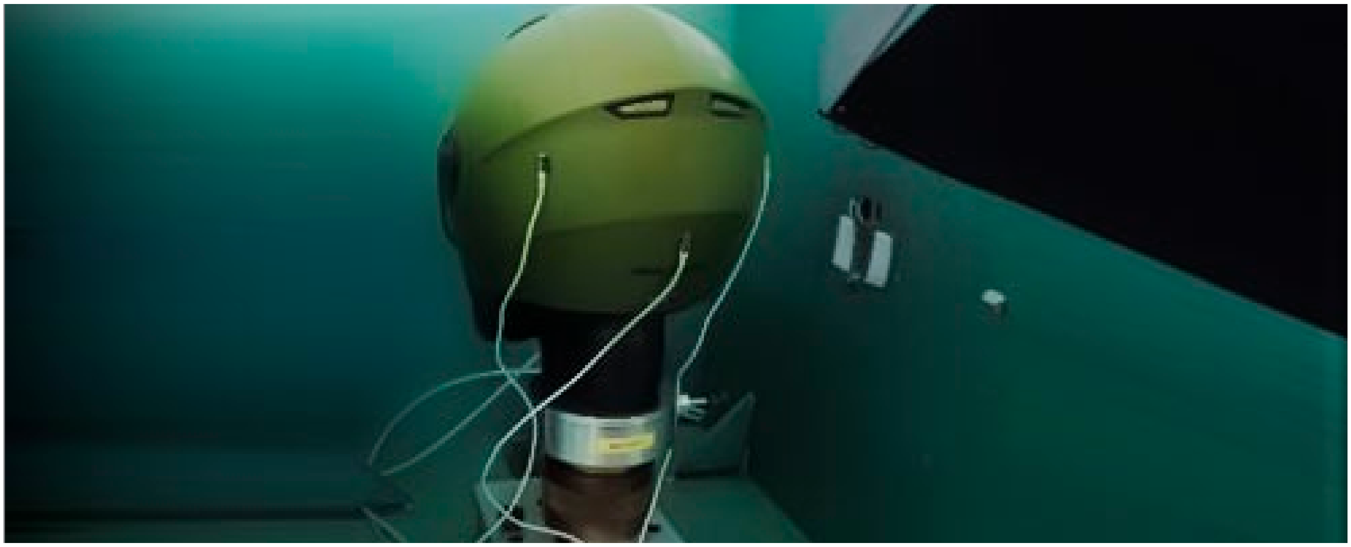

Lessons Learned from the Advancements of Shock Sensors for Product Testing

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Impact testing for product development and verification requires the user to first determine the correct parameters to measure, and then to select the best sensor to make those measurements. Due to the unique qualities to the object under test, there is often no industry standard to fall back on in making that determination. Yet, manufacturers, certifying bodies, and test houses all need reliable methods for validating equipment, especially when that equipment effects human safety. This paper explores advancements in shock sensors, including multi-mode damping, ESD protection and low noise cables. We will compare the legacy and new technologies, and demonstrate the improvements in the new offerings.

Lesson One: The Advantages of Multi-Mode Damping

It seems counterintuitive that you can break a 2,000 g accelerometer by dropping it on the floor, but this happens in many facilities all over the world. Did the accelerometer see more than 2,000 g's in the fall? Maybe, but it is more likely the impact introduced resonances that were responsible for the damage. Many assume that the benefit of damping is to protect the sensor in the application, which is true, but it is also true that the accelerometer is most vulnerable to damage before it is mounted. Once properly mounted, the accelerometer is ready to serve as a relative motion sensor to the unit under test (UUT). Before that step, it may be hit at an angle, struck by another sensor thrown into a bin, or unintentionally shocked with electrostatic charge. Failure analysis in these situations can become contentious, as there is no way to determine whether a sensor was defective or mishandled.

As a supplier of thousands of accelerometers each year, we needed a way to help our customers and ourselves by minimizing accelerometer damage in the field. Damping is the obvious solution, but which is best: oil damping or gas damping? Oil damping has limitations in terms of the types of sensing elements it can damp, risks affecting the sensor's performance over temperature, and can result in poor frequency response. Gas damping has its own challenges, as it is harder to control the amount of damping, measure how much damping you have, and generally less effective at eliminating resonance. Oil damping is only practical on bulk strain gages and is messy and costly, while piezoresistive MEMS have too small internal volume for fluid fill. Although with an oil damped sensor you can tightly control the damping at room temperature, the fluid becomes more viscous at low temperatures and more runny at high temperatures, changing the performance of the sensor significantly. So, gas damping of piezoresistive accelerometers was the best way forward, but how could we get enough useful damping without limiting frequency response?

Piezoresistive MEMS accelerometers are manufactured using semiconductor-type processes, with each sensor based on a stack of three wafers: a core (middle location including the seismic mass), a base (the support on the bottom) and a lid (the cover on top). These three wafers are bonded together, and during this process we introduce pressure and temperature to control the amount of gas sealed inside the accelerometer. A combination of damping features on the mass, spacing of the wafers (the gap), and the pressure sealed inside control the amount of damping.

The primary reason to add damping is to protect the accelerometer from frequencies that would damage it. In order to do this, we need to understand the natural frequencies of the accelerometer, as these are the culprits that could excite ringing and cause damage to the accelerometer or to the measurement if not well understood. Our 2,000 g damped accelerometer has two closely spaced frequency modes, the first at 25 kHz (sensing direction) and the second at 36 kHz (diagonal tilt direction). The sensor design is such that we can successfully damp both of these modes with multi-mode damping, giving flat frequency response in most cases out to10 kHz and no significant resonance up to 40 kHz. This provides the right balance of enough damping to prevent ringing, while still maintaining excellent frequency response.

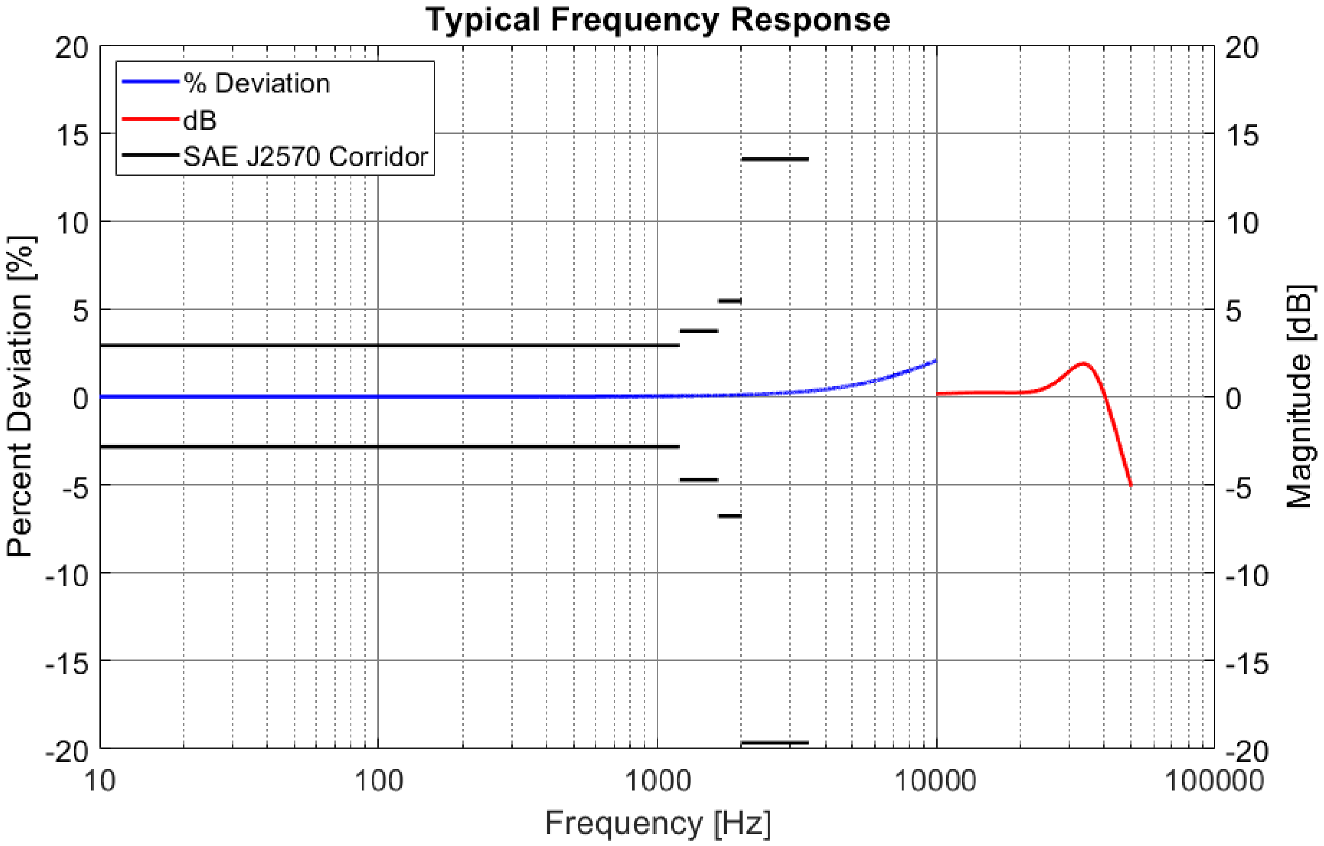


Chart 1: Multi-mode damping typical frequency response

This highly successful gas damping not only protects the accelerometer prior to mounting, but also protects from dangerous ringing during test. While it is possible to damage or break an accelerometer through ringing, the more common problems caused by ringing are the introduction of zero shift or saturation of the data acquisition. Either of these circumstances can lead to bad data, particularly when you integrate to get velocity.

Undamped vs. Damped Experiments

To demonstrate the benefits of damping, we collaborated with the French test center, CRITT Sport Loisirs, which aims to promote the development of the sports and recreation industry. CRITT has laboratories authorized to test and certify products within this field via equipment including drop test benches and air launchers. We tested two types of Endevco sensors during projected metal particle impact on a motorcycle helmet. Data was collected through a Dewesoft Sirius multi-channel conditioning and data acquisition system with a maximum sampling rate of 100 kHz.

Sensors used included:

- 7264C Undamped piezoresistive accelerometer for anthropomorphic test dummy (ATD) testing, 2,000g range, resonant frequency 26kHz
- 726CH Multi-mode damped piezoresistive accelerometer, 2,000g range, no significant resonance up to 40 kHz

Test #1: Metallic Ball Impact on Helmet Face Shield

Our first test consists of a projectile bench capable of launching a metallic ball (simulating a piece of gravel) at a speed of 190 m/sec, with one 726CH accelerometer close to the shock. Two other sensors, one 7264C and one 726CH, are mounted with Petrowax on either side the face shield at an equal distance in order to compare the response.

Picture 1: Metallic ball about to impact face shield

Picture 2: 726CH separating from face shield

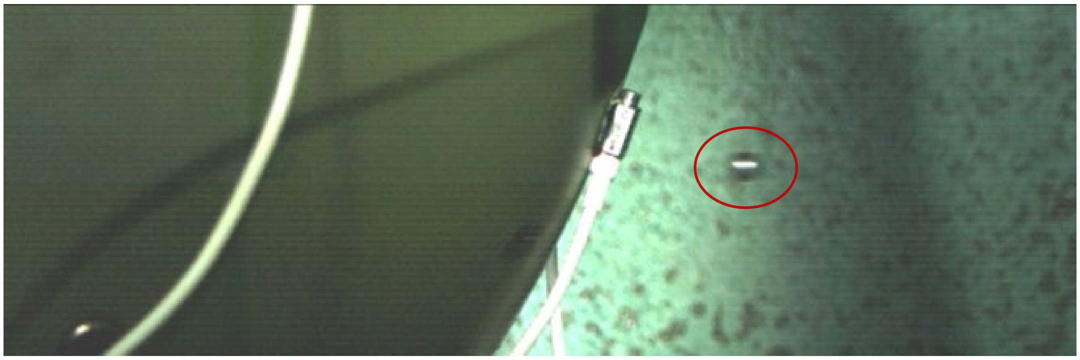
Test #1 Observations and Conclusions

During the test, the sensor closest to the impact de-mounted and the data was not useful. This test demonstrates one of the challenges test engineers face: successful mounting of sensors to their UUT.

Test # 2: Metallic Ball Impact on Rear of Helmet

In our second test, the same bench is used, but this time the metallic ball targets the rear of the helmet. Again, the 726CH is mounted close to the intended impact point with an additional 726CH and 7264C, all mounted with Petrowax at equal distance on the rear of the helmet to compare both behaviors.

Picture 3: Test set-up for metallic ball impact on rear of helmet



Picture 4: Metallic ball about to impact rear of helmet

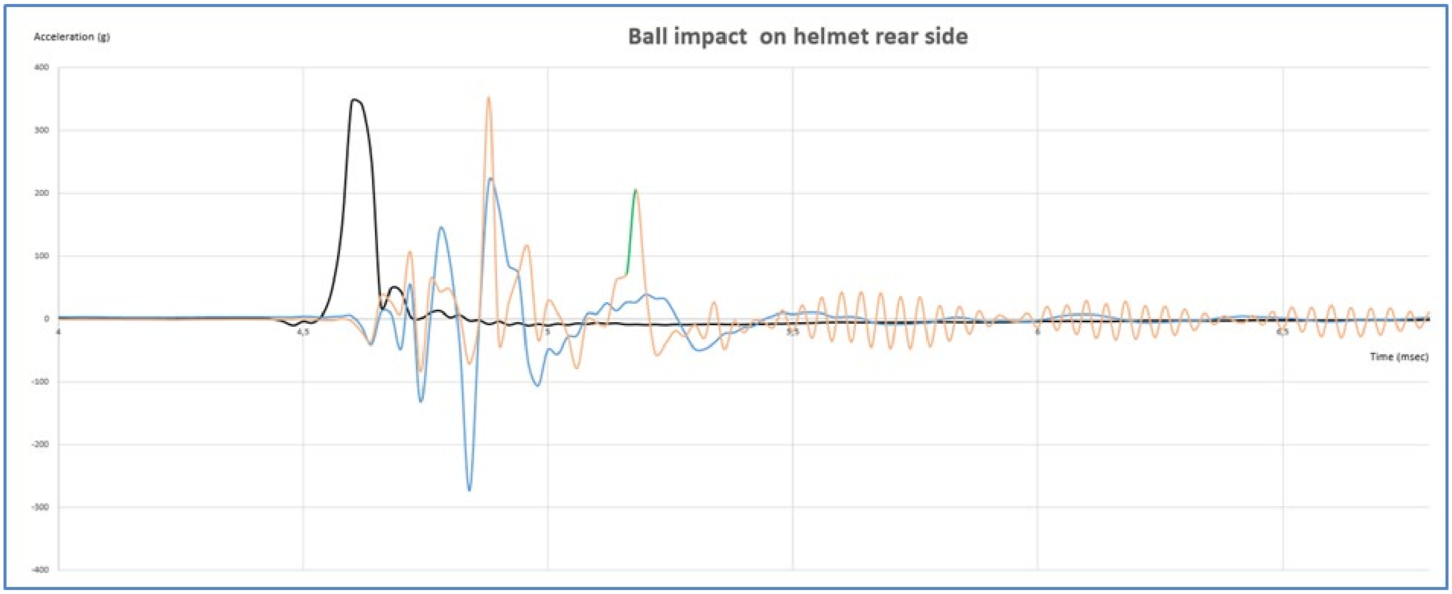
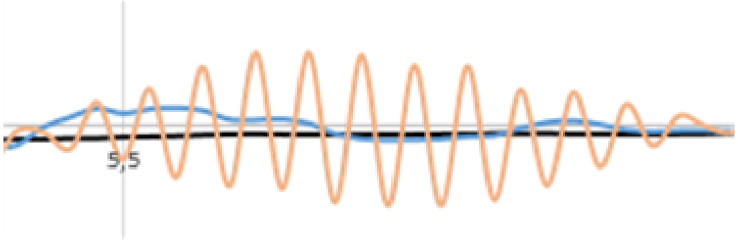


Chart 2: Results from ball impact on rear of helmet

Test #2 Observations

The data from the 726CH mounted in the center (black trace) shows a 350g shock with the quick rise and short duration of a typical hard shock. This impact transmitted equally to both of the side sensors (orange and blue traces) in ~20µsec. Note that the center 726CH stopped providing output because it once again popped off after impact.



The area of the chart after the primary impact shows the behavior of the undamped accelerometer compared to the damped version. The low frequency of the impact is measured by both sensors, but the sensing element of the undamped 7264C continues to resonate. The frequency of the orange curve (7264C) is ~24 kHz, which corresponds to the 7264C's natural frequency. The 726CH on the side, which has virtually no resonance due to multi-mode damping, is vibrating at ~1850 Hz, which is the response of the structure.

Test #2 Conclusions

The rear side of the helmet is hard enough to present the typical behavior of a structure impacted by a Dirac pulse of energy, causing the mechanical components to resonate at their natural frequencies. Both 7264C and 726CH accelerometers can measure the natural frequency of the helmet structure, but the undamped 7264C also rings and provides output at its natural frequency.

Lesson Two: The Importance of ESD Protection

Another little understood potential failure mode for sensors is caused by exposure to static electricity, even the amounts you can transmit through the human body. Piezoresistive sensors in particular can be damaged this way, so ESD precautions should be taken when inspecting, mounting and troubleshooting piezoresistive accelerometers. ESD damage will typically result in a large shift in Zero Measurand Output (ZMO) or, in extreme cases, an open leg of the Wheatstone bridge.

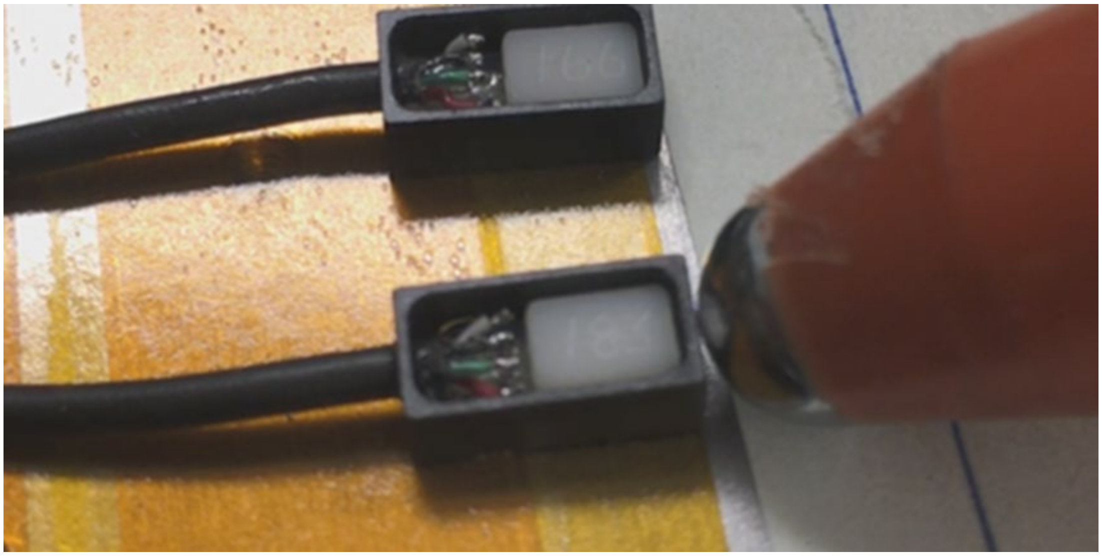
To help minimize ESD damage in the field, newer Endevco sensors add a quad diode to the same circuit board as the accelerometer. The diode is connected to all four signal paths in the circuit (+EXC, -EXC, +OUT, -OUT) so that a sudden ESD spike can be "shunted" through the diode, before it gets to the die. This increases the ESD protection from Class 1A (up to 500 V) to Class 3B (>8000V) per Section 5.2 of MIL-STD-1686C, significantly reducing the risk of accelerometer failure due to handling.

ESD Experiment

Damped piezoresistive accelerometers, legacy 757A and new 757AH, are subjected to a series of ESD tests using an ESD simulator "gun" at the Endevco Design Center in Irvine, CA. The ESD simulator gun is in direct contact with the unit housing while successive shocks are applied:

- From time t = 0s to time t = 30s, the ESD gun is off.
- From time t = 30s to time t = 60s, an ESD shock is supplied from the gun at 5 second intervals. So, one shock happens at t = 30s, another shock happens at t = 35s, another one at t = 40s, and so on. The final shock occurs at t = 60s.
- After t = 60s, the ESD gun is kept off**.**

Since the ESD gun only has one tip, we could only test one unit at time.



Picture 5: ESD gun tip in contact with Al housing of uncovered 757AH device

For each unit, seven units legacy 757A (no quad diode) and eight units 757AH (with quad diode), we performed three different tests, with the ESD gun set to three different voltage levels.

- "0kV Test" – The ESD gun is unplugged, so there is 0kV of voltage going to the unit. This is a "control" test. The purpose is to see whether the gun tip itself has any effect on the unit's output, separate from ESD shocks
- "1.8kV Test" – The ESD gun is set to output 1.8kV on a single shock
- "3.6kV Test" – The ESD gun is set to output 3.6kV on a single shock

Since the units were tested at three levels each across 15 units, there are 45 data sets. We will not include all 45 plots in this report as many of the sensors had similar behaviors, instead representative data plots and a summary of the results is provided.

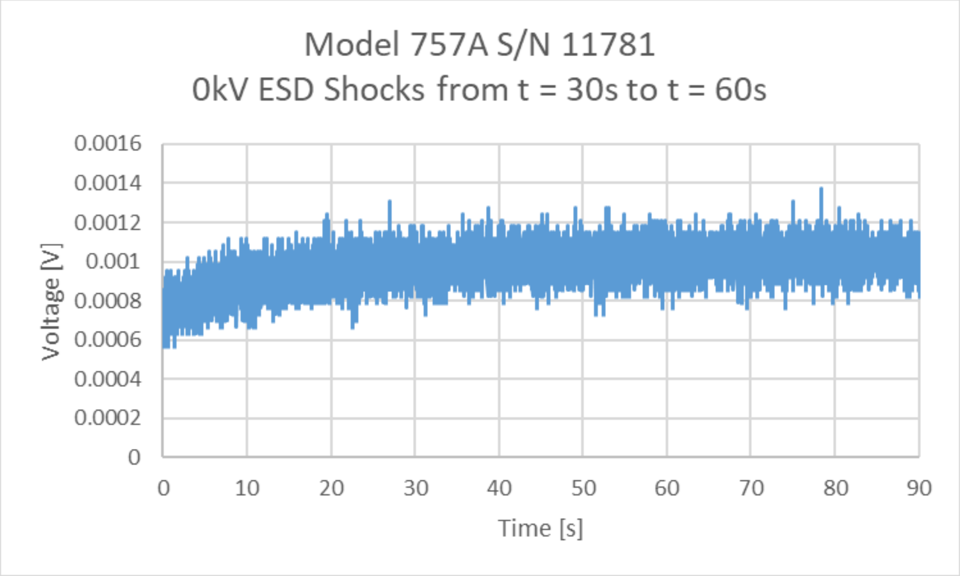


Chart 3: 757A S/N 11781 output is very consistent through the 90 seconds, especially after it has had time to warm up. This was common for all 0kV tests, so no further 0kVcharts are included.

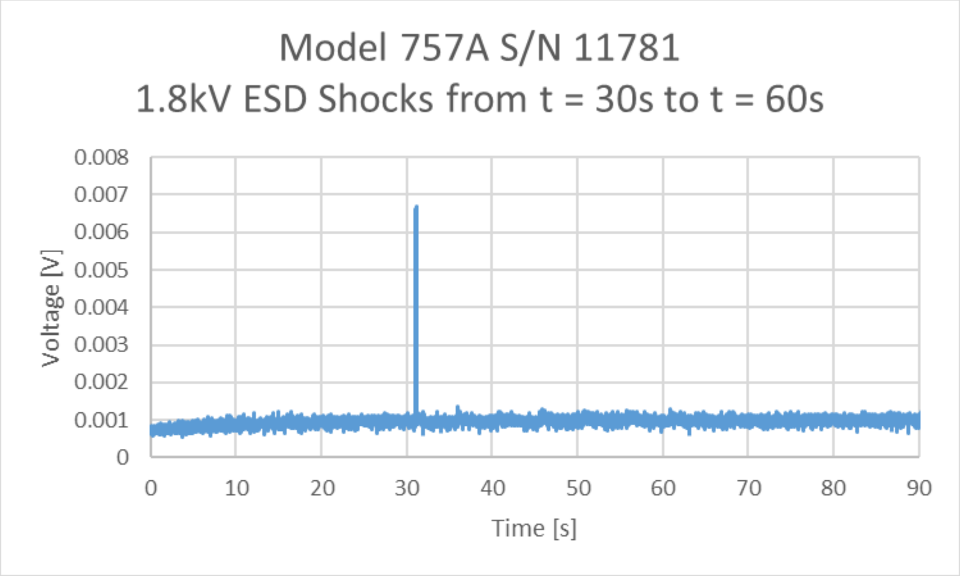


Chart 4: 757A S/N 11781 had a single noticeable peak, around time t = 30s. Since this is around the time that the gun tip was pressed onto the housing, the disturbance from the bump could have caused the peak.

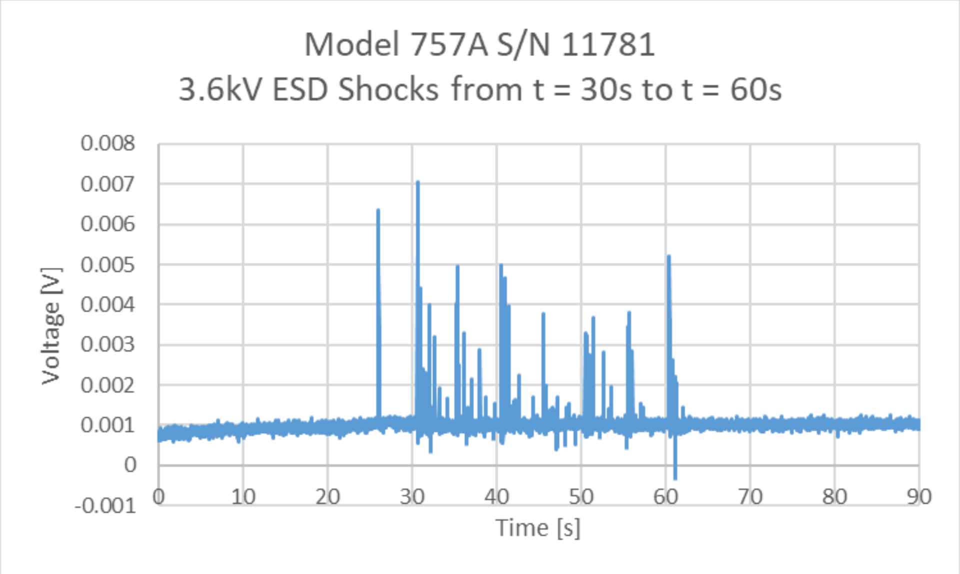


Chart 5: 757A S/N 11781 has a clearly visible response to the shocks from t = 30s to t = 60s. After the ESD shocks ended around t = 60s, the sharp peaks ended as well.

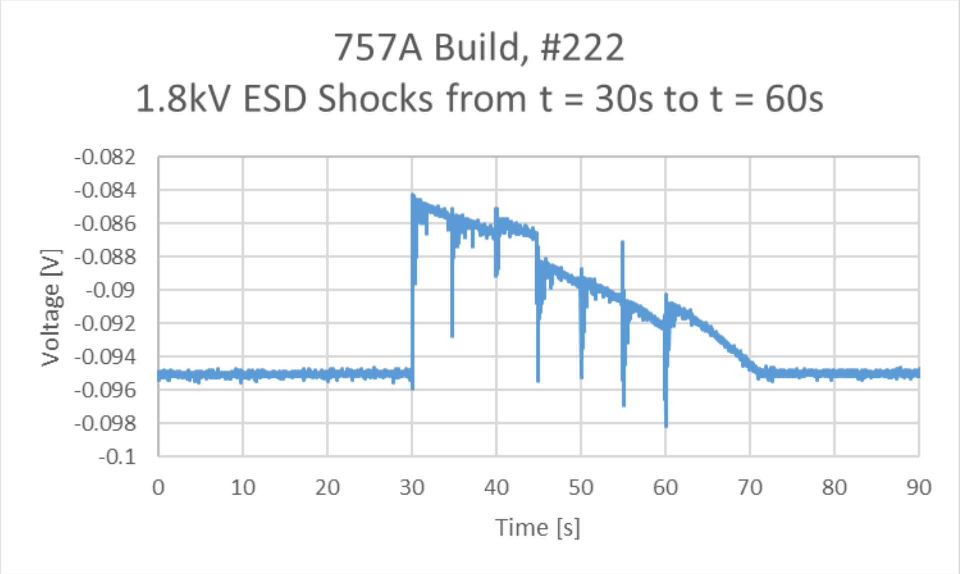


Chart 6: 757A S/N 222 during 1.8kV shocks, the unit had an initial ZMO shift of about 10mV after the first shock. The unit also had peaks in output, responding to each shock applied at t = 35s, t = 40s, t = 45s, etc. Over time, the unit's output recovered to the initial value (around -95mV) before the shocks.

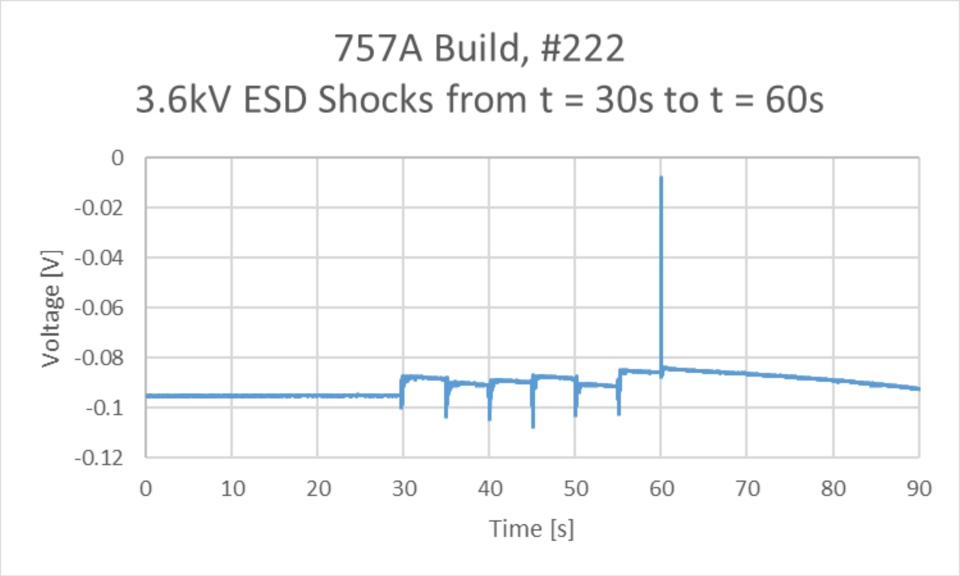


Chart 7: 757A S/N 222 responded more strongly to 3.6kV shocks. There was one very large peak at t = 60s, but the output slowly recovered to the pre-shock value. While this unit was strongly affected, it survived and recovered.

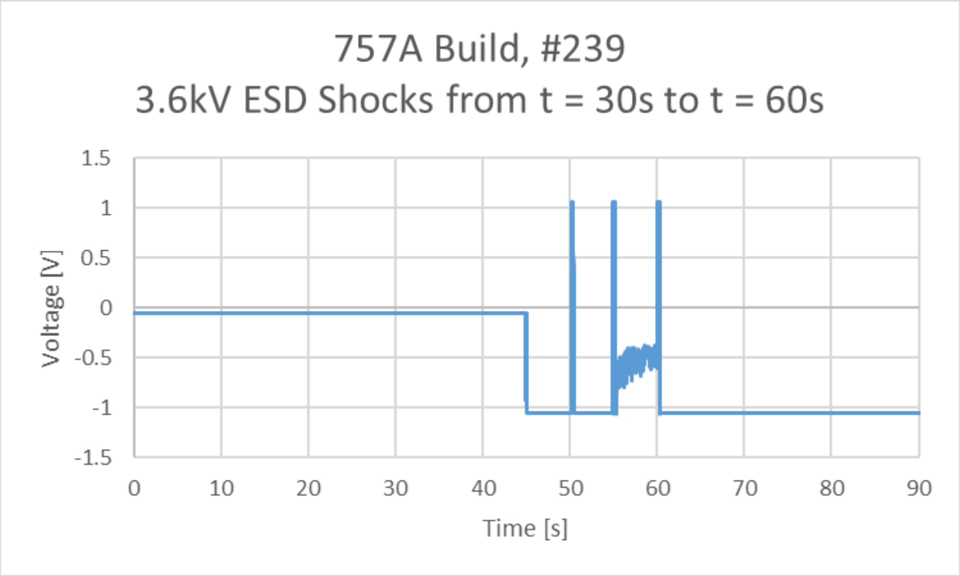


Chart 8: 757A S/N 239 showed minimal response in the 1.8kV test, but the change in output during 3.6kV shocks was dramatic. This unit experienced a permanent ZMO shift. The ZMO before the 3.6kV shocks was about -55mV and after the ZMO is measured as a constant -1056mV, which is the minimum voltage that can be measured by the data acquisition setup.

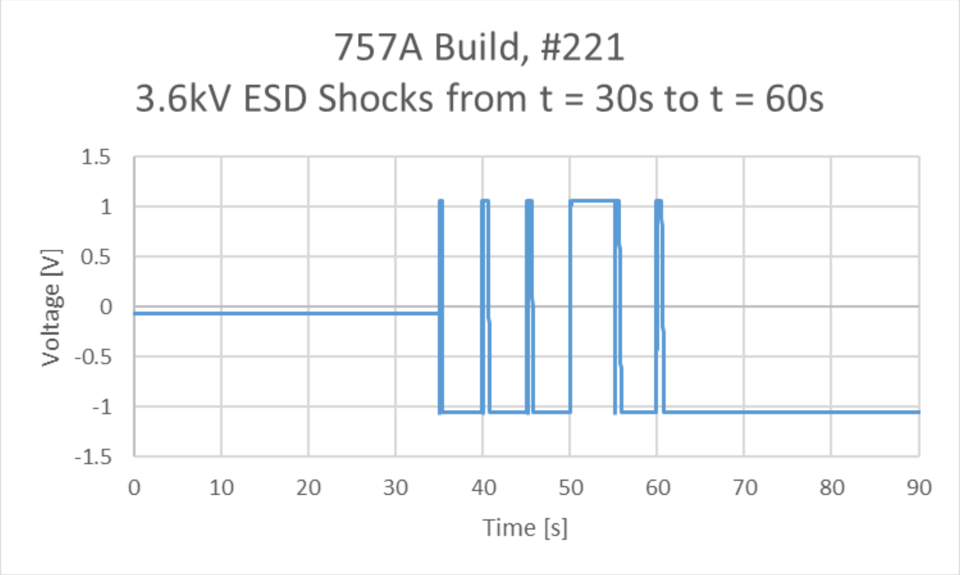


Chart 9: 757A S/N 221 shows permanent ZMO shift and damage at 3.6kV

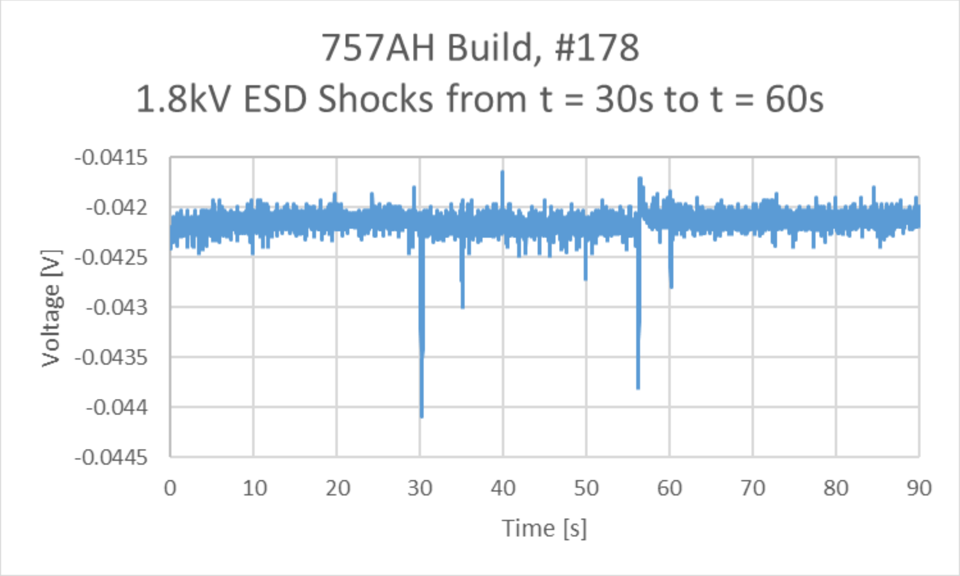


Chart 10: 757AH S/N 178 with quad diode protection responds to some of the 1.8kV input

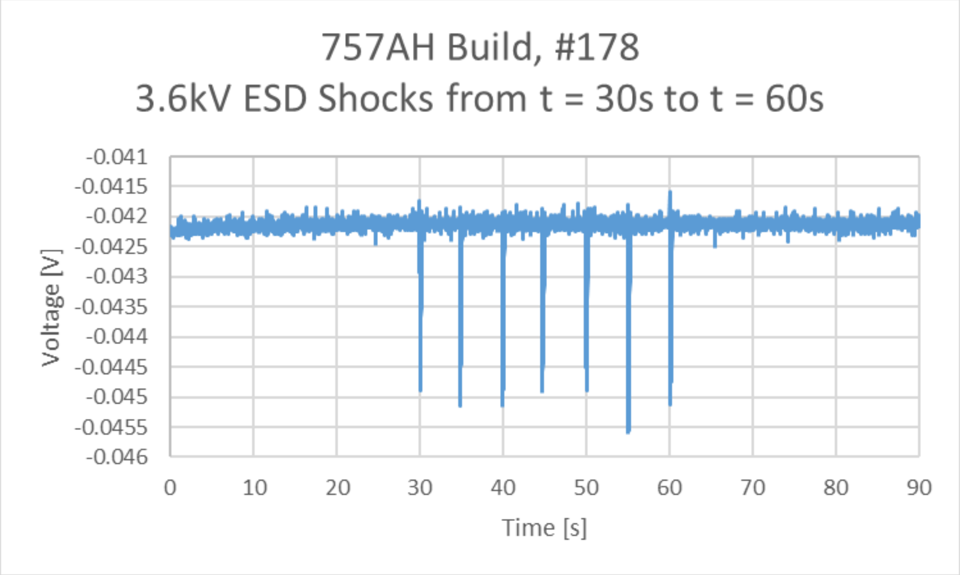


Chart 11: 757AH S/N 178 outputs in response to 3.6kV but is not damaged

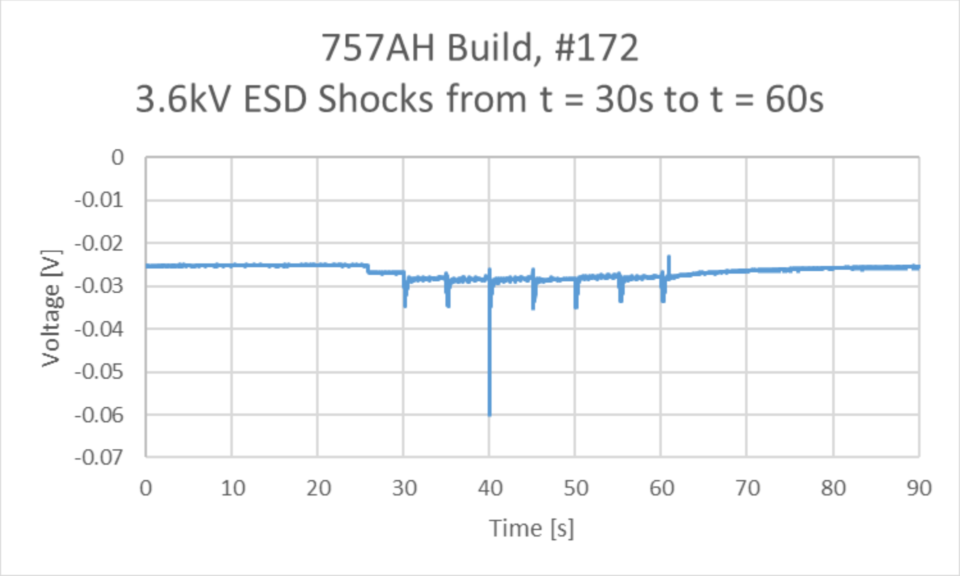


Chart 12: 757AH S/N 172 outputs in response to 3.6kV but is not damaged

ESD Test Observations and Conclusions

Almost all of the units, 757A and 757AH included, displayed some response to the ESD input signals. All units had an exposed section of aluminum on the inside of the housing. This exposed aluminum was in close proximity to the soldered wire leads. When the ESD gun was brought in contact with the housing and switched on, there was a fast buildup of charge within the housing material. The entire housing was covered in the anodize coating, except for the exposed spot on the inside. The closest metallic object to the bare metal of the housing was the sensor wire terminations, inside the housing. Therefore, visible ESD sparks appeared between the housing and wire terminations. From here, the sharp change in voltage can travel towards the sensor or towards the data acquisition system. Either way, this can cause a disturbance in the unit’s output.

The 757A does not have any sort of protection against ESD damage. If an ESD pulse arrives inside the sensor housing, there is nothing stopping it from traveling into the sensor die itself. The sharp increase in voltage and heat can permanently damage the resistors inside the sensing element.

The 757AH does have ESD protection, in the form of a quad diode. This diode will mitigate large voltage spikes that appear on any of the four signal paths of the sensor (+EXCITATION, -EXCITATION, +OUTPUT, -OUTPUT). The quad diode inside all of the 757AH units absorbed the ESD shocks, and so all of the 757AH units survived ESD exposure with no permanent damage.

Four out of the seven 757A units were permanently damaged due to the ESD shocks administered during these tests. None of the eight 757AH units suffered permanent sensor damage. The ESD survivability of the 757AH unit is thanks to the quad diode, which is not present in the 757A.

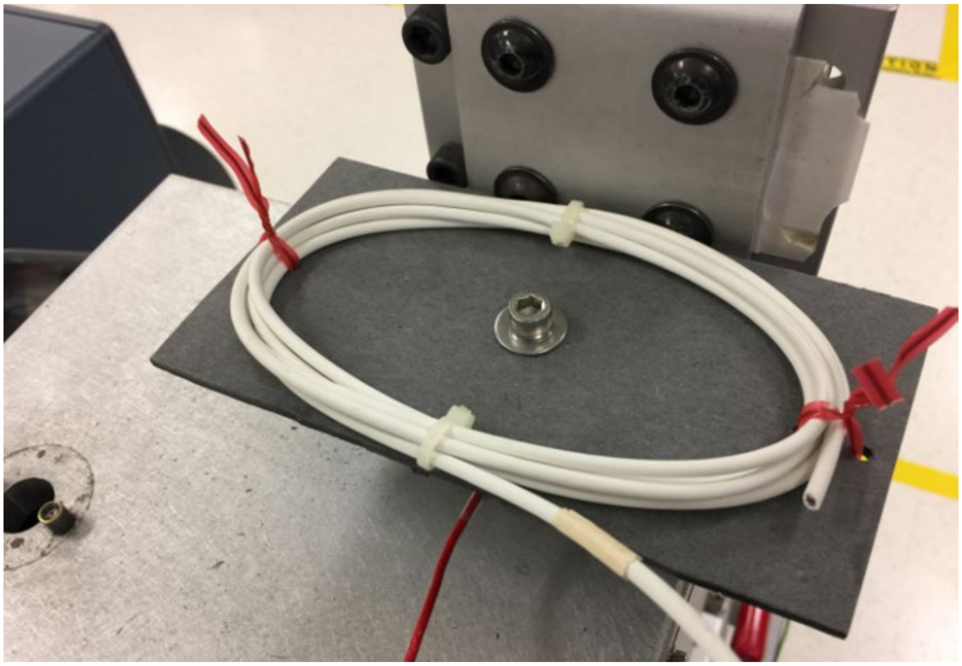
Lesson Three: The Effect of Motion-Induced Cable Noise

Another factor that is important to consider in your measurement chain is the cable connecting your accelerometer to your data acquisition system. Almost all cables provide some output in response to motion. Cable motion can generate a static build-up of charge between the various elements of the cable, which results in accelerometer output called triboelectric noise. In some applications, even with careful tie-down, the cable can be jarred or impacted. This possibility is magnified in high-shock, dynamic environments which tend to forcefully move instrumentation cabling.

Cable Noise Experiment

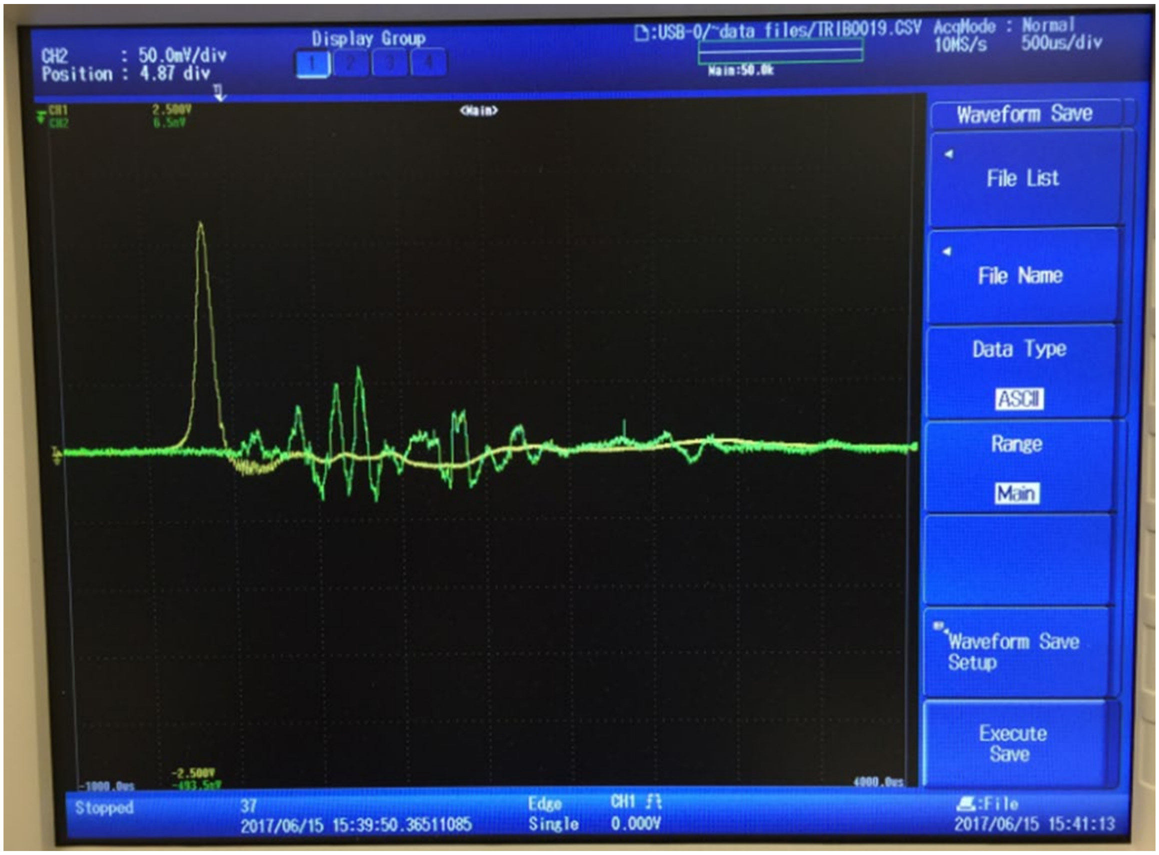
A test method was developed at the Endevco Design Center in Irvine, CA to quantitatively measure the triboelectric noise contribution from cables. In this test, we compare the results for our legacy cable to a newly improved cable. A length of accelerometer cable is coiled up and secured to a platform with one end of the cable attached to a dummy Wheatstone bridge. The purpose of the dummy bridge is to add a resistive load to one end of the cable, simulating a sensor, which can be powered with an excitation voltage. The dummy bridge includes four static resistors which are not sensitive to acceleration. The bridge is powered via an Endevco Model 136 signal conditioner. Test conditions for the dummy bridge are 3000 ohm bridge loading, 5V excitation and 60x gain on the signal conditioner. The cable is shocked at 1,500g and bridge output is recorded. Because the cable is attached to a dummy bridge, any change in output is a result of cable noise. We get a measure of cable noise susceptibility by looking at the peak output in response to the shock event. Lower peak response means the cable is more resilient to noise induced from shock.

This test method was created with the specific intent to amplify cable noise in a shock test, for easier measurement and analysis. The plots and numerical data below are only useful for comparing relative amounts of noise between cables. They should not be interpreted as a measure of actual cable noise in a real sensor.



Picture 6: A length of accelerometer cable is coiled up and secured to a platform

Picture 7: One end of the cable is attached to a dummy Wheatstone bridge. The bridge is powered via a signal conditioner



CH2 : 50.0mV/div
Position : 4.87 div

:USB-0/~data files/TRIB0019.CSV
AcqMode : Normal
10MS/s 500us/div

Stopped
37
2017/06/15 15:39:50.36511085
Edge Single
CH1 0.000V
:File
2017/06/15 15:41:13

Picture 8: Output of cable noise test

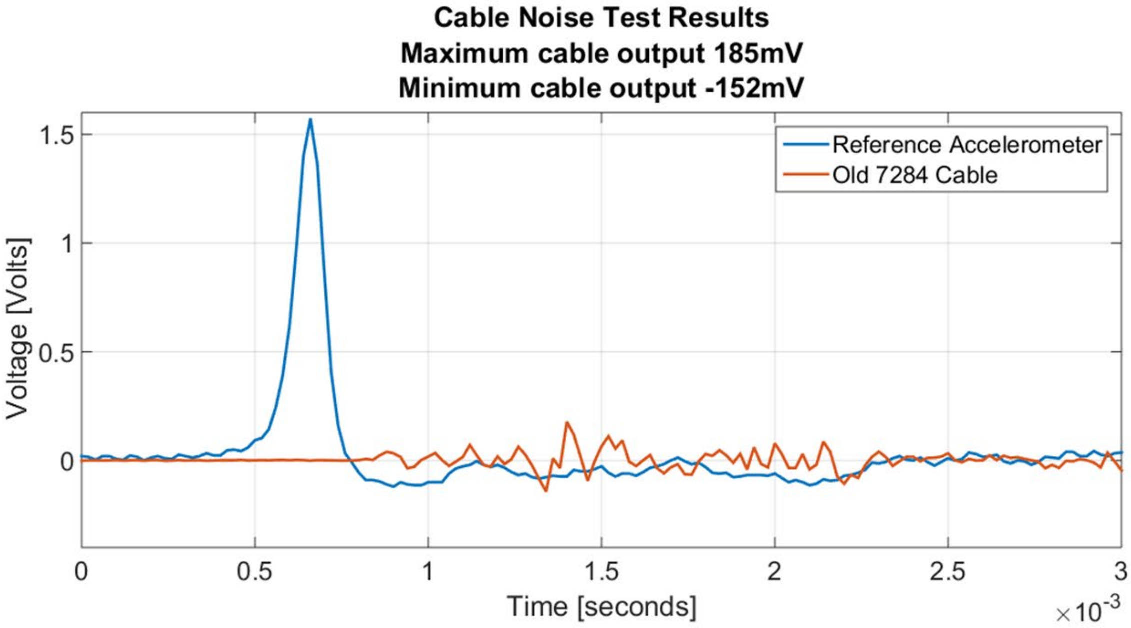


Chart 13: Legacy 7284 cable test result

- Cable noise response 0.2 ms after shock event
- Cable output lingers for several additional milliseconds
- Peak output (185 maximum / -152 minimum) mV

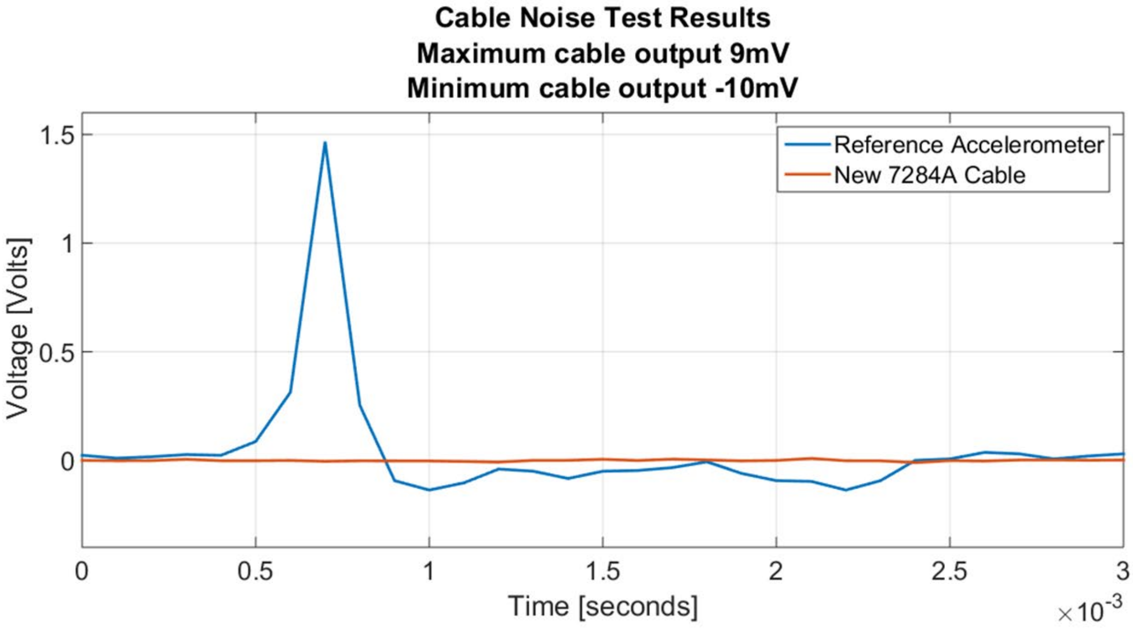


Chart 14: New 7284A cable test results

- Virtually no distinguishable increase in noise during shock
- Peak output (9 maximum / -10 minimum) mV

Cable Noise Test Conclusions

The shock test was repeated eight times on each cable with the 7284 cable having 147 maximum / -183 minimum mV output on average, and the 7284A cable having 9 maximum / -8 minimum mV output on average. This improvement in noise mitigation is achieved via the cable construction. The 7284A cable utilizes a layer of graphite coating over each conductor to dissipate charge. This mitigation of charge buildup means the cables are far less likely to transmit artificial signal from cable motion.

While low-noise cable can greatly improve the noise observed in a system, it is not a cure-all. Proper cabling practices are required to minimize noise:

- Secure the cable to a rigid, stationary structure to minimize movement
- Leave approximately 1-2 inches of loose/slack cable next to the accelerometer entry point.
- Avoid looping or stacking the cable over itself

Summary

Impact testing has always been one of the most challenging physical measurements for engineers and researchers. It is no longer adequate to just specify a shock sensor by its usual performance parameters such as bandwidth, sensitivity, and linearity. We have shown in this paper that the proper amount of internal sensor damping, the ability to withstand ESD, and the use of a cable with low motion-induced noise can all contribute to better impact measurements that produce higher test fidelity.

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