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Cause of and Solution for Cable Generated Noise in MEMS Accelerometer Signals

Written By

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ABSTRACT

While it is well known that triboelectric effects in cables can provide an additive error signal contribution to piezoelectric accelerometers operating in a charge mode, these same triboelectric effects have not been considered of consequence in signals from piezoresistive (MEMS) accelerometers encountering mechanical shock. However, not infrequently when measuring pyroshock the signals from MEMS accelerometers do not precisely integrate to zero velocity. This work shows that triboelectric effects in cables have the potential to be a contributor to less than perfect integration of signals from MEMS accelerometers. This additive signal contribution, which to varying degrees depends on cable type and configuration, also contaminates the resultant calculated shock response spectrum (SRS).

INTRODUCTION: The triboelectric[1] effect (also known as *triboelectric charging*) is a type of contact electrification in which certain materials become electrically charged after they come into contact with a different material and then become separated (such as through rubbing). One example of materials that can acquire a significant charge when rubbed together is glass rubbed with silk. The polarity and strength of the charges produced differ according to the material types, surface roughness, temperature, strain magnitude, and other parameters. Thus, this effect is not very predictable, and only broad generalizations can be made about it.

TRIBOELECTRIC EFFECTS IN PIEZOELECTRIC ACCELEROMETER SIGNALS: Signal generation within a cable (as opposed to cable pickup) attributable to triboelectric effect has long been known to occur in the output from piezoelectric sensors (force, pressure, acceleration transducers) operating in a charge mode (i.e., without contained electronics (non ICP® or non IEPE)). For this effect to occur there must be cable motion. Since all instrumentation cables are combinations of metal conductors, inner dielectrics, metal shields, and outer jackets of differing materials, it would be expected that any motion of the cable would result in some triboelectric effect (signal generation). As it is associated with piezoelectric accelerometers this motion has traditionally been attributed to cable vibration. Figure 1 shows one example of this charge generation within a coaxial cable.

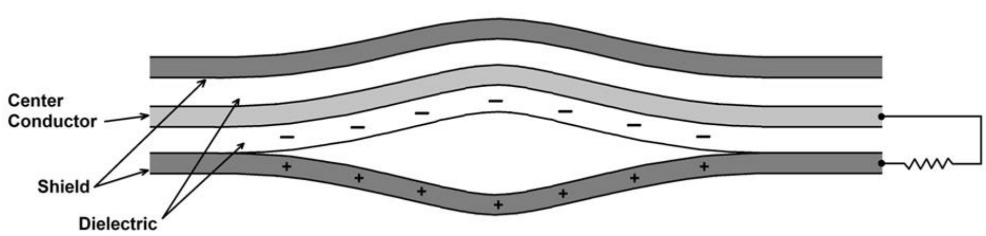

Figure 1. Charge Generation within a Coaxial Cable

Examining Figure 1, during cable vibration charge builds up due to relative motion between the shield (in this case positive) and the dielectric (in this case negative) due to rubbing. The shield and dielectric separate, and the mobile charge on the shield flows into the charge sensing amplifier resulting in additive noise superposed on the acceleration signal. Under continuing cable vibration different portions of the shield and dielectric open and close and triboelectric induced noise effects become an ongoing, additive contribution to the signal. One contributory solution is to pack all the internal cable interfaces with graphite, which essentially functions as a conductive shunt when the cable materials separate, thus eliminating charge buildup. Figure 2 shows such a graphite lubricant between the dielectric and the shield to minimize triboelectric effects.

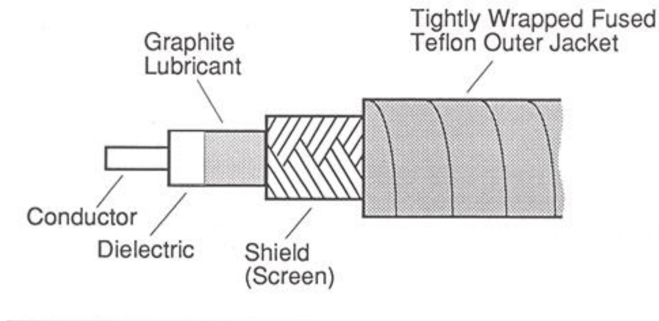

Figure 2. Graphite Treated Low-Noise Cable for Piezoelectric Accelerometers Operated in a Charge Mode

TRIBOELECTRIC EFFECTS IN PIEZORESISTIVE (MEMS) ACCELEROMETER SIGNALS: Pyroshock is the decaying, oscillatory response of a structure to high-amplitude and high frequency mechanical excitation. The frequencies that comprise this oscillatory response can extend to thousands of Hertz and beyond. They are a subset of the resonant frequencies of the structure.

The aerospace industry was the first to recognize the potential destructive effect of pyroshock. The firing of explosive bolts, nuts, pins, cutters, and other similar devices initiated this pyroshock. Subsequently, it was recognized that other environments (e.g., the sudden release of strain energy and metal-to-metal impact), although not initiated by explosive devices, produced effects similar to pyroshock. Because the stimuli that initiate pyroshock are applied instantaneously, the structure’s net velocity change is zero. Pyroshock measurements are attempted with both mechanically isolated piezoelectric accelerometer and MEMS accelerometers[2]. The electrical equivalent of a thermally uncompensated MEMS accelerometer is shown in Figure 3 and obviously requires a 4-wire shielded cable (e.g., Figure 4) as opposed to the coaxial cable associate with the charge mode accelerometer.

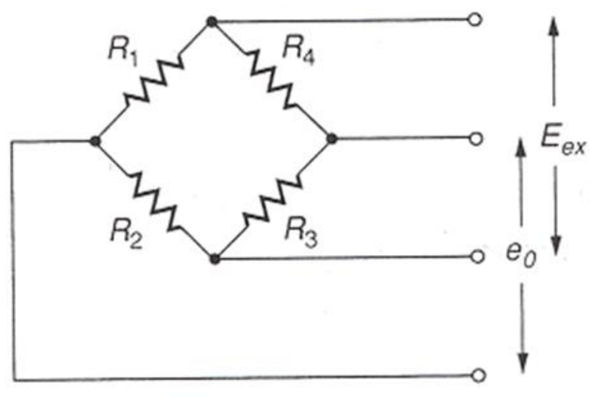

Figure 3. Electrical Model of MEMS Sensing Element

Figure 4: Representative 4-Wire shielded Cable

It has been known for decades[3] that when encountering pyroshock piezoelectric accelerometers, particularly non-isolated ones, frequently do not integrate as they should to zero. This is due to dipole rotation in their ceramic sensing elements. In theory, MEMS accelerometers should not have this problem because this phenomenon does not exist in semiconductor materials. However, not infrequently this non-return to zero (zero shift) also occurs in the signal output from MEMS accelerometers attempting to measure pyro shock. This work indicts triboelectric effects in 4-conductor shielded cables as a previously undocumented cause.

INVESTIGATION: While pyroshock is most studied in the aerospace and defense industries, it readily occurs in other industries such as oil and gas exploration. Frac or perforating guns are used to punch holes in the casing or liner of an oil well to connect it to the reservoir. In cased hole completions, the well will be drilled down past the section of the formation desired for production and will have casing or a liner run separating the formation from the well bore. The final stage of the completion will involve a string of perforating guns with shaped charges. These guns are lowered down to the desired depth and fired to perforate the casing or liner. A typical perforating gun can carry many dozens of charges. This comprises a very severe pyroshock environment to the well casing and the entire well recovery system.

The author was involved with an investigation where strain gages (1000 ohm encapsulated Karma foil gages of a specific configuration in 2-active arm bridges) were being used to monitor structural inputs to a perforation gun and recovery tubing within a well. A custom designed, shock-hardened, data acquisition system was used in-situ to acquire, digitize, and store data. Active strain gages bridges were mounted at structural locations of interest along with a placebo bridge. The placebo bridge was comprised of a gage pair mounted on a mechanically isolated structure in proximity to and made from the same material as that on which the Karma gages were mounted. The placebo bridge, fully powered, was intended to monitor the electrical noise floor of the data acquisition system. Its output should ideally be 0 volts. Bridge supply voltage was constrained by the data acquisition system to 3 volts.

The initial field test surprisingly showed that both the active strain gage bridges and the placebo bridge produced comparable magnitude signals (Figure 5)!! Possible causes were opined to be: (1) instrumentation amplifier cross talk, (2) unpowered signal generation within the strain gages themselves, and (3) triboelectric generated noise in the instrumentation cables. Initially, triboelectric cable effects were deemed as an unlikely cause due to the low source impedance of the resistive strain gage bridge.

A detailed investigation to determine causality occurred over a several month period. After extensive testing, amplifier cross-talk was first eliminated as a cause. The next investigative phase then involved evaluating various types and pairs of strain gages for unpowered signal generation. The test matrix included: (1) one bridge with encapsulated 1000 ohm Karma gages in 2 opposite bridge arms, (2) one bridge with encapsulated 350 ohm Karma gages in opposite arms (differences or similarities between the 1000 and 350 ohm gage pairs would be informative), (3, 4) 350 ohm bridge configurations using paired Constantan gages in opposite arms with identical gage patterns as the 350 ohm Karma gages (both with and without encapsulation), and (5) a Karma 1000 ohm encapsulated gage pair bonded with cyanoacrylate adhesive as opposed to the epoxy type used in all prior testing. Unpowered strain gage bridge testing of the above matrix was performed on a Hopkinson bar. Identical gages pairs were mounted sequentially and diametrically opposite so that they could be compared under the same mechanical stimulation. Again, no power was applied to the bridges and care was taken to assure that no cabling touched the bar. Testing results exonerated any signal generation within the gages. The last possible cause then had to be signal generation in instrumentation cabling attributable to triboelectric effects.

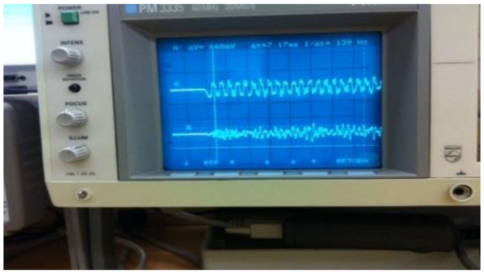

Figure 5. Top Trace Powered Active Bridge; Bottom Placebo Bridge

A mockup of cabling as configured within the frac (perforation) gun was made as shown in Figure 6. Three resultant impact studies determined the existence of a noise source due to a charge/current generation effect in the multicolored (red/black/green/white) transitional wiring to a Belden 4-wire shielded cable. When constrained by the yellow Kapton (Figure 6) tape, traveling waves due to impact of the surface of the perforating gun section would mechanically couple into this wiring. The same results were obtained independent of whether the test item was made of 4340 steel (original material) or aluminum.

Figure 6: Transitional wiring to 4-Wire Shielded Cable

The next test series involved replacing the wiring configuration of Figure 6 with Vishay 430 FST cable with the colored wires taped down as shown in Figure 7. The gages shown were physically adjacent but wired separately. There were symmetric gages on the bottom of the instrumented section so each bridge again contained an active 2-arm gage pair. When impacted with no power applied to the bridge it was observed that the triboelectric cable response was somewhat lower in magnitude but still present.

The results of the above testing were to:

1. disprove the hypothesis that the signal conditioning electronics were somehow cross talking with one another,

2. exonerate the strain gages themselves as a source of signal noise generation, and
3. conclude that any signals emanating from the placebo circuit in the actual perforating gun testing had to be occurring in the strain gage signal wires affixed to the structure under test. These same signals would also be contaminating the active 1000 ohm Karma strain gage bridge cabling under actual field testing.

Figure 7: 1000 Ohm Karma Gage Pairs Cabled with Vishay 430 FST Cable

SOLUTION INVESTIGATION: The solutions to cable noise attributable to triboelectric effects include, among others: (1) in vibratory environments minimize cable "whip", (2) in severe mechanical impact environments avoid securing the cable to any structure in such a manner that stress waves couple into it (keep it as free as possible), and (3) use as much graphite as possible as a cable filler between cable constituents. Testing was performed to evaluate these solutions postulates. Figure 8 shows three cables affixed to a long, slender bar with aluminum tape. The cables were identically terminated in both 350 and 1000 ohm metal film resistor bridges that were mechanically isolated from the bar. During the course of testing various types of support tapes were used. Figure 8 shows only one of many test configurations in terms of cable routing. The test bed was a Hopkinson Bar with a 1 inch square cross section and a length/width ratio of 48:1 to assure essentially 1-dimensional wave motion. The bar was impacted numerous times on its end and cable triboelectric responses were monitored.

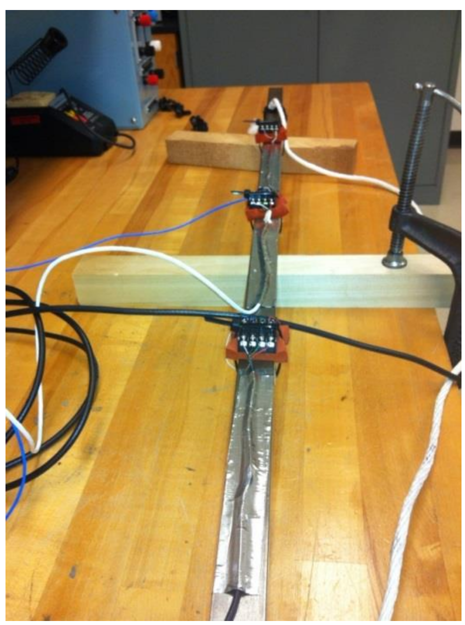

Figure 8. 1 inch by 1 inch Square Hopkinson Bar Used in Testing

The center (white) cable is Measurements Group 430-FST, a 30 AWG Teflon coated stranded cable with braided shield. Measurements Group is also the strain gage manufacturer. The upper (blue) cable is a PCB-Model 034 teflon-coated, graphite-filled cable. PCB procures this model cable from an external source. This cable was observed to produce lower noise levels in laboratory and field testing, but was harder to work with since it had solid 34 AWG wiring. The lower (black) cable was a special silicone rubber coated cable manufactured special for the author. As noted, the cables were terminated in resistive bridges that are totally strain isolated from any mechanical input. Figure 9 shows one set of comparative test results (special black cable (purple trace)) to Measurements Group (white cable (yellow trace)) when the bar was impacted on its end. Both cables shown are the same AWG wiring. Among other things the special cable is packed full of graphite. The graphite has minimized signal generation since it conducts electricity and helps preclude charge generation between conductors. In every test the special (black) cable generated the least triboelectric output.

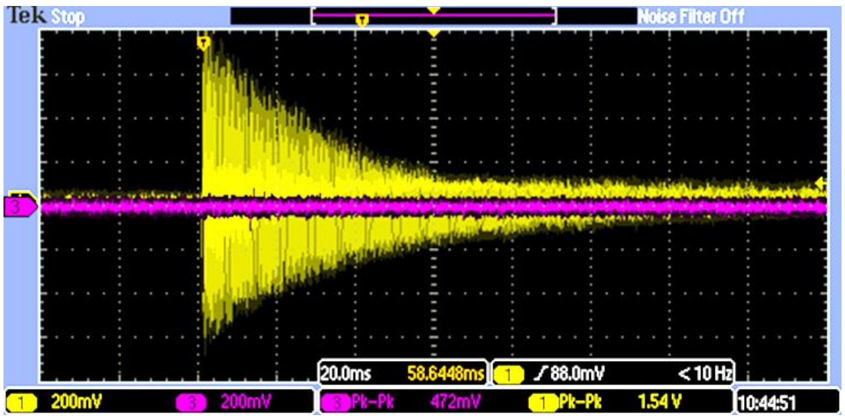

Figure 9: Comparison of Strain Gage Manufacturer's Cable to Special Fabricated Cable

The improved performance in terms of the minimal or almost no triboelectric signal emanating from the specially fabricated cable was expected based on the following research by the author:

1. Teflon (white and blue cable) and silicone rubber (black cable) are adjacent to one another in the triboelectric series. When rubbed against a metal, such as the perforating gun case or the shield of a cable, they will both gain electrons.
2. A static dissipative material (resistance between insulators and conductors) such as graphite will allow the transfer of charge buildup due to triboelectric effects to electrical ground.
3. Teflon and polypropylene (white and blue cable) have dielectric values about the same, nominally 2.2 compared to 3-8 for silicone rubber (black cable).
4. Teflon (white and blue cable) and silicone rubber (black cable) will both operate and sustain their integrity above 350 F (anticipated perforating gun maximum operating temperature).
5. Teflon (white and blue cable) has nominally twice the density of silicone rubber (black cable) and is 500 times stiffer. Thus, the mechanical impedance of Teflon (square root of modulus time density) should be about 33 times that of silicone rubber.

Opinion: The increased flexibility of silicone rubber, complimented by its much lower mechanical impedance, should make it more impervious to physical movement and stress wave coupling than Teflon. This turned out to be the case. The graphite filler was another requisite.

CONCLUSION: While the previous work occurred as a byproduct of monitoring structural dynamics with strain gages, its conclusions should transfer directly to MEMS accelerometers. That is because MEMS accelerometers are electrically modeled by the same resistive bridge circuit as strain gages. To validate this premise, two PCB 60KG MEMS accelerometers were special built. One had the new silicone rubber cable affixed to it and the other the existing PCB Model 34 cable. Both accelerometers had their cables identically bonded to the 1 inch square 48 inch long Hopkinson bar. The accelerometers themselves were allowed to hang off the bar. With no power applied to either bridge, the results of Figure 9 were essentially replicated. This was as expected.

This cable design change is being incorporated into all future PCB MEMS accelerometers intended for pyroshock applications (Figures 10 and Figure 11) reflecting continuous product improvement. In addition to these findings, results of this study indicate that for any accelerometer cable encountering pyroshock one should: (1) minimize cable contact points with the surface being impacted as much as possible and (2) use the minimum hold down surface area.

Figure 10: PCB MEMS Accelerometers with PCB Model 034 Single Wire Cable

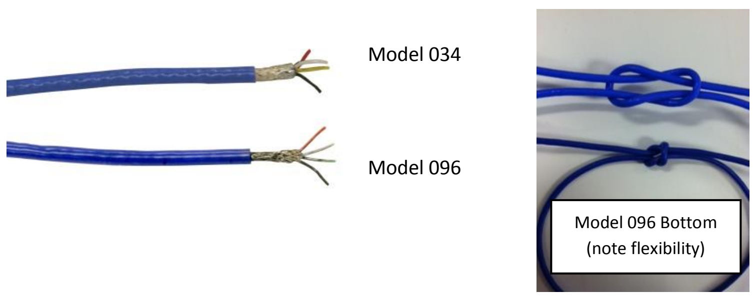

Figure 11: PCB MEMS Cable Model 034 Comparison to New Model 096 Stranded Wire Silicone Rubber Cable

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