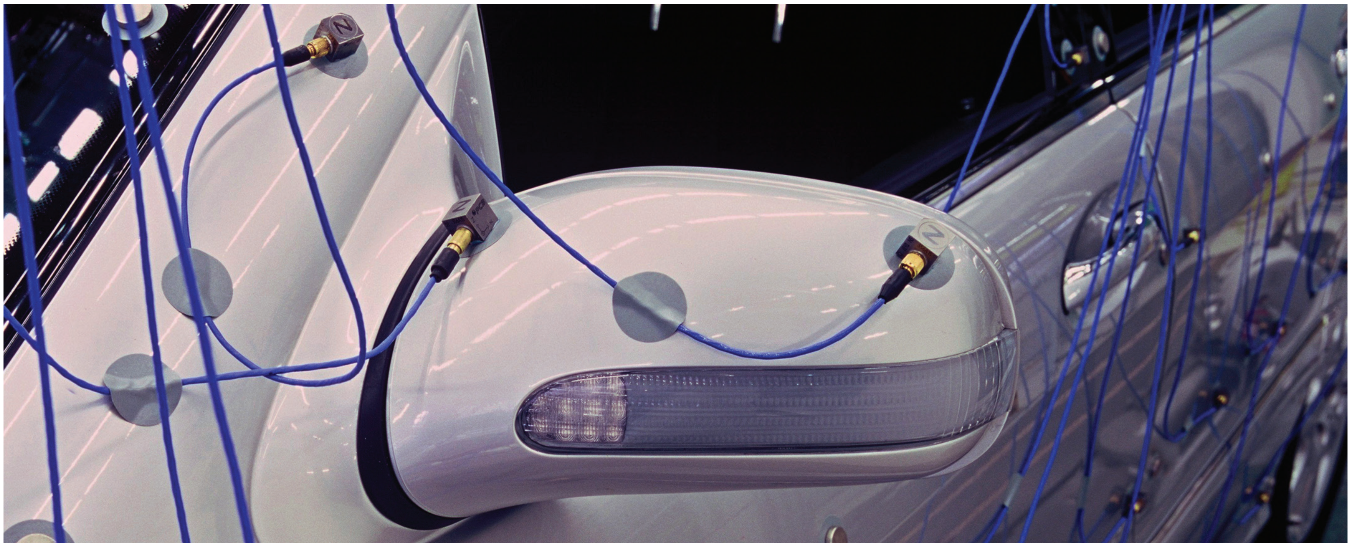
PCB PIEZOTRONICS
AN AMPHENOL COMPANY



TN-33

The Instrumentation Cable: Critical but Often Neglected

Written By
Patrick L. Walter, Ph. D.

The Instrumentation Cable: Critical but Often Neglected

Patrick L. Walter, Ph. D.

Senior Measurement Specialist
PCB Piezotronics

Professor of Engineering
Texas Christian University

ABSTRACT:

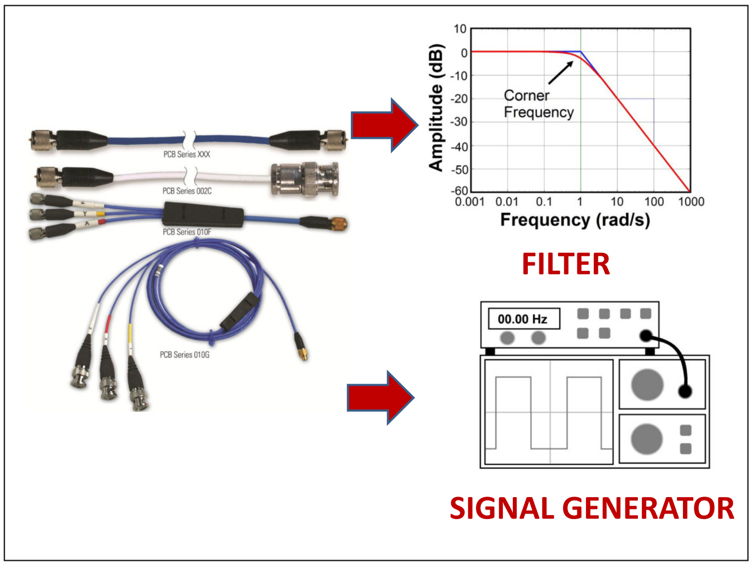
Compared to other measurement system components such as high-performance transducers, signal conditioning amplifiers, anti-aliasing filters, and high-speed and high-resolution digitizers, interconnecting cables are often viewed as lacking glamour. Their functionality is frequently considered as analogous to fluid flow in a pipe where everything that enters exits successfully. Nothing could be further from the truth! Cables are extremely important, and can be one off the largest sources of problems in instrumentation systems. Properly selected cables are necessary to enable information bearing signals from transducers to be transmitted with fidelity for recording and analysis. This paper provides guidance for selecting appropriate instrumentation cables with specific focus on signal modification that can occur when improper cables are chosen. This modification can occur due to either filtering by or signal generation within the cables or a combination of the two.

INTRODUCTION:

Typically instrumentation system designers worry about parameters such as low and high-frequency -3dB points, signal-to-noise ratios, anti-alias filter types and settings, data digitization rates, bit resolution, data post processing algorithms, and more. The interconnecting cabling, in spite of the fact that it must transmit the signal with fidelity, is often an afterthought. In instrumentation system design cable selection considerations should include, as a minimum, items such as:

- hermeticity and surety at the connector
- operating temperature range
- impedance
- shielding
- noise generation
- abrasion resistance
- strength
- weight
- compliance
    - bend radius
- outgassing (in vacuum operation)
- cost

This list could be further expanded to also encompass the cable connector. The connector is typically comprised of a large number of intricate parts. Pin chatter during vibration is just one of many observable connector malaises. This article focuses on (1) inadvertent signal filtering attributable to the cable impedance and (2) noise generation internal to the cable (see Figure 1).



Fugure 1: The cable can function as both a filter and a signal generator

TRANSDUCER SIGNALS:

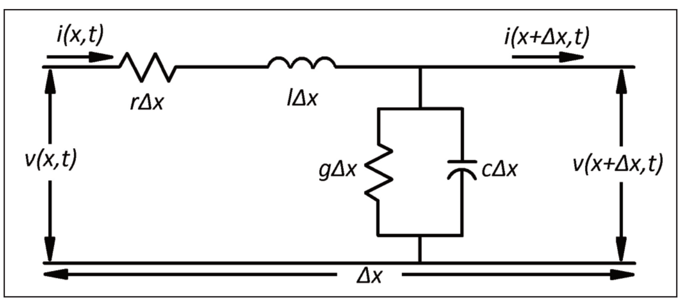
Static pressure and force measurements are typically acquired by resistive bridge-type transducers. More often than not these measurements use transducers containing metal strain gages, but semiconductor gages can also be employed. Alternately, strain itself can be the measurement parameter of interest, and the metal strain gages are then affixed to the particular structure of concern and connected into a Wheatstone bridge circuit. For all of these measurements the cable must transmit without attenuation the bridge supply voltage to the appropriate input corners of the bridge circuit to preclude signal attenuation. Thus, cable resistance must be considered.

Vibration measurements are typically made with piezoelectric accelerometers at frequencies below 2,500 Hz. Today, most piezoelectric accelerometers contain integral electronics (IEPE = ICP®) operating from a 4 milliamp constant current supply. For hazardous vibration tests requiring long cable lengths, this current may have to be increased. Similarly, when using ICP® type accelerometers to measure high frequency mechanical shock (e.g., to 10,000 Hz) with intermediate to long cable lengths, higher drive currents may again be required. This higher current is necessary to overcome filtering attributable to the cable capacitance, which must be considered. In some instances (e.g., very high temperatures) the piezoelectric accelerometer may not contain these integral electronics but have them remotely placed. In this later situation other cable concerns become involved, which have yet to be discussed.

Air blast measurements are extremely demanding in terms of high frequency requirements[1]. Piezoelectric or semiconductor (MEMS) technology is typically used. Wide band amplifiers are required to enable digitization of data to frequencies as high as or higher than 1 million/samples second. The associated explosive environment may require standoff transducer distances in terms of 100s to low 1000s of feet. Due to this extremely high frequency data requirement, both the cable's capacitance and inductance must be considered as they can contribute to signal distortion or modification (filtering).

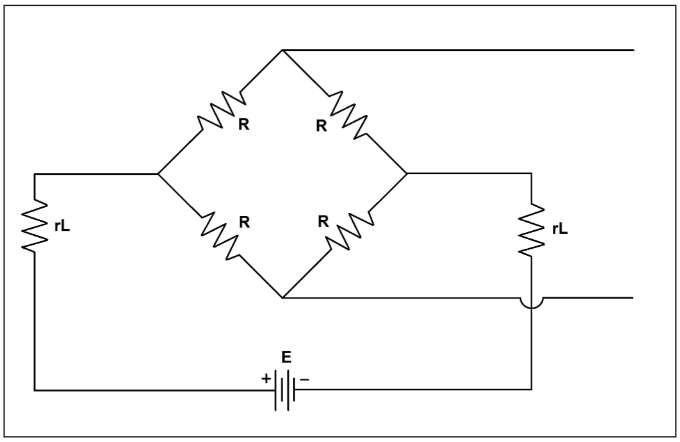
FILTERING WITHIN THE CABLE:

Filtering will be defined here as any attenuation or modification of the frequency content of the output signal from the transducer attributable to the cable. To understand this effect, we will look at impedance sources exclusively associated with the cable. These are the cable resistance r per unit length, capacitance c per unit length, inductance l per unit length, and cable conductance g (leakage from one conductor to another) per unit length[2]. Figure 2 below provides a lumped mass model of a cable segment Δx long. Input and output currents and voltages are also shown. Instrumentation cables are typically tightly bundled or are configured as twisted pair or coaxial so that conductance can usually be ignored.

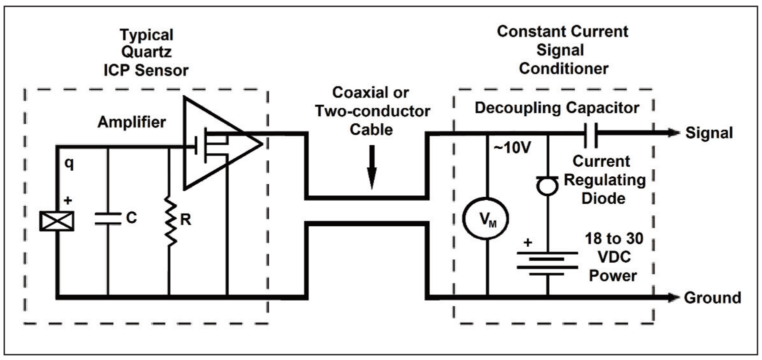


Fugure 2: Lumped mass model of a cable Δx long

Bridge transducers making static measurements are the easiest to analyze with regard to cable signal attenuation and will be discussed first. Figure 3 shows that the effect of the series line resistance *rL (L = cable length)* is to limit the supply voltage E available at the bridge. Therefore the supply voltage must be increased by the ratio of $(2rL + R_{bridge}) / R_{bridge}$ to avoid signal attenuation.



Fugure 3: Series line resistance limits bridge supply voltage



Fugure 4: ICP® transducer with constant current supply

Figure 4 schematically shows an ICP® piezoelectric accelerometer and/or pressure transducer used for dynamic measurements. We will consider the effect of the coaxial or two-conductor cable between the constant current diode and the amplifier. For very long cable runs, one has to assure that there is adequate current to drive the cable capacitance. If the time varying current *i(t)* supplied to the cable is *i(t)* = (I)sin(2πft), then at frequencies such as are being discussed circuit output voltage is:

$$v(t) = (1/C)\int i(t)dt$$

$$= [(I / 2\pi fC)\cos(2\pi ft)]. \qquad (1)$$

Here, C is the total cable capacitance *cL*. It can be seen that the magnitude of the measured voltage is inversely proportional to this total capacitance C = *cL*. Thus, measured signal voltage *v(t)* decreases with increasing cable length. This same inverse relationship holds for frequency. Conversely, the voltage is directly proportional to the supply or drive current. Depending on the upper frequency of measurement interest, for long cable runs as C increases the supply current must also be increased to preclude signal attenuation. Nomographs[3] of this frequency vs. current relationship are readily available to enable this determination for any value of cable length (i.e., capacitance).

Cable capacitance in the output leads can also significantly affect the signal from the bridge transducers (metal strain gages and MEMS) of Figure 3 at frequencies greatly above 0 Hz. Signal attenuation can again occur. The effect of this capacitance C = *cL* in parallel with the output voltage signal can be calculated as follows.

$attenuation\ ratio = 1\sqrt{(1+(2\pi f(2rL+R_{bridge})(cL))^2)}$. (2)

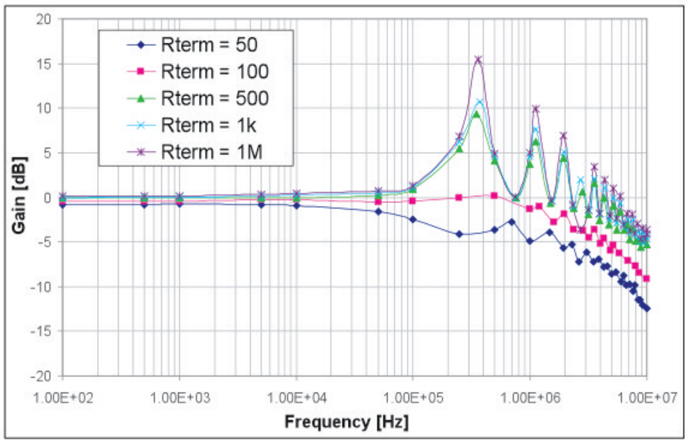
If this attenuation ratio value is close to 1.0, no signal is lost. If, for example, this ratio calculates to a value of 0.9, the signal will be attenuated (i.e., be in error) by 10% at frequency *f*. The highest measurement frequency of interest should be used in this calculation.

The magnitude of the impedance of a capacitor is 1/(2πfC) and an inductor 2πfL *(L here is inductance)*. At lower frequencies cable capacitance dominates as a concern but at higher frequencies (e.g., as encountered in high frequency mechanical shock or blast measurements) the total cable inductance L = *lL* (2nd L here is cable length) also comes into play. Figure 5 shows the measured frequency response of 400 feet of Belden[4] non-paired #82418, 4-conductor cable, 22 AWG, fluorinated ethylene propylene insulation, Beldfoid® shielded, with a nominal inductance of 0.15 μH/foot and a conductor-to-conductor capacitance of 30 pF/foot. Note the 5 different response curves measured for the same cable! Each response is associated with a different cable termination impedance. Also note that at frequencies to 50 KHz the termination impedance of the cable has no effect on its frequency response. With an infinite termination impedance (1 M'Ω used here) we see resonant peaks occurring within the frequency response with the first being nominally 330 KHz. With a termination impedance of 100 'Ω we notice that for this same cable the flat frequency response region is extended by a factor of 10 from 50 to 500 KHz. Obviously in this example at frequencies above 50 KHz, dependent on termination, the cable has the potential to greatly magnify or attenuate the signal it is transmitting. This effect must be understood.

Considering the infinite load case, the resonant frequency of the cable should closely approximate its natural frequency. The velocity of propagation of the signal down the cable, using the nominal values per foot of capacitance and inductance provided, is equal to[2]:

$1/\sqrt{lc} = 0.47 \times 10^9$ feet/second. (3)

If the cable operates directly into a high impedance amplifier (typically R ≥ 1MΩ)), at high frequencies reflections can occur. The first



Fugure 5: Frequency response of 400 feet of a specific cable

reflection will occur at a frequency (f) corresponding to a wavelength (λ) equal to four (4) times the cable length (4*L*).

As an example, assume in a test using the above specific Belden cable we observe a resonance of 100,000 (i.e., 1×10^5) Hz. The corresponding wavelength λ can be calculated as:

$\lambda f = (4L)f$ = propagation velocity or (4)

$\lambda = 4L = (0.47 \times 10^9$ ft./sec.) / $(1 \times 10^5$ Hz) = 4700 ft.

Thus, a cable length of (4700/4) or 1175 feet should be observed as the cause of the oscillations at 100,000 Hz. Signal fidelity can only be maintained to approximately 20,000 Hz (100,000/5) or one-fifth the frequency of this oscillation.

To test our understanding of this phenomenon redirect thinking back to the obtained, experimental frequency response of Figure 5 for 400 feet of the 4-conductor shielded Belden instrumentation cable #22 AWG. Note the resonant frequency at 330,000 Hz for the infinite load (R = 1MΩ). If we calculate the fundamental wavelength for this cable, and use the above propagation velocity of 0.47×10^9 ft./sec., which is a nominal value for this cable, we get $\lambda = 4L = (0.47 \times 10^9$ ft./sec.)/(3.3×10^5 Hz.) = 1,424 ft. or a cable length of 1,424/4 = 356 feet, which agrees reasonably well with its known value of 400 feet.

How do we improve this frequency response? The characteristic impedance for a cable at very high frequencies is expressed as:

$$Z = \sqrt{l/c} \qquad (5)$$

which for the preceding cable can be calculated to be 70.7 ohms. If the cable is terminated properly ($\sqrt{l/c}$ = 70.7 ohms), there will be no reflections at high frequencies. Figure 5 shows for the test termination impedance of 100 ohms (close to 70.7 ohms) an improvement by almost a factor of 10 in frequency response flatness. Thus, when high frequencies and long cable runs are involved, the cable termination impedance matching can become very important.

SUMMARY OF CABLE FILTERING EFFECTS:

The above paragraphs have enabled us to evaluate:

1. Signal attenuation in static (0 Hz or dc) resistive bridge measurements due to cable resistance

2. Signal attenuation at high frequencies and long cable lengths in integral electronic ICP® piezoelectric transducers due to line capacitance

3. Signal attenuation at intermediate frequencies in resistive bridge (metal strain gage or MEMS) transducers due to signal line capacitance

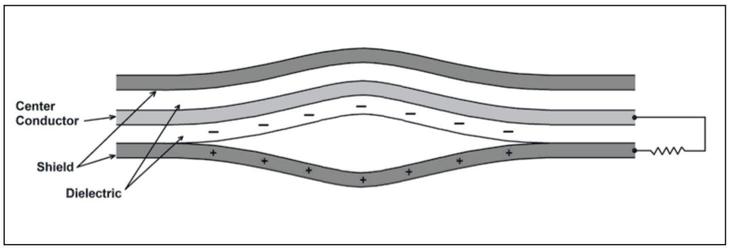
4. Signal modification in very high frequency measurements over long lines such as high frequency mechanical shock or blast measurements due to both capacitive and inductive loading of the signal lines

The cable parameters that control this signal modification must be known and their effects evaluated to assure signal fidelity.

SIGNAL GENERATION WITHIN THE CABLE:

Signal generation within a cable (as opposed to cable pickup) occurs attributable to what is known as a triboelectic effect. This effect is important when dealing with bridge type sensors providing millivolt level signals or piezoelectric sensors (accelerometers, pressure transducers, force transducers) without contained electronics (non ICP®). For this effect to occur there must be cable motion. The triboelectric[3] 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). 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. One example of materials that can acquire a significant charge when rubbed together is glass rubbed with silk. 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). This motion can be attributed to cable vibration or, in mechanical impact environments where cables are taped or securely tied down, cable compaction due to traveling stress waves underneath them. The greater the relative motion between the cable constituents, the more charge that is generated. Figure 6 shows one example of this charge generation within a coaxial cable.

Examining Figure 6, during cable vibration charge builds up due to relative motion between the shield and the dielectric due to rubbing. Subsequently the shield and dielectric separate, and the mobile charge on the shield flows into the next stage of signal conditioning resulting in additive noise superposed on the signal. One 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.



Fugure 6: Charge buildup due to cable motion

Figure 7 below provides a chart of the Triboelectric Series. The farther apart materials are from one another on the table the more charge build up they generate if rubbed together.

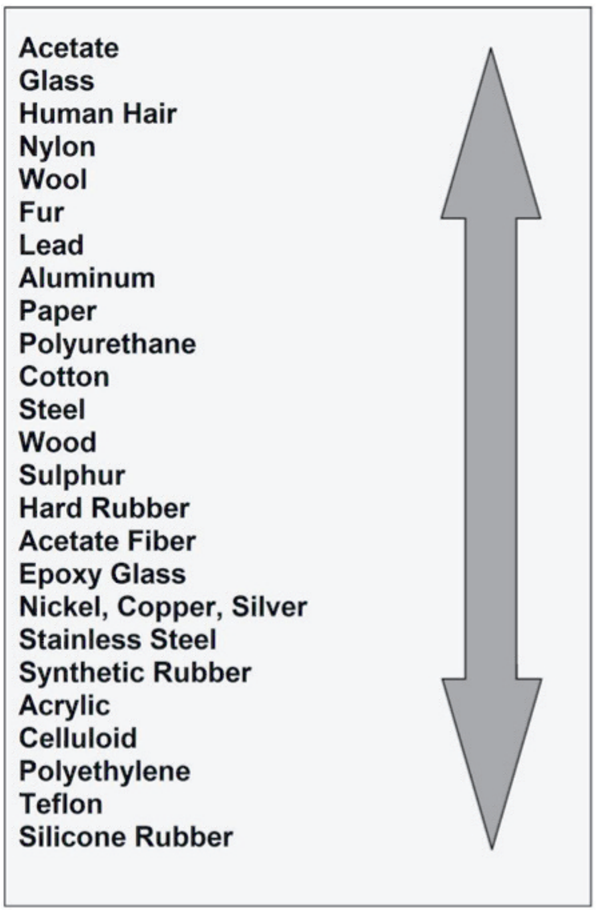
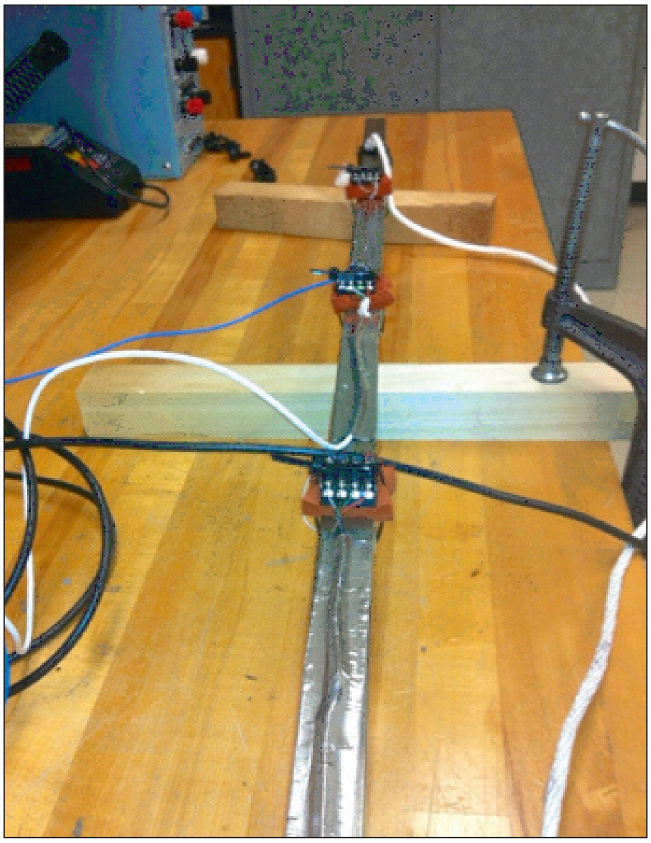


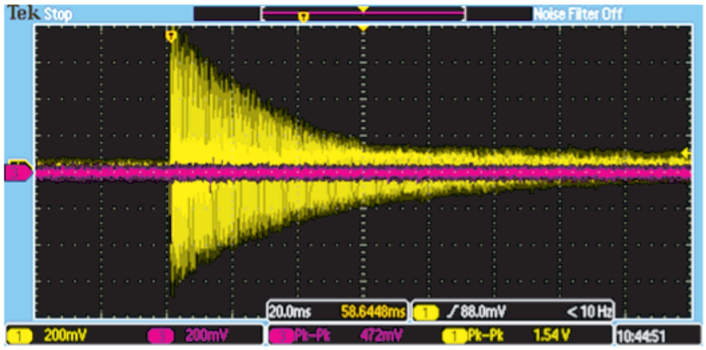
Figure 7: Triboelectric Series

The solutions to cable noise attributable to triboelectric effects are: (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. Relating only to item (3), Figure 8 shows two cables affixed to a long, slender bar with aluminum tape. The cables were identically terminated in 350 and 1000 ohm resistors that were mechanically isolated from the bar. During the course of testing various types of tapes were used. Figure 8 shows only one of many test configurations in terms of cable routing. The bar has 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 responses were monitored.



Fugure 8: Longitudinal rod (Hopkinson Bar) used in cable testing

The center (white) cable is from Measurements Group (strain gage manufacturer) and the lower (black) is a special cable manufactured for the author by Calmont Wire and Cable[5]. As noted, the cables were terminated in resistive bridges that are totally strain isolated from any mechanical input. Figure 9 shows comparative test results (Calmont (purple trace) to Measurements Group (yellow trace)) when the bar is impacted on its end. Both are shielded and contain the same AWG wiring. Among other things the Calmont is packed full of graphite. The graphite has minimized signal generation.



Fugure 9: Relative cable triboelectric response tests

SUMMARY OF CABLE NOISE GENERATION EFFECTS:

While not predictable due to dependency on cable materials, construction, and motion, triboelectric charge generation in the cable can be a significant error contributor in measured signals. When dealing with non-ICP piezoelectric transducers, or transducers operating at millivolt signal levels, graphite cable treatment should be provided to minimize this effect. Other parameters such as cable flexibility should also be considered.

CONCLUSIONS:

Careful attention must be paid to cable selection when designing instrumentation systems. Cable operating temperature range, impedance, shield coverage, abrasion resistance, strength, weight, compliance, outgassing, and cost are among needed considerations. However, the potential for the cable to provide signal attenuation by inadvertent filtering or adding internal charge generated noise to the measured signal attributable to triboelectricity is often overlooked. Hopefully this article has provided insight into these little recognized error sources.

REFERENCES:

(1) Walter, Patrick L., Air Blast and the Science of Dynamic Pressure Measurement, Sound and Vibration, pp.10-16, December 2004.

(2) Magnusson, Philip C. et. al., Transmission Lines and Wave Propagation, CRC Press, ISBN 0-8493-0269-2, 2000.

(3) Signal Conditioning Basics for ICP® & Charge Output Sensors, PCB Piezotronics Tech Support, www.pcb.com.

(4) Belden Wire and Cable, Indianapolis, IN.

(5) Calmont Wire and Cable, Santa Ana, CA.

Who is Patrick L. Walter?

Patrick Walter graduated in 1965 with a BSME from The Pennsylvania State University and hired into a Component Test (shock, vibration, climatic, … and functional test) organization at Sandia National Laboratories in Albuquerque, NM. Concurrent with his employment, he completed his MSME in 1967 at the University of New Mexico. He subsequently became a Project Leader in a flight telemetry organization and was responsible for transducer calibration as well as both transducer and flight electronics development. Among other early accomplishments, he developed some of the first high shock sensing capabilities for large caliber guns and earth penetrators. In 1976, Sandia sponsored his doctorial studies at Arizona State University (ASU) with now Professor Emeritus Peter K. Stein, founder of ASU's Laboratory for Measurement System Engineering. Pat's PhD dissertation involved analyzing structural test data from the Trident I strategic missile system.

In 1978, Dr. Walter resumed full time employment at Sandia and was promoted into test management shortly thereafter. Among the many organizations/functions he supervised were Transducer Development and Calibration, Measurement Consulting, Telemetry Component Development, Telemetry System Packaging for Weapon System Stockpile Surveillance, Mass Properties, Test Facilities Development, and Precision Inertial Test System Development. In 1987 he was transferred as Supervisor Test Operations for the Kauai Test Facility, a rocket launch facility on the Pacific Missile Range Facility (PMRF), Kauai, HI. Subsequently he became responsible for developing and launching rocket systems from Sandia and NASA facilities. These rocket focused activities supported President Regan's Strategic Defense Initiative (SDI).

Post Cold War (1991-1995) Dr. Walter established a joint Sandia-Federal Aviation Administration (FAA) program as part of the FAA's congressionally mandated Aging Aircraft Program. He validated this program with the aircraft and engine OEMs, the Air Transport Association, and other organizations, and it remains contributory today on Albuquerque International Airport.

During his entire Sandia tenure (1965-1995), Dr. Walter's professional focus was on flight, field, and laboratory measurements (e.g., displacement, velocity, strain, accelerations from milli-gs to > 100,000 gs, acoustic level pressures to 10's of thousands of psi, temperature, flow, and much more) to support test and evaluation activities. His professional interests spanned the entire measurement chain: transducers, signal conditioning, acquisition systems, and end data analysis.

In 1995, Pat accepted a position in the Engineering Department at Texas Christian University (TCU). Professor Walter developed TCU's Experimental Mechanics and Structural Dynamics Laboratories and established an industry based Senior Design Program focused around test, calibration, and control activities. From 1996-2003, he consulted for Endevco Corporation, a major supplier of dynamic instrumentation. From 2003 through today he consults as Senior Measurement Specialist for PCB Piezotronics, the world's largest supplier of dynamic instrumentation. Occasionally, he also consults for various aerospace and defense contractors on test measurement applications. Through TCU's Engineering and Extended Education Departments, he has developed a Measurements Systems Engineering short course, which he teaches nationally and internationally.

Pat is a 30+ year member of both the Society of Experimental Mechanics and the International Automation Society as well as a member of the American Society of Engineering Educators. He has authored one book, numerous book chapters, and more than 100 journal articles and reports (see TCU Engineering website). During the late 1970s he chaired a working subgroup of the Telemetry Group of the National Test Ranges. In 1989, he received both a USDOE Albuquerque Office Quality Award and a joint Certificate of Appreciation Award from Sandia Labs and Allied Signal for his work on the Trident II program. In 1990 he received an Award of Excellence from the USDOE Nuclear Weapons Program, and in 1994 he received a Meritorious Achievement Award from Sandia Labs. In 1995 (upon his retirement from Sandia), he received a letter of commendation from Senator Pete Domenici, then head of the U.S. Senate Budget Committee. In 2002, Prof. Walter's TCU engineering seniors won the Design News national competition award ($20,000). In 2006, Prof. Walter received a Commander's coin from Aberdeen Test Center (U. S. Army) and in 2008 he received Edwards AFB Instrumentation Special Recognition coin (#19). In 2008, he was awarded the Shock and Vibration Information Analysis Committee's (SAVIAC's) Lifetime Achievement Award. SAVIAC represents the Department of Defense, Department of Energy, and the Defense Treat Reduction Agency in this subject area. Most recently (2009) he was recognized as a Senior Life Member of ISA.

PCB PIEZOTRONICS
AN AMPHENOL COMPANY

3425 Walden Avenue, Depew, NY 14043 USA

pcb.com | info@pcb.com | 800 828 8840 | +1 716 684 0001