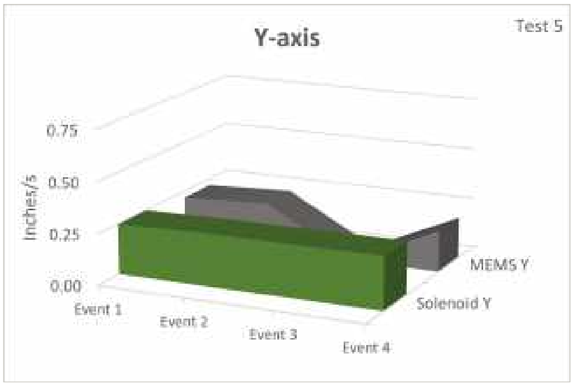
Test Results for Controlled Weight Drop - Test 5

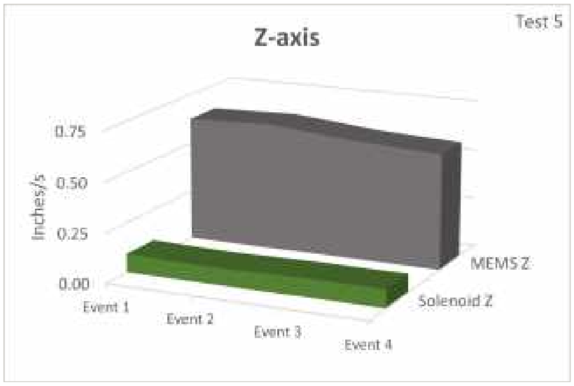
The following data sets represent test variations in height and distance from the solenoid and MEMS devices.

	Weight Drop	Axis	Solenoid Peak (inches/s)	Solenoid Dominant Frequency (Hz)	MEMS Peak (inches/s)	MEMS Dominant Frequency (Hz)
Test 5 Height: 24", Distance from edge: 84.5", Distance from wall: 13"	Event 1	Z	0.093	32.2	0.627	0.5
		X	0.287	127.2	0.496	0.5
		Y	0.250	1.5	0.216	0.5
	Event 2	Z	0.085	42.8	0.640	0.5
		X	0.294	123.5	0.682	0.5
		Y	0.258	2.2	0.236	0.5
	Event 3	Z	0.092	33.5	0.602	0.5
		X	0.296	124.5	0.482	0.5
		Y	0.258	2.2	no data reported*	no data reported*
	Event 4	Z	0.093	33.8	0.582	0.5
		X	0.287	126.5	0.560	0.5
		Y	0.259	2.0	0.202	0.5

Table 5. Peak levels and dominant frequencies for each controlled weight drop, Test 5.







Standard Deviations

Solenoid	MEMS
X-axis: 0.11	X-axis: 2.32
Y-axis: 0.11	Y-axis: 0.43
Z-axis: 0.10	Z-axis: 0.66

(Up to 41% variation between events.)

MEMS vs. Solenoid
(recorded peak value variations)
X-axis = 132%
Y-axis = 28%
Z-axis = 653%

Figure 19. Comparing solenoid versus MEMS peak levels of four weight drops, Test 5.

Observational Conclusion

Across all five tests, the MEMS data shows extreme variation in peak levels. The MEMS device struggled to provide repeatable data despite the impact consistency between events, as shown by the solenoid data. These results continue to show incredibly poor performance.

Across all five tests, the solenoid data have comparable peak levels with very low standard deviations. These values are well within the environmental variations between tests and show a very high level of repeatability across multiple impacts.

* The device under test did not report any data for this event on this channel, and the cause for this remains unknown.

Test Results for Jackhammer Event J1 and Event J2

An electric jackhammer was used to create events of longer duration with 5-second intervals. The jackhammer was applied to the base of the structure. This vibration type has a smaller impact than the weight drops but provides a sustained event with a wide range of frequency content.

		Solenoid		MEMS	
Jackhammer	Axis	Peak (inches/s)	Dominant Frequency (Hz)	Peak (inches/s)	Dominant Frequency (Hz)
Event J1 75"	Z	0.038	50.5	2.712	0.5
	X	0.011	102.2	1.800	1.5
	Y	0.003	223.3	2.508	1
Event J2 48"	Z	0.208	120.8	1.899	0.5
	X	0.007	48.2	0.910	0.5
	Y	0.003	48.2	0.451	0.5

Table 6. Peak levels and dominant frequencies for jackhammer Event J1 and Event J2.

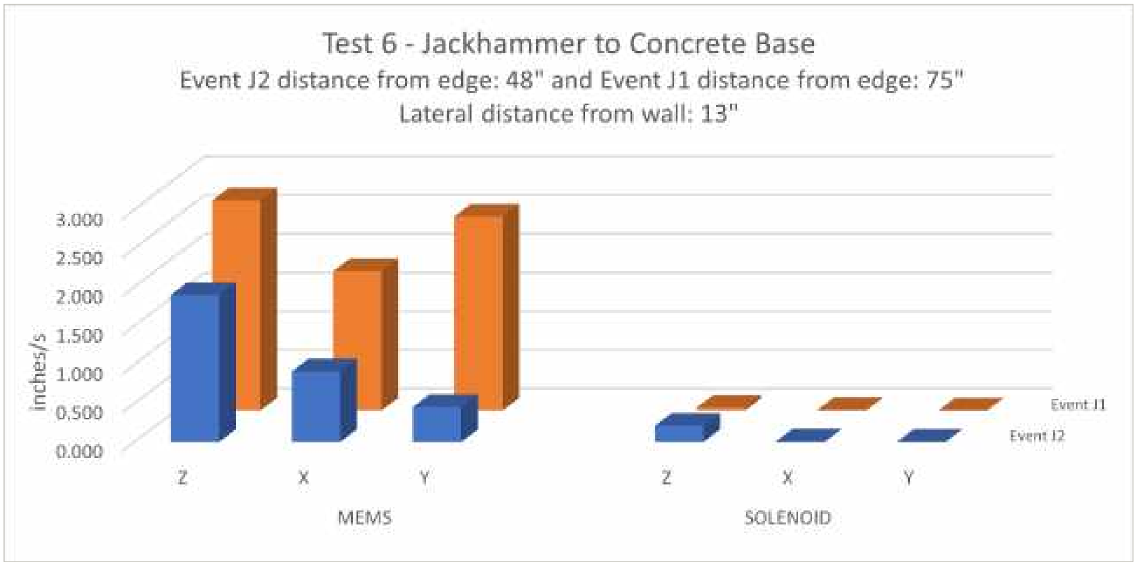


Figure 20. Peak levels of two jackhammer events as recorded by a solenoid device vs. MEMS device.

The MEMS device failed to capture much of the high-frequency content and incorrectly reported peak data at the 1 Hz frequency. The reported levels were much higher than the actual event. This is due to vibration rectification error causing the MEMS device to report false data. The continuous nature of the jackhammer means that this error mode occurs very often, with reported peak values much higher throughout the entire measurement time.

Expanded Jackhammer Data

Figure 21 expands the jackhammer strike data for event J1 with plots in the time domain, solenoid (left), MEMS (right). The X-axis is in blue, the Y-axis is in red and the Z-axis is in green.

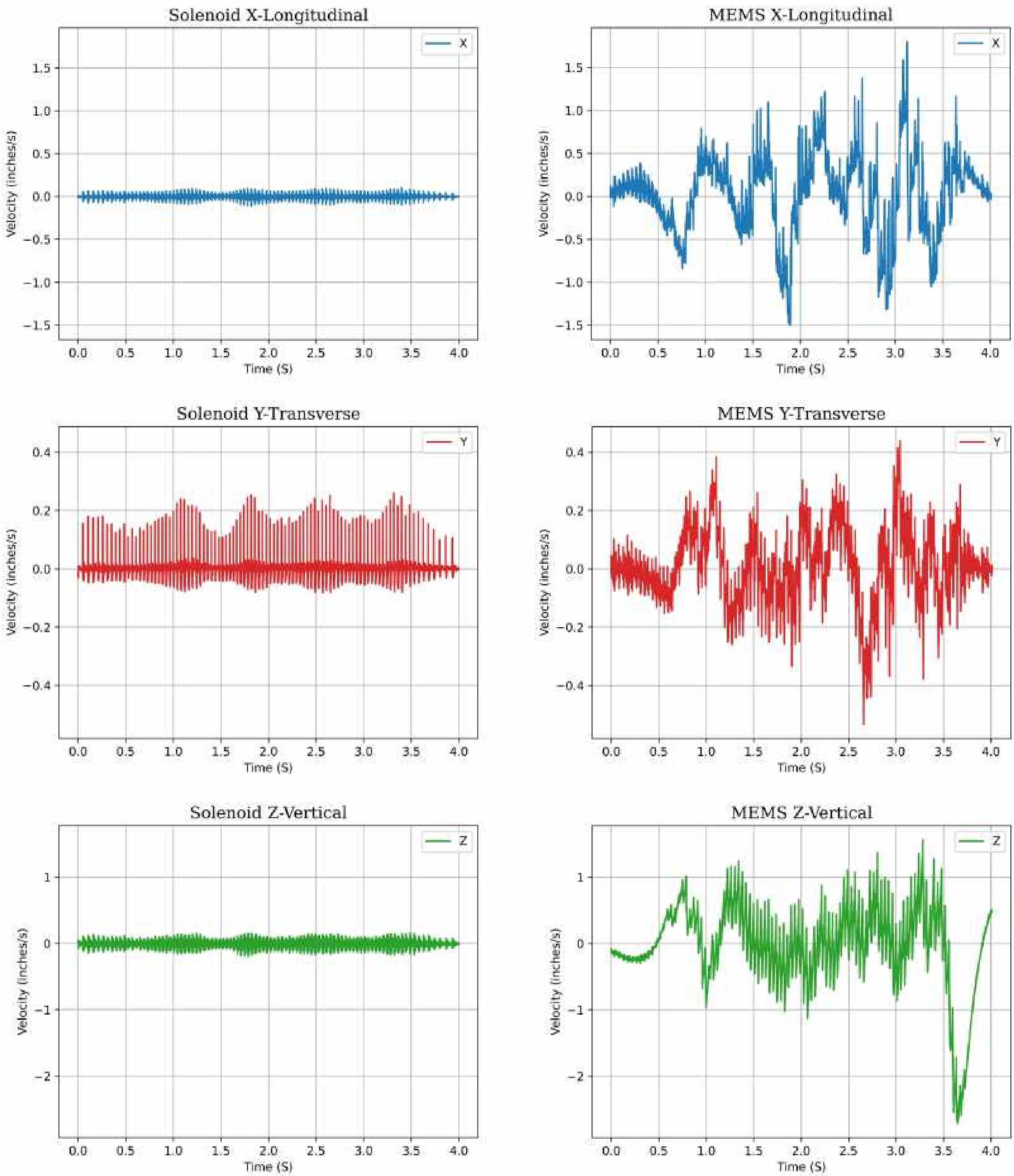


Figure 21. Jackhammer time domain data solenoid (left) MEMS (right), Event J1.

Observational Conclusion

The jackhammer generated frequencies that caused VRE failure in the MEMS device. This resulted in the loss of both time domain and frequency data.

Expanded Jackhammer Data

Figure 22 expands the jackhammer strike data for event J1 with plots in frequency domain, solenoid (left), MEMS (right). The X-axis is in blue, the Y-axis is in red and the Z-axis is in green.

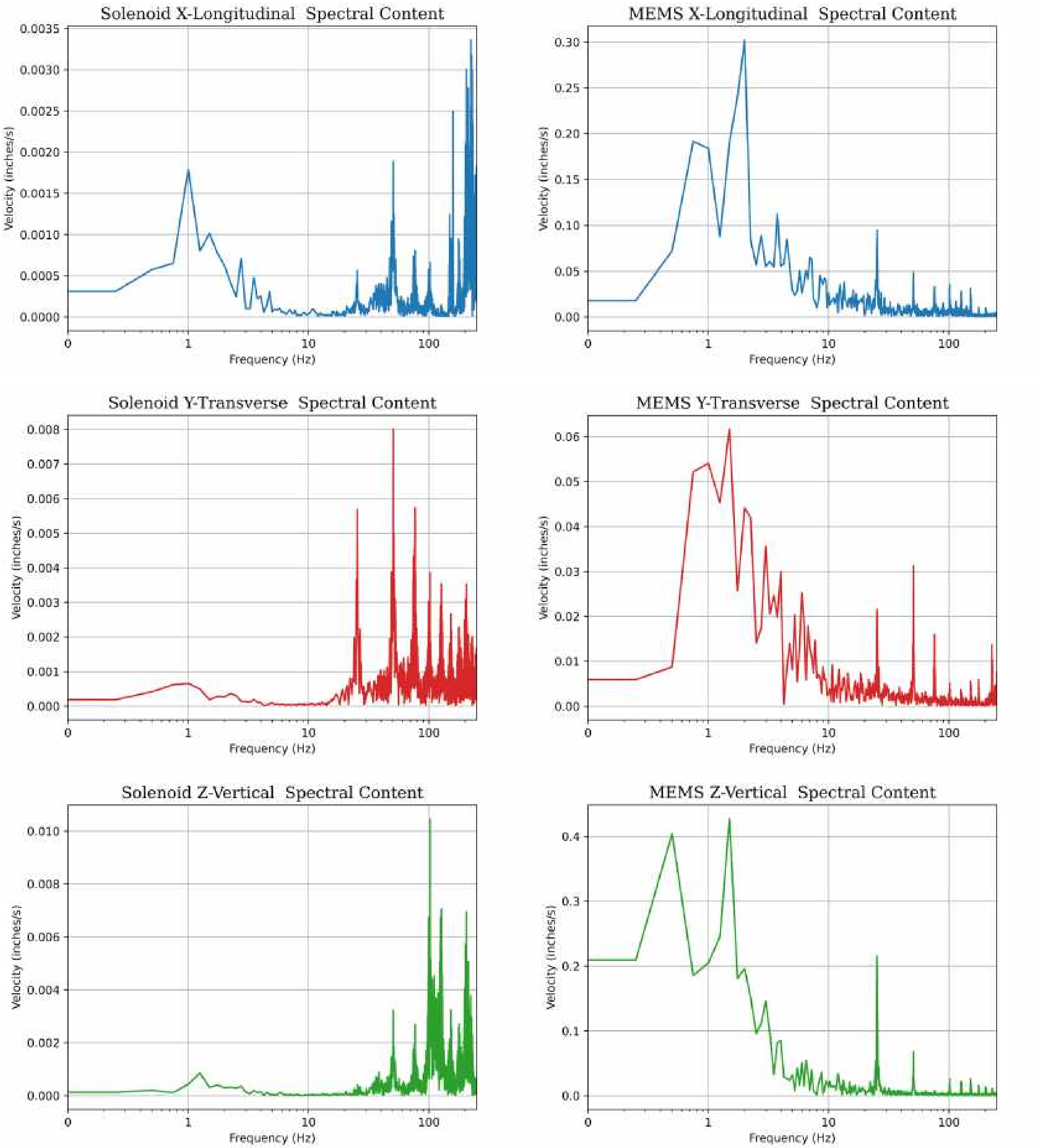


Figure 22. Jackhammer frequency domain data with the solenoid (left) MEMS (right), Event J1.

Observational Conclusion

The VRE in the MEMS device caused it to falsely report low-frequency peaks that mask the true spectral content of the actual signal.

Expanded Jackhammer Data

Figure 23 expands the jackhammer strike data for event J2 with plots in the time domain, solenoid (left), MEMS (right). The X-axis is in blue, the Y-axis is in red and the Z-axis is in green.

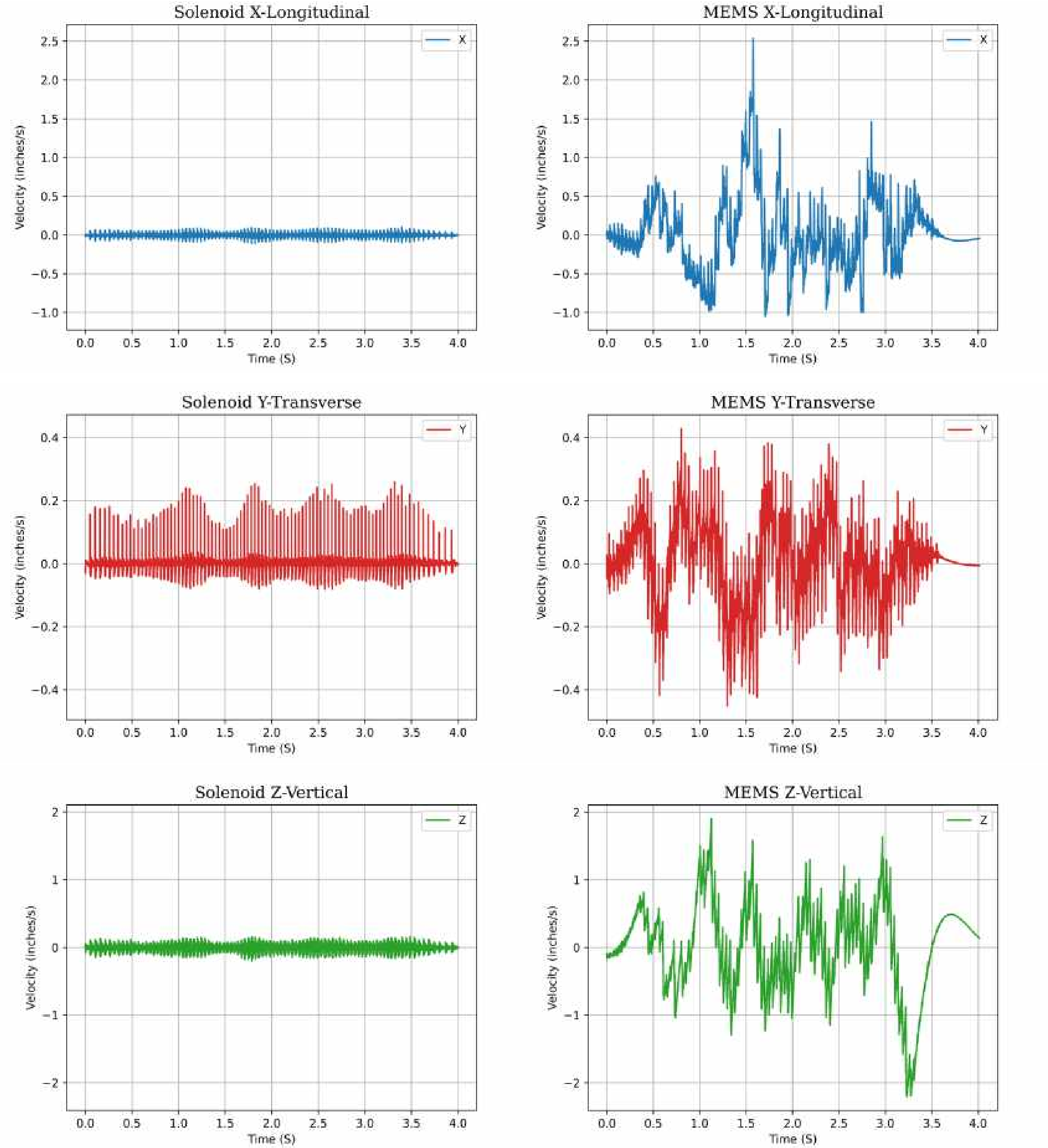


Figure 23. Jackhammer time domain data, solenoid (left) MEMS (right), Event J2.

Observational Conclusion

The MEMS device experienced VRE failure with jackhammer vibrations. This resulted in the loss of both time domain and frequency data.

Expanded Jackhammer Data

Figure 24 expands the jackhammer strike data for event J2 with plots in the frequency domain, solenoid (left), MEMS (right). The X-axis is in blue, the Y-axis is in red and the Z-axis is in green.

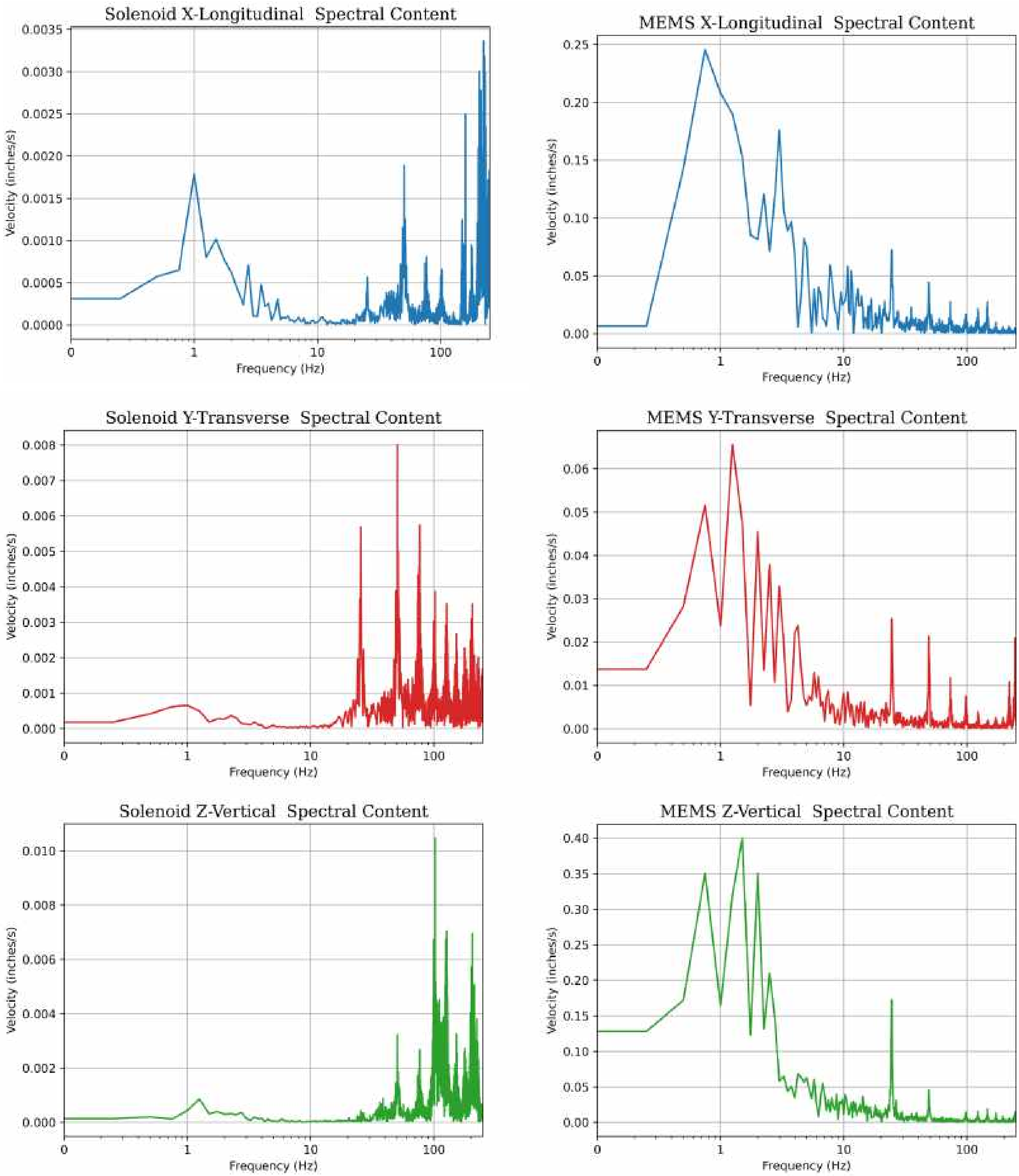


Figure 24. Jackhammer frequency domain data solenoid (left), MEMS (right), Event J2.

Observational Conclusion

The VRE in the MEMS device caused it to falsely report low-frequency peaks that mask the true spectral content of the actual signal.

Urban Construction Site - Hoe Ram Rock Breaker

The solenoid and MEMS vibration sensors were installed on an active construction site in Ottawa. A hoe ram was used to fracture the bedrock in order to excavate an underground parking area for a seven-story mid-rise project.

Both the solenoid and MEMS vibration sensors were configured to the ISEE-2017 Performance Specification for Blasting Seismographs. The vibrations on the active construction site were considerably below the ISEE specifications, prompting both devices to be set to very sensitive levels to maximize data collection. The trigger level for event storage on the MEMS device was set to 0.0276 in/s (0.7 mm/s) which was the lowest possible setting. The solenoid geophone was configured to 0.0197 in/s (0.5 mm/s) to guarantee capturing all events that the MEMS device recorded.

Figure 25. Urban construction site breaking through bedrock.

At the time of monitoring, the active hoe ram was operating in an excavation area roughly 18 feet deep, and the building being monitored was eight feet from the nearest edge of the construction site. Total excavation site was 95 feet by 82 feet with vertical walls.

Though vibration levels at this construction site were low, vibration waveform patterns for the solenoid geophone were consistent and as expected, where MEMS produced irregularities.

The MEMS vibration sensor occasionally triggered and recorded data when the solenoid, configured for higher sensitivity, did not. An instance of these uniquely recorded events by the MEMS device is illustrated in the time and frequency domain graph (Figure 27).

Surprisingly, the vibration rectification error effects were detectable with this MEMS vibration sensor even at minimal overall vibration levels. Time domain data revealed an offset from 0 inches/s that started to rise before a discontinuity appeared in the data approximately 250 to 500 milliseconds later across all channels. This effect was particularly noticeable in the Y and Z axes. After the discontinuity, it required approximately 0.75 to 1 second for the signal to stabilize. In the frequency data we see the characteristic 1 Hz peaks, a result of the VRE being integrated from acceleration to velocity.

The evidence suggests that the MEMS vibration sensor will exhibit VRE errors even when the vibration is well below the compliance standards. Its sensitivity to higher frequencies leading to vibration rectification is not solely a byproduct of high signals but instead the sensor is prone to failure even at low-level signals. In this case, the higher frequencies outside of the measurement band caused the MEMS vibration sensor to trigger and report inaccurate data. Accurately, the solenoid geophone did not detect signals. The true vibrations at the site within the frequencies of concern were likely more in the sub 0.025 inches/s range, as corroborated by the data recorded on either side of this anomaly.

Figure 26. The MEMS and solenoid devices were mounted side-by-side along a concrete wall on an adjacent building to the construction site, 18 inches above the ground.

In instances where both the solenoid and MEMS vibration sensors captured data (Figure 28 and Figure 29), the MEMS data exhibited a certain level of variability, undulating above and below the 0 inches/s point. This is particularly noticeable in the X and Y axes of the MEMS vibration sensor. In contrast, the solenoid data followed expected patterns, with a more natural signal centered around 0 inches/s and symmetrical peaks on the positive and negative velocities. As evidenced in previous data, this drift seen in the MEMS vibration sensor can be attributed to the VRE causing an offset, which then integrates into an error during the conversion from acceleration to velocity. This drifting causes inconsistent peak values for each of the hoe ram impacts.

Urban Construction Site - Hoe Ram Rock Breaker

Time Domain and Frequency Domain Plots of a Non-Event

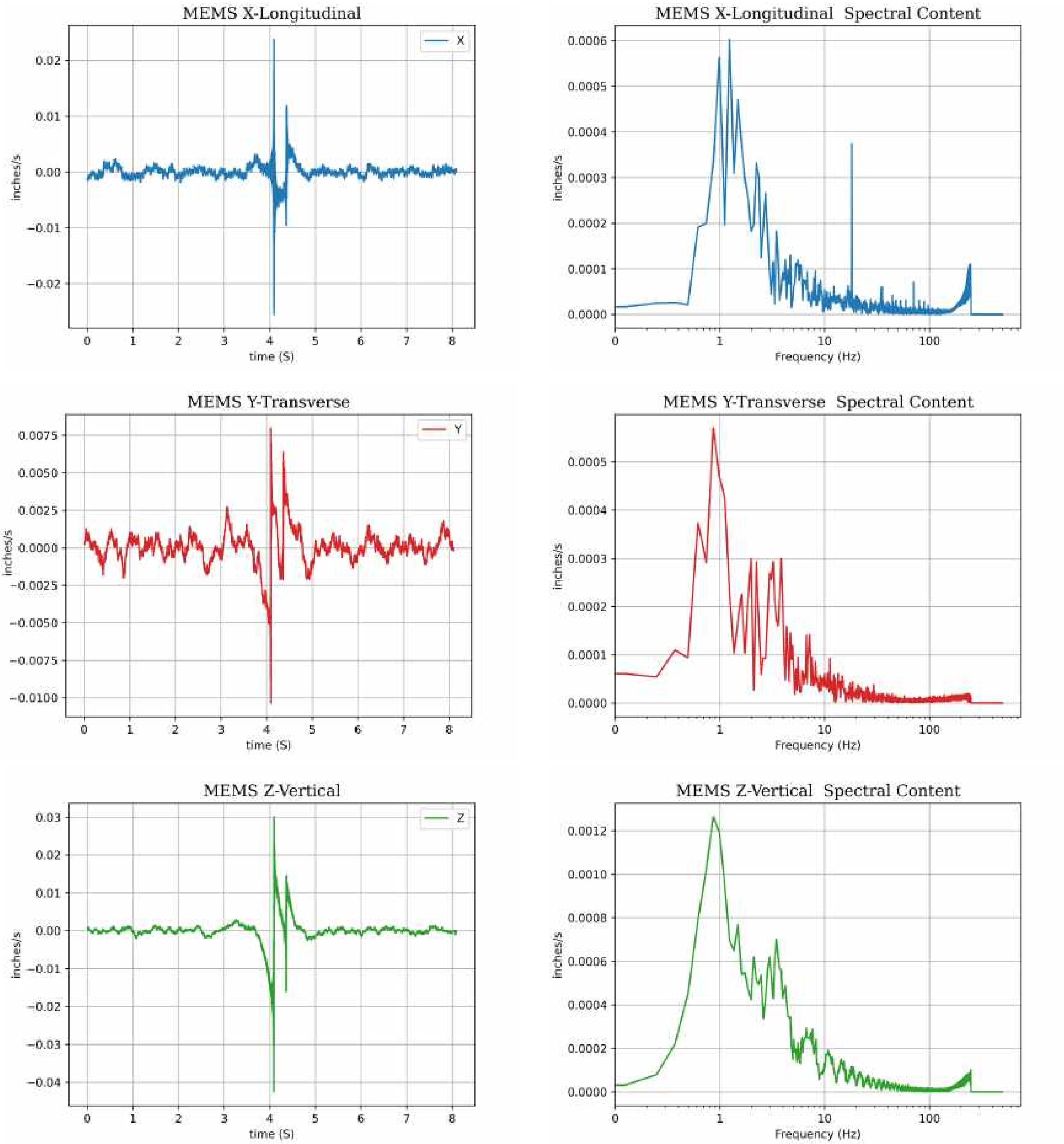


Figure 27. Hoe ram rock breaker time and frequency domain data for MEMS recording a non-event.

Urban Construction Site - Hoe Ram Rock Breaker Time Domain Plots

Figure 28 expands the hoe ram rock breaker data plots in the time domain, solenoid (left), MEMS (right). The X-axis is in blue, the Y-axis is in red and the Z-axis is in green.

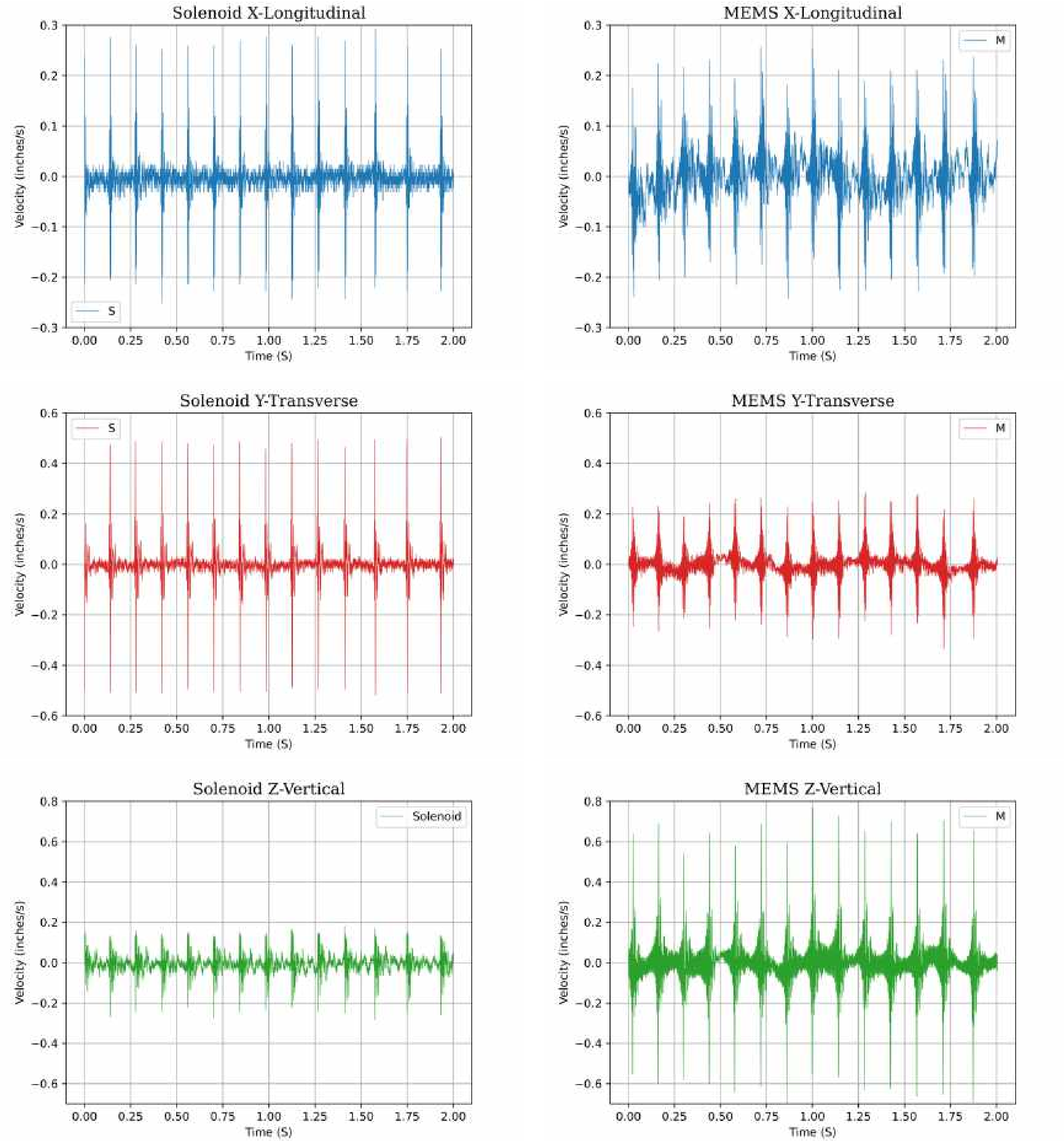


Figure 28. Hoe ram rock breaker time domain data for solenoid (left) and MEMS (right).

Urban Construction Site - Hoe Ram Rock Breaker Frequency Domain Plots

Figure 29 expands the hoe ram rock breaker data plots in the frequency domain, solenoid (left), MEMS (right). The X-axis is in blue, the Y-axis is in red and the Z-axis is in green.

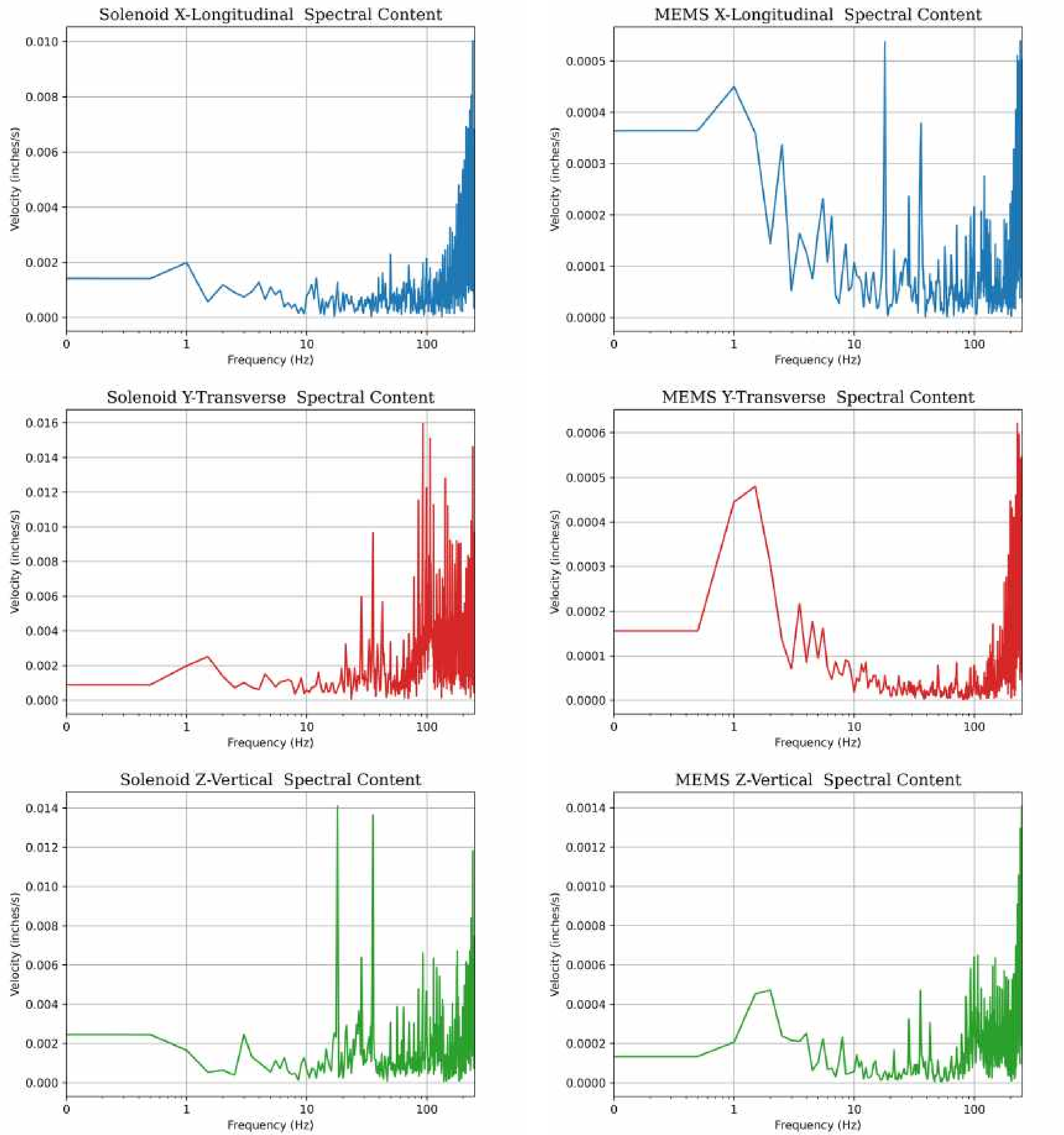


Figure 29. Hoe ram rock breaker frequency domain data for solenoid (left) and MEMS (right).

Conclusions

Though the tested MEMS vibration sensors offer the advantages of smaller size and self-leveling, they are ill-suited for reliably capturing and reporting vibration events in industrial, construction and blasting industries.

While the frequencies of interest only extend to a few hundred hertz, as these are the frequencies that can cause damage, the actual frequencies created by everyday events extend into the kilohertz range. Such vibrations may not cause structural damage but they cause a MEMS sensor on the commonly available ADXL355 or ADXL357 chips to report erroneous data due to the vibration rectification error (VRE) issue.

All sensors must measure vibration as a velocity, usually in inches/s or mm/s. Solenoid sensors measure this directly, while MEMS vibration sensors measure acceleration and must use integration over time to calculate velocity. Any small amount of noise or ‘DC’ error present at the sensor’s input can get amplified to a substantial error, as evidenced by the data presented here.

Our tests have shown that these factors caused false reports and exceedances of the compliance standard being tested against, as well as completely masking actual exceedances.

The frequencies that geophones encounter on a job site cannot be controlled. There is no way to ensure that these higher frequencies are mechanically filtered out before the MEMS device samples the data. The type of MEMS vibration sensors used in the tested device are sensitive to frequencies starting in the 1 kHz range which, as shown, are incredibly easy to generate using common events on a construction or blasting site. Our opinion is that this type of sensor should not be trusted for compliance reporting in the vibration monitoring industry.

What Are MEMS Accelerometers and How Do They Measure Acceleration?

Accelerometers work on the principle of measuring the force that is exerted on a mass due to acceleration. The most common type of accelerometer used in modern electronics is based on the Micro-Electro-Mechanical Systems (MEMS) technology. A MEMS sensor consists of a tiny mass, known as the "proof mass", that is suspended by a set of springs. The proof mass is typically made of silicon or quartz, and is etched with a pattern of electrodes that allows it to detect the force of acceleration. When a MEMS sensor experiences an acceleration, the proof mass moves relative to the accelerometer's anchors due to the inertia of the proof mass. As the proof mass moves, it causes a change in capacitance between the electrodes on the proof mass and those on the accelerometer's anchors.

This change in capacitance is measured by the accelerometer's electronics and is proportional to the acceleration experienced by the proof mass. To cover the full required range for vibration compliance monitoring, the tested MEMS vibration sensor contains a set of six MEMS chips, three ADXL355 chips to measure acceleration up to 2g and three ADXL357 chips to measure acceleration up to 40g.

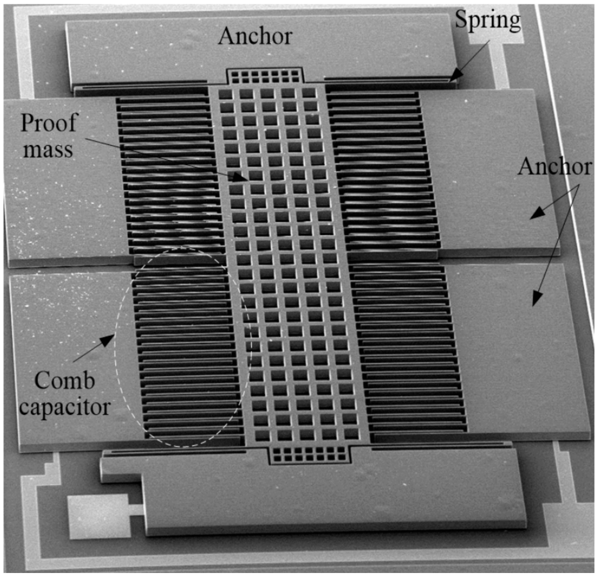


Figure 30. The main components of a MEMS accelerometer: Proof Mass, Springs, Anchors and Comb capacitors[1] (for illustrative purposes only).

MEMS sensors must convert acceleration measurements into velocity

Solenoid sensors are electromechanical devices that measure velocity directly. They are composed of a mass attached to a flexible spring surrounded by a coil and magnet. When ground movements offset the magnet in relation to the coil, the change in the electrical field induces an electric current that can be measured to determine the amplitude and velocity of the ground movement.

MEMS sensors measure acceleration instead of velocity. The vibration monitoring industry however, requires velocity. MEMS must therefore convert acceleration measurements into velocity. To do this mathematically, they must integrate the acceleration values over time to produce velocity values.

In ideal conditions, this conversion is generally acceptable. Correct velocity data can be determined from the acceleration data (aside from the velocity data being slightly delayed due to the integration process). In the real-world, measurements are rarely under ideal conditions.

Errors in the acceleration data from a MEMS sensor appear both as false values as well as an offset in the signal. When the acceleration data gets converted to velocity (by integrated over time), the errors are magnified. The result is incorrect velocity data that consists of erroneous data with incorrect frequencies and levels being reported. Often, the true vibration data is completely obscured by the false data.

1. Jiangbo He and Wu Zhou et al. " Structural Designing of a MEMS Capacitive Accelerometer for Low Temperature Coefficient and High Linearity", MDPI. Technical Article. https://pdfs.semanticscholar.org/5780/6ecb5be5d2edcdb25bd285a4181f0bef508a.pdf

Vibration Rectification Error (VRE) Summary

Vibration Rectification Error (VRE) in MEMS vibration sensors is a prominent phenomenon that occurs when mechanical vibrations cause non-linearities in the sensor's response, resulting in errors in the measured signal. One unavoidable error occurs when the sensor measures a vibration frequency equivalent to the natural frequency of the sensor's internal structures amplifying the sensor's output signal. This effect is known as resonance. When the mechanical vibration frequency matches the MEMS natural frequency, the MEMS begins to resonate, causing the output to increase significantly, leading to false acceleration signals which can corrupt the real data. Converting the acceleration (the natural output of a MEMS vibration sensor) to velocity (used in our industry) introduces an error that builds on itself, resulting in invalid data being reported against the compliance standards.

Advantages Versus Disadvantages of Solenoid and MEMS Devices

Solenoid Advantages

- Highly reliable and linear.
- Used extensively in geophone sensors for over 70 years.
- Particularly sensitive in the desired frequency range of 2 Hz to 250 Hz (ISEE Standard) and 1 Hz to 315 Hz (DIN Standard).
- Signals are directly proportional to vibration velocity (inches/s or mm/s).
- Directly measures velocity, the unit of measurement that is specified in compliance standards.

Solenoid Disadvantages

- Triaxial geophones must have their three axes level, and closely aligned with the calibration orientation.
- Occupies more physical space.

MEMS Advantages

- Can be mounted off-level without a significant impact on their output.
- Easy on-site installation.
- Occupies less physical space.

MEMS Disadvantages

- Non-linear output.
- High noise floor relative to solenoid.[2]
- Sensitive to generation of false data with high frequency vibrations.
- Less sensitive to low signals when compared to a solenoid sensor.
- Limited dynamic range of measurement.
- Multiple sensors must be incorporated into a geophone to cover the full range of up to 10 inches/s (254 mm/s) that must be measured under the ISEE and DIN 45669-1 standards. A 40g accelerometer is required to measure up to 10 inches/s at 246 Hz.
- Measures acceleration (m/s^2) rather than velocity.
- Any errors (i.e. integration) due to DC imbalances that appear on the accelerometer output (commonly caused by Vibration Rectification Error) will be integrated into a ramp that will eventually exceed the magnitude of any actual vibration and become the dominant output waveform.
- May cause false readings and consequently, incorrect compliance reports.

2. Long Pham and Anthony DeSimone, "Vibration Rectification in MEMS Accelerometers", Analog Devices, Inc. Technical Article, https://www.analog.com/media/en/technical-documentation/tech-articles/vibration-rectification-in-mems-accelerometers.pdf

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