Kulite TD 1014

Best Practices for Reducing Pressure Measurement Noise, Part 2: Installation

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Part 1 of this series focused on the electronic design elements that are selected to reduce measurement system noise. Differential input amplifiers with EMI/RFI common-mode filters, isolated instrumentation-grade power with line conditioning, and signal conditioners with advanced diagnostics are recommended front-end components of dynamic pressure measurement systems. Optimal electrical performance cannot be achieved without their inclusion. These electronic noise controls must be paired with appropriate passive electrical and magnetic controls to attain the highest signal-to-noise, SNR, and best measurement uncertainty for a dynamic pressure measurement. Thoughtfully selected and properly installed instrumentation-grade cable and connectors together with protective housings that may include conduit and enclosures constitute the field portion of the dynamic pressure measurement system.

Much of the more spectrally rich EMI/RFI sources are present some distance from the front-end electronic components, but may envelop a portion of the dynamic pressure measurement system field installation. Electromagnetic and radio frequency interference sources, EMI and RFI, will couple into the signal path as extraneous noise in both the permanent system wiring and any test-specific wiring. Part 2 of the series provides guidance for proper field installation including the avoidance of known noise sources and coupling mechanisms. This technical document also identifies the best material and installation practices to apply for successful measurements in challenging test, measurement, and control applications. The entire system containing analog circuitry, both the front-end electronics and the field wiring, should be safeguarded from noise by following long-established practices described in this technical document.

Model Installation

An isolated sensor with shielded signal wiring encapsulated within a conductive metal shell offers the best theoretical installation model for minimizing electronic interference. The shield of the internal wiring is returned to the DAq reference voltage. The enclosures and conduit encompass the low-level signal from the measurement source to the measurement system as shown in Figure 1. The resulting continuous Faraday cage absorbs or reflects the EMI and RFI over the complete field installation. The entire protective barrier should be grounded to the facility superstructure to achieve a nearly constant ground potential.

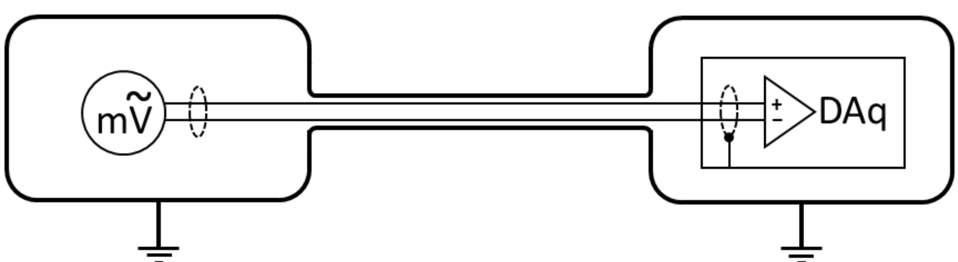


Figure 1: Low-Level Dynamic Signal Shielding with Faraday Enclosure

A Faraday cage captures any external electrostatic charge. Ground connection is required to drain the buildup of charge to avoid capacitive coupling of charge to the internal components.

 (TD 1014 Rev. 7/13 /2022)

Installation and Material Considerations

It may be necessary to install the field wiring for critical measurements as shown in Figure 1, but it would be impractical to designate a fully-encompassed signal path for each analog signal connected to a large channel measurement system. It is also unwise to assume a constant ground potential along the field installation. Consequently, multiple design elements and best practices have been developed for the field installation. These methods involve most, if not all, of the following:

- Signal routing and physical separation from noise sources (physical controls)
- Wiring and electro-mechanical barriers (material controls)
- Electronic control elements
- Wiring and shielding assembly
- Electrical treatment of the shield

Physical Controls: The near field strength of a point source is inversely proportional to the cube root of the distance. Increasing the amount of separation from a known magnetic or alternating voltage source will noticeably reduce the coupled energy into the field wiring. AC power and control wiring that carries current to a final element such as a solenoid valve or motor should be segregated from low-level sensor signals. Typically, conduit and cable trays are dedicated for each source type to ensure proper separation.

1. When large physical separation is impractical, avoid running cables parallel to known magnetic fields for any distance.
2. The signal wiring should cross system power or control cables at a 90° angle as this will minimize the noise coupling area. Take precautions to prevent the wires from touching.
3. Do not allow cables to move freely near components that produce magnetic fields. Segments of cable will generate voltages proportional to the strength of the magnetic flux if the cables cannot be restrained from vibrating relative to the magnetic field. The resulting noise will include the frequency and harmonics of the magnetic source and the lower "beat" frequency of the cable.
4. Do not allow the cable to vibrate at high frequencies/amplitudes as continuously altered surface contact area between the dielectric and conductor can build up a charge that superimposes noise on the signal wiring. This noise type is indistinguishable from dynamic pressure signals.
5. Remove any unnecessary length of wiring or coil the excess cable in a tight "figure 8" pattern.

Material Controls: Several forms of plastic are used to coat the conductors. In addition to providing high electrical isolation, the coating exhibits a known dielectric constant and a dissipation factor. FEP and TFE Teflon as well as polyethylene or polypropylene insulation all have much lower dissipation factors and will absorb less energy than the most commonly used conductor insulation, polyvinylchloride (PVC).[1] The dielectric properties of PVC are also higher than FEP, TFE, or polyolefins. A higher dielectric constant of insulation stores more energy and increases the capacitance of the cable. Minimizing cable capacitance is critical in limiting noise on high-frequency signals. PVC coated wiring is acceptable for most general-purpose installations, but Teflon-coated wiring/cable jacketing is best for more critical measurements. Additionally, Teflon offers good flammability performance with the highest dielectric strength and highest operating temperature of the commonly available wiring/cabling insulation materials.

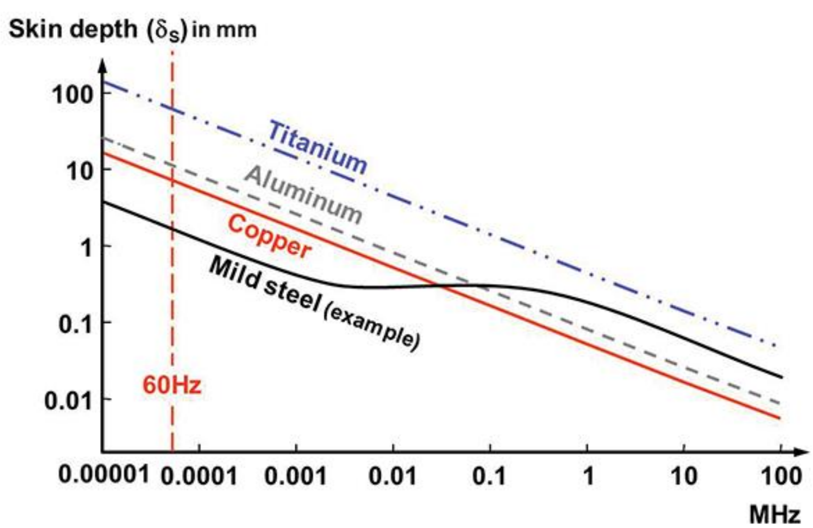
The stranded conductors used in signal wiring are typically coated in tin, silver, or nickel to avoid corrosion and support higher temperature operations. Any corrosion of the individual strands will result in an inability to withstand repeated flexing and will lead to eventual failure, usually near a solder or crimp connection. Tin solders easily and is the least expensive coating for use at temperatures below 300° F. Tin coating increases the surface resistance causing some signal transmission loss, but these effects are immeasurable at the frequencies associated with most dynamic pressure measurements.

Nickel plated wire is used in high-temperature applications because it offers the best corrosion resistance due to the formation of a protective surface oxide. Nickel-coated wire is difficult to solder without active fluxing compounds, but crimp insert connectors and special solder kits are available for working with nickel-coated wires. The surface resistance of nickel coated wires is lower than that of tin-coated wires. Silver-coated wiring is easy to solder, reduces the surface resistance slightly lower than pure copper, and supports installations over the entire TFE operating temperature range. Its expense is most easily justified when very high frequencies are anticipated due to the minimal signal transmission loss. Silver has the lowest room temperature resistance of any metallic element and provides the best lubricity to minimize internal electrostatic charge buildup at high vibration levels.

Electrical enclosures and conduit can offer attenuation of unwanted noise sources. Conductive metal barriers both absorb and reflect external noise. Secure facilities will often entrain communications cabling and sensitive analog video signals within a thick-walled ferrous conduit. This method prevents any emanations that may be monitored by a 3rd-party. A secondary benefit of this installation is that nearby magnetic sources do not penetrate and cause degradation of the signals inside the conduit. Installers can add EMI and RFI controls to existing systems when necessary to reduce radiated noise. These include:

1. Enclosing sensitive amplifiers and electronics inside instrument racks designed specifically to reduce EMI/RFI at known interference frequencies.
2. Enclose permanent signal transmission lines within conduit. Metallic conduit is very effective for limiting the undesirable effects caused by wireless transmitters including hand-held radios.
3. Install conductive tape and gaskets to eliminate entryway and enclosure gaps and openings.

Always use the appropriate material for the frequency and field strength. Keep in mind that the outer surface should be conductive. Aluminum is the least effective common material for lower frequency magnetic interference. Aluminum is followed by copper, steel, and mu-metal (nickel-iron alloy) in that order.[2] Magnetic shielding made with high-permeability alloys like mu-metal do not block all magnetic fields. Rather they provide an unimpeded path for magnetic field lines around the shielded area. Mu-metal is least effective at higher frequencies followed by steel, aluminum, and copper in that order. See Figure 2 for the skin depth vs. frequency for common metals used for EMI shielding and compliance, EMC.[3]



Material	Skin Depth δ (mm)
Aluminum	$\frac{84}{\sqrt{f\ (Hz)}}$
Copper	$\frac{66}{\sqrt{f\ (Hz)}}$
Steel	$\frac{6.6}{\sqrt{f\ (Hz)}}$
μ-Metal	$\frac{2.8}{\sqrt{f\ (Hz)}}$

Figure 2: Skin Depth vs. Frequency for Common Enclosure Materials

The intensity of a transmitted field decreases exponentially relative to the thickness of the shielding material as shown in Figure 3. Skin depth, δ, is the thickness of a conductive material that attenuates 63.2% (e^{-1}) of the incident energy. Each skin depth of material further reduces the remaining energy by 63.2%, about -8.6 dB per additional skin depth.

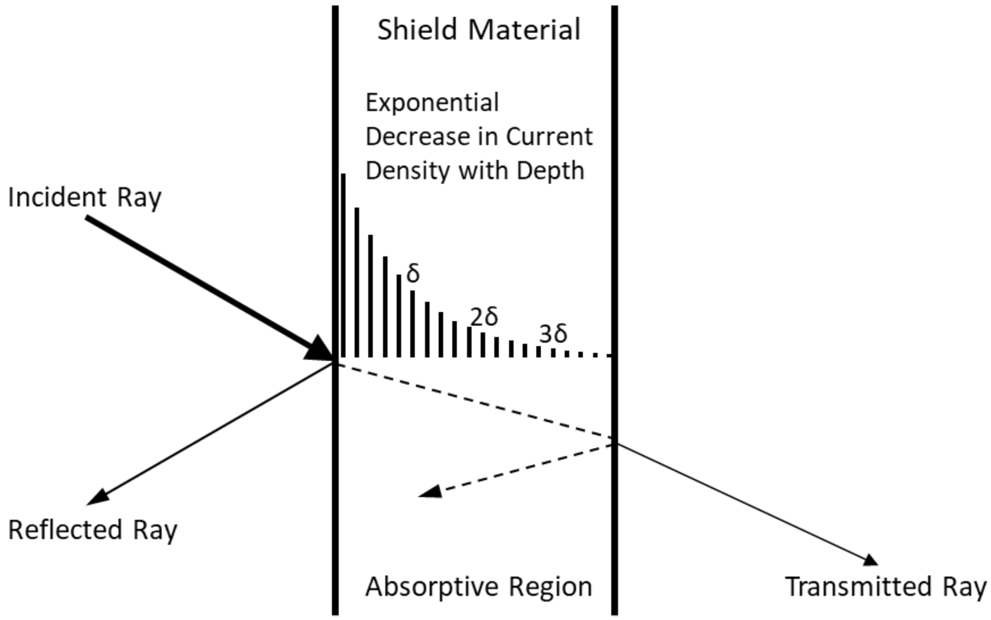


Figure 3: Reflective and Absorptive Energy Loss with Conductive Shielding

The high permeability of steel works best at lower frequencies, but is less effective at frequencies above 100 kHz. The skin depth of steel at 60 Hz is 0.85 mm. It would take a wall thickness of about 7.8 mm, about a third of an inch, to attenuate 60 Hz radiation by -80 dB. Energy at 1 kHz would be attenuated to a similar level with less than 2 mm of steel. As frequencies increase, it becomes clear that thin layers of copper or aluminum are effective at shielding very high-frequencies above 1 MHz.

Electronic Control Elements: Collapsing fields emanating from the coils of solenoid valves and relays generate short duration transients (from a few hundred kHz to several MHz) that can reach into the kilovolts as the stored energy finds various paths to the local ground potential. These coils are effectively inductors and must release all stored current when power is disconnected. Install metal oxide varistors (MOVs) across all AC-powered valves and relays or diodes across DC-powered valves and relays. This addition will provide a means of absorbing the radiation and voltage spikes associated with collapsing magnetic fields as valves and relays are de-energized. The desired behavior of a MOV is to exhibit a high resistance at operational voltages and develop a low resistance as the unwanted spike approaches a predetermined “clamping voltage.” No meaningful current shunts the solenoid coil through the MOV or diode when powered under normal conditions. The MOV clamping voltage is rapidly reached as the coil is de-energized resulting in the instantaneous high current condition that is dissipated inside the MOV as thermal energy. Similarly, the diode known as a “flyback diode” absorbs the energy stored in the coil when the current powering the coil is suddenly interrupted. Otherwise, this stored energy, usually at much higher voltages than the input power, can arc and damage internal contacts or interconnected components.

Part one of this series introduced the power line conditioner. The power line conditioner is a critical component of any dynamic data acquisition system. It should also be a part of control systems or other equipment that require high current flow to operate when they are in the near field of the pressure measurement system field installation. Devices such as stepper motor controllers, ON-OFF controllers, and pulse-width modulated motors and heaters switch current at high frequencies and will change the local ground potential. A line conditioner powering the control system will galvanically transfer AC power from the local AC power source to the control system. This configuration provides a control system reference potential that is electrically isolated from the pressure system field wiring and will attenuate back EMF generated by the control system that would otherwise be reflected into the AC power system.

Ferrite cores offer an alternate approach to attenuate RFI/EMI. They attenuate high-frequency common-mode current. The ferrite cores have minimal resistance at DC, but exhibit peak resistance at a specific high frequency before rolling off. Round cable snap-on split core ferrites may be installed on transducer wiring in the field for troubleshooting purposes without tooling. The cores may be placed on individual wires to suppress EMI/RFI in a common-mode fashion. Alternately, they may be placed around the entire cable to reduce both conducted and radiated emissions such as that found with DC brushless motor controllers. Different magnetic material and impedance cores are available to achieve the greatest attenuation at a specific frequency. Historically, ferrite cores were most useful in attenuating frequencies above a few MHz, but relatively new formulations are available to attenuate much lower frequencies that align well with dynamic pressure measurements.[4]

Wiring/Cabling Assembly: The maximum frequency range of dynamic pressure signals ranges from DC to 100 kHz. Much of the magnetic noise in this range penetrates cable shielding with minimal attenuation as copper and aluminum shielding are not terribly effective against low-frequency magnetic fields. Twisted pair cabling is the first line of defense against inductive coupling caused by the presence of alternating current or the movement of permanent magnets. This is a form of physical control since the source to conductor distance in twisted pair wiring is nearly the same for each conductor. The quality of symmetry, in large part, of the double helix twisted pair conductors determines the magnetic noise immunity of a cable. Twisted pair cables are designed for differential, electrically balanced applications including excitation distribution/sensing and signal transmission. Use twisted-pair cabling with separate pairs for all balanced, differential functions. The power and sense pairs are both seen as low impedance, DC-only conductors that will minimally impact any adjacent signal pair. Multi-pair or separate single-pair cables for input power, output signal, and sense wiring are both acceptable for long cable runs.

Maintaining proximity between the wires in each balanced pair from the pressure transducer to the measurement system will minimize the physical current loop area and ensure that local magnetic flux affects each wire within the transmission pair to a similar degree. A balanced impedance over its entire length supports the common mode rejection sought in low-level, differential signal applications. Equation 2 may be used to estimate the noise voltage induced by magnetic field on a closed-loop single-turn.[5]

Equation 1: $$V_n = 2\pi f B A \cos\theta * 10^{-8}$$

B is the rms value of flux density (gauss)
A is the closed loop area in cm^2
θ is angle of *B* to area *A*

Area is minimized with proper cable selection and installation. Equation 2 mathematically describes the previously recommended physical controls to minimize noise pickup: 1) large separation between magnetic sources and the field wiring and 2) orientation of the magnetic source to the field wiring.

Any alternating magnetic field induces a voltage flux into the signal wiring. The 360° configuration of the twisted signal pair produces locally equivalent alternating regions of flux. Twisting the conductors creates small negative and positive increments in the signal wiring that theoretically yield a net field strength of zero over each twisted cycle. A shorter twist cycle, 3 per inch, will generally produce improved magnetic immunity. Different twist ratios of adjacent pairs within a cable is the primary means of reducing crosstalk between signals located within a single cable. Twisting the wires has an added benefit of locally equivalent parasitic charge on each conductor. Symmetrical parasitic voltages produce induced noise signals equal in magnitude within both conductors. The resultant noise present in the measured response is dependent on how well the source and cable are balanced as well as the CMRR of the amplifier.

Capacitive coupling is caused by the presence of alternating electrical fields. Capacitively coupled noise leads to a buildup of charge that produces a noise current. The simplest and most effective barrier against electrostatic noise pickup and far field electrical interference is a conductive shield. A properly selected and installed shielded cable will act as a Faraday cage which works because an external charge cannot exist on the interior of a closed conducting surface. Shielding will reflect as well as attenuate very high-frequency radiation due to an impedance mismatch between free air/shield and skin effect, but the primary function of shielding is the capture of the charges that would otherwise reach the signal wiring so they may be drained off to a satisfactory reference potential. The electrostatic noise rejection is inversely related to the DC resistance of the shield leading to some charge coupling into the conductors.

There are two types of shields used in instrumentation cabling – tape and braid. Tape shields are typically constructed using polyester that has been coated on one side with aluminum. The non-conductive portion of the tape is in contact with the cable jacket. The twisted pair and conductive drain wire are surrounded without gaps by the spiral-wrapped metallized tape shield. Braid shielding is constructed using woven copper that has been coated with tin, silver, or nickel to prevent oxidization. Tightly woven braid shielding with its lower resistance will be approximately 5X more effective at diverting low-frequency noise due to its lower impedance as AC voltage induced on the signal is directly proportional to the shield impedance.

Cable having multiple twisted, shielded pairs (tape with drain wire) surrounded by an outer overall braid shield offers the best protection against electrostatic noise and high-frequency noise. Installers should ensure each shield is isolated from other shields in the cable bundle until the shields are properly terminated, typically at the measurement system ground. Do not ground both ends of the shield as that will lead to indeterminate negative consequences. Induced magnetic noise, V_{Noise} (rms), in a conductor in parallel with a second conductor for a typical ground loop may be estimated with Equation 2.[5]

Equation 2: $$V_{Noise}(rms) = 2\pi f M I$$

f = frequency in Hertz
M = Mutual cable inductance in Henries
I = Current in Amperes

The mutual inductance of a general-purpose instrument cable such as Belden 8728 is nominally 0.18 µH per foot and the outer shield resistance is 16.6 Ω per 1000'. Assuming a run of 100' with 2 V difference in potential at either end, one can estimate the induced voltage (60 Hz EMI) at 8 mV rms due to the shield current. When considering the peak-to-peak noise levels are likely 25 mV, the 100 mV full-scale pressure signal may be severely compromised if the twist ratio is nonsymmetric or the amplifier CMRR is low at line frequency. Noise voltage on the shield simply must be eliminated by removal of the ground loop as shield to conductor capacitance will cause the common-mode noise to couple directly to the signal.

Wiring/Cabling Assembly General Guidelines:

1. Use cabling with separate twisted pairs for all balanced, differential functions.
2. Do not permit the flow of AC current within the same cable/shield as the pressure signal.
3. Minimize the physical separation of each conductor to its mated pair in the cable until terminated at the transducer or measurement system.
4. If not provided with a low-resistance path via drain wire or braid, the charges can be coupled into the signal conductors through the shield-to-cable capacitance producing a noise current.
5. Use individually shielded, twisted-pair wiring with an outer overall shield when possible.
   a) The helical tape shield offers 100% coverage which is best for high-frequency noise.
   b) Braid shielding is more effective at minimizing low frequencies due to its lower DC resistance.

Shield Termination Guidelines:

1. Do not leave both ends of the shield unterminated. An unterminated shield allows charge to build up and will produce a noisier signal (potentially unusable) than a similar unshielded cable.
2. Do not tie both ends of the shield directly to the reference voltage except when the entire structure is at the same potential such as aircraft installations. Otherwise a very large loop area will be created that leads to excessive noise pickup.
3. Use a separate shield for every measured signal and ensure each shield is isolated from other shields in the cable bundle until the shield is terminated.
4. Keep the shield termination as short as possible since long shield connections are effectively added inductance that will lead to excessive noise pickup, especially at higher frequencies.
5. Use 360° shield connection with conductive connector housings or gaskets into enclosures.
6. Never tie shields together to minimize connector pin count.
7. Never allow the shield to share the path with a signal return conductor.

Failure to follow these guidelines will almost always result in poor-quality data when common EMI/RFI sources are present such as fluorescent lights, desktop computers, wireless communications, heaters, motors, and valves. Items 6 and 7 are the two most often encountered common impedance pathway issues after single-ended input channels. As seen in the example above, it is never acceptable to allow current flow in the shield for any distance. This is especially true if the shield and -signal are connected as no amount of common-mode rejection will help when only one of the signal wires is subject to current flow.

In low-frequency applications, maintaining shield continuity using a pin on an intermediate connector may be acceptable as long as the outer shell of the connector is at the local ground potential and offers a good amount of shielding for the length of signal wire within the connector housing. Do not place multiple shields on an intermediate connector pin to avoid using higher density connectors as noise induced on a single shield is superimposed on any other shield it may contact unless they are individually terminated at the proper reference voltage potential. Thus, the baseline signal noise will be increased by the root-sum-square of all shields sharing the same pin. In aircraft installations the shield(s) should be connected to the connector shell as the airframe is designed to be at the reference potential. This is the case for intermediate bulkhead connections as well as the measurement system connection in aircraft.

Figure 4 illustrates why the electrostatic shield should be connected to an appropriate reference potential in a typical lab environment.[7] The example below is for a 100 Ω source at room temperature. Higher resistance, 1,000 Ω typical, Kulite pressure transducers would exhibit proportionally higher noise levels. A shield grounded at the DAq is often the best practice for shorter cables or low frequency applications.

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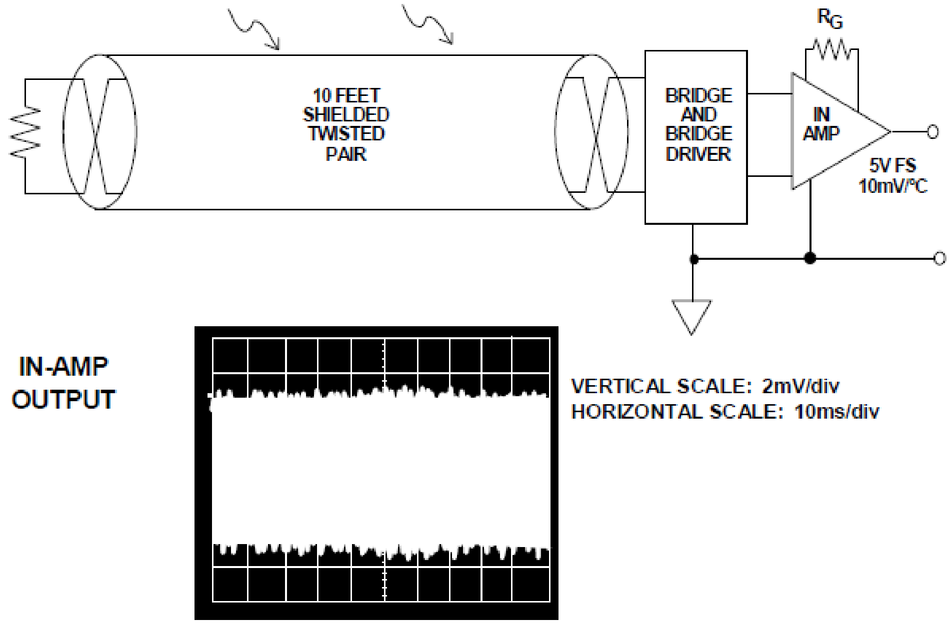

Figure 4: Ungrounded Shielded Cables Act as Antennas

Figure 5 illustrates why the electrostatic shield should never carry any current. Small mismatches between the measurement system reference potential and a nearby earth ground will cause power-line frequency AC current to flow and will have serious data quality consequences including noise and unstable readings.

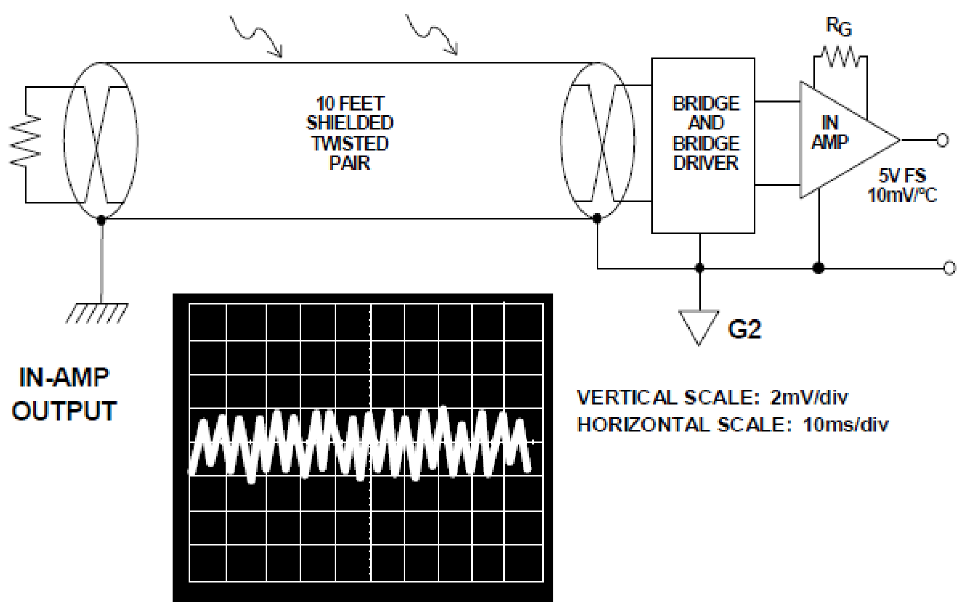

Figure 5: Grounding Both Ends of a Shield Produces Low Frequency Ground Loops

Three common approaches to terminating the shield are to be considered for each installation.

1. Grounded shield at the measurement system.
2. High-frequency shield using hybrid ground at the measurement system.
3. Driven shield from measurement system at the signal common-mode voltage.

Grounded Shield is the most common shield treatment for cables shorter than a few hundred feet. Shield wiring tied to the transducer body is available as an option which returns the charge to the transducer case and ultimately the installation ground potential. The shield is unterminated (floating) at the transducer in most Kulite products so that charge may be returned to the measurement system reference potential. The ground termination is often made to the shell of the system connector or to the chassis as the cable enters the enclosure. Either option should provide a full 360° shield coverage until the signal wiring is safely inside the measurement system chassis. Avoid terminating the shield at the board-level analog ground unless that is the "star" point for the measurement as this unnecessarily introduces common impedance noise. The star grounding approach ensures that the current flowing in any path will not force a voltage drop in a return path for another circuit and appear as an erroneous input signal.

This shield treatment is used in most low frequency applications including dynamic data acquisition. The tape or braid shield acts as a Faraday cage surrounding the conductors and minimizes the ingress (or egress) of electric fields. Charge is drained into the reference potential at the measurement system. Some charges are coupled into the signal conductors through the shield-to-cable capacitance. The use of braid shield with Teflon insulation will minimize this effect and help to keep the noise floor low. Braid shields are effective at shielding EMI into the low MHz range, but braids typically do not provide the best protection against very high frequency interference (very short wavelength) due to the presence of small holes. 95% or lower coverage is the typical specification and can become an issue if significant EMI sources above 10 MHz are present, especially if there is also significant cable movement.

Very long cables often pass through several electrical enclosures. The signals may be interfaced using intermediate bulkhead connectors or terminal strips. It is best to maintain uninterrupted shield continuity through multiple cable segments, within connectors as required, if the ground potential and overall cable length is electrically short. When multiple segments are used in areas known to have significant EMI/RFI, it may be necessary to tie the shield to the reference potential at one end of each intermediate cable.

When the transducer is electrically isolated from the local ground potential and the shield is grounded to the case of the transducer, it is acceptable to also ground the shield at the measurement system. This is sometimes the case when composite materials are tested in a wind tunnel. The high-altitude conditions are simulated using very dry air. The transducer will be isolated from the local facility ground potential and the shield will drain off the static charge built up on the test article by the passing dry air.

High Frequency (Hybrid) Shield is an approach to allow for the simultaneous blockage of low frequency ground loop current while permitting higher frequency current flow in the shield. The shield and case of the transducer are typically grounded at the measurement point and a bipolar capacitor connects the shield to the measurement system reference potential. A hybrid shield is often best for ground-referenced amplified signals, electrically long cables, and/or a very high-frequency of interference. Additionally, ferrite beads or split-core ferrites may be necessary at the measurement system to absorb high-frequency current which effectively blocks the high-frequency common-mode RFI.

Amplified dynamic pressure transducers referenced to local ground are uncommon in field installations. Electrically long cables are not seen in practical dynamic pressure measurements either. A cable is viewed as electrically long when its overall transmission distance is greater than the wavelength of the interference source divided by 2π. This distance is about 480 meters for a 100 kHz noise source that might interfere with valid pressure measurements. That transmission distance is too long to support a frequency response of 100 kHz.[8] The most common hybrid shield scenario for dynamic pressure measurements is when the shielded cable must transverse a known high-frequency source.

Grounding both ends of the shield permits high-frequency currents to circulate in the shield which will counteract the high-frequency noise current flowing in the signal conductors. These counteracting currents create magnetic fields due to mutual inductance between shield and signal pair that reduces the magnetic fields emanating from the signal conductors. The result is a high level of magnetic shielding at the frequency of interference. The impedance of the capacitor is high at low-frequencies effectively blocking the flow of power line frequency currents (50/60 Hz) in the shield. The impedance of the capacitor falls at higher frequencies and should be selected to largely pass the frequency of interference local to the transducer installation. Smaller values of capacitance significantly undermine the common-mode performance of the shield at lower frequencies, but are effective at high frequencies.[9] The capacitor values typically range between 0.1 µF and 10 µF.

Driven Shield is a shield that is maintained at the common-mode voltage, V_{CM}, of the incoming pressure signal. This approach works especially well for low-level, high-frequency signals. Driving the shield with a low impedance voltage equivalent to V_{CM} minimizes capacitive coupling while increasing frequency response due to a minimal voltage potential between the shield and signal wiring thus effectively lowering noise coupling. However, a driven shield is not very effective at rejecting external near field interference. Typically, a tape shield with 100% coverage surrounds the signal pair and is maintained at V_{CM} by a low impedance amplifier inside the measurement system while the electrically isolated outer braid shield is returned to the measurement system potential. This approach usually yields the lowest overall noise pickup as leakage currents are largely eliminated. Driven shields are often used when the impedance of the source is very high such as professional audio or medical sensing applications.

Conclusion

Noise coupled into dynamic pressure signal wiring is minimal in most cases if the practices described in the two technical documents in this series are followed. Understanding the interference sources and their coupling mechanisms will generally lead to an acceptable mitigation of the noise accumulated on field wiring to acceptable levels. These solutions will include a range of design elements including the installation of shielding and enclosures, the installation of twisted-pair shielded cabling, and the proper placement and termination of the signal conductors and cable shield.

Common sense installation approaches such as wrapping the individual transducer leads of miniature pressure probes with a thin PTFE thread seal tape come with installation experience. This action is a temporary means of minimizing the area of the circuit loop formed by the individual wires and should be a natural outcome of comprehending this material. Also, understanding the electrical and magnetic nature of the test article will guide installation practices and potentially permit the occasional usage of unshielded internal wiring if the test article acts as a Faraday cage.

Following the suggested shield termination approaches should prevent the buildup of noise voltage and uncontrolled current on the shield within the field installation. On occasion, high levels of EMI/RFI surrounding the transmission medium will necessitate the installation of local amplification exhibiting a lower source impedance better suited for noise rejection. The installation of the complete measurement system, including the A/D converter as close to the measurement point as practical will often lead to the lowest measurement uncertainty. However, shielding the measurement system within a Faraday cage and transmitting the digitized data using differential line drivers and receivers or optical fiber is only required for cases of extreme interference. As with all system installations, it is strongly advised to implement a partial installation to understand the EMI/RFI environment, subsequent measurement limitations, and expected performance. A cost-benefit analysis should then be executed during the critical design phase of the project to limit redesign costs associated with a post-installation corrective action.

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