KULITE SEMICONDUCTOR PRODUCTS, INC.
One Willow Tree Rd, Leonia, New Jersey 07605
Tel: 201-461-0900 • Fax: 201-461-0990 • http: // www.kulite.com

Kulite TD 1013
Best Practices for Reducing Pressure Measurement Noise, Part 1: Electronics

Prepared by Steve Carter

The acquisition of high-resolution dynamic pressure measurements requires careful attention to wire and cable management to minimize the pickup of extraneous noise. Electromagnetic and radio frequency interference sources, EMI and RFI, are pervasive in most test and measurement installations. These sources can be challenging to overcome in industrial and process control applications. This technical document series will introduce the common sources of noise, several noise coupling mechanisms, and guidance for minimizing any detrimental effects on the dynamic pressure measurements. In every case, the entire system containing analog circuitry should be examined and optimized for performance and cost. This system includes the transducer, interconnect wiring, electrical connectors, signal conditioner, amplifier, A/D converter, and enclosures. Part 1 of this series addresses electronic mitigation options. Part 2 will provide best practices for proper field installation.

Many types of electromagnetic and electromechanical EMI/RFI controls are available as mitigation elements. Proper selection of the transducer electrical interface and the conditioning electronics are always the first actions to consider because they will often establish the corrective actions. The importance of interfacing electronics that incorporate circuitry to minimize interference outside the frequencies of interest cannot be understated. Two other technical documents in this series have presented the qualities of the transducer/transmitter electrical interface[1] available to researchers and test engineers as well as the properties of quality signal conditioners.[2] This technical document presents the applicable methods to minimize noise coupling mechanisms that are best implemented only after these two documents have been read and comprehended. Noise is almost always manageable as mitigation actions utilize the mathematical descriptions attributable to the physical properties of electromagnetism. References covering the laws of electricity and magnetism will not be addressed in this document. Rather, this document should be viewed as a troubleshooting and repair companion guide for individuals involved in the measurement of dynamic pressure.

Noise Coupling Mechanisms

All forms of interference require a source, coupling medium, and a receiver to exist. The primary focus of noise control involves wiring and cabling best practices. Additional physical controls applied to the receiving electronics will be introduced in this document as they should be used as the foundation for accurate measurements. Together, the appropriate wiring configuration and the inclusion of additional design elements are the most effective means to reduce noise pickup to an acceptable level.

Interference Categories

There are three major types of interference encountered in dynamic pressure measurements.

1. Capacitive coupling caused by the presence of alternating electrical fields
2. Inductive coupling caused by the presence of alternating magnetic fields
3. Conductive coupling caused by common impedance pathways

Capacitive and inductive coupling may also be broken down into near-field and far field interference. The wavelength of the interference will determine if the source operates in the near field or far field. For example, a 1 MHz source having a wavelength of approximately 300 meters must originate from beyond 48 meters ($300/2\pi$) to operate as far field interference. It may then be assumed that the medium for far field interference is free space where the EMI/RFI field intensity is inversely proportional to the square of the distance from the source.

Since bandwidth requirements for dynamic pressure measurements rarely approach 1 MHz, near-field interference is the more concerning coupling mechanism for dynamic pressure measurements. One can assume the transducer and wiring are installed physically and electrically close to the noise source. Fortunately, electrical controls to block interference sources of 1 MHz and above are readily available. Addition of these design elements are unlikely to alter the dynamic pressure data of interest.

Input Modes

The most important design element of dynamic pressure measurement systems is often the voltage input mode. When accuracy is critical, a differential input configuration is always preferred over a single-ended input. The figures below illustrate the typical noise reduction improvement on the same ground-referenced signal when interfaced to single-ended (Fig. 1a) and to differential input (Fig. 1b) electronics.[3]

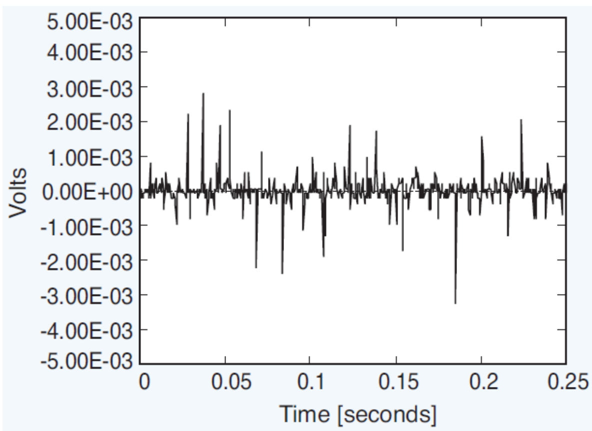

Figure 1a: Single-ended Measurement:

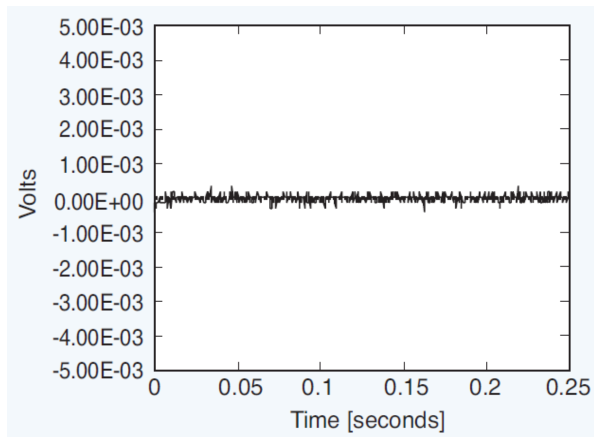

Figure 1b: Differential-Input Measurement

Differential measurement electronics are specifically designed to measure the small voltage difference encountered during the presence of larger common-mode voltages existing on both input wires and avoid common impedance pathway issues. The voltages may be as high as half of the excitation level while the signal level is usually in the millivolt range. The input impedance of either differential input is typically 1 MΩ or higher to ground ensuring negligible current flow in the signal wiring. The noise and DC voltage common to both input wires is reduced by the common-mode rejection ratio (CMRR) of the amplifier when measured in a differential input mode. This allows for amplification of the differential signal to match the input range of the A/D converter and greatly improve the dynamic range of the pressure signal. Differential voltage measurement also permits the use of balanced shielded/twisted pair cable to minimize both capacitive and inductive noise coupling.

A single-ended input configuration should rarely be used with unamplified, bridge-based transducers because the negative data system input is assumed to be at ground potential. Single-ended inputs will ground the negative signal bridge terminal causing current to flow in the signal wiring. This approach only works when a separate isolated power supply is available for each unamplified transducer. Single-ended inputs exhibit lower accuracy than differential measurements for ground-referenced inputs due to common impedance noise generated by power return current. Pseudo-differential inputs are typically no better than single-ended inputs because the negative input must usually be within ± 1 volt of ground potential and the input impedance may be as little as 50 Ω. Pseudo-differential inputs are compatible with unamplified transducers when using a balanced bipolar supply and the transducers are manufactured in a balanced bridge configuration, but the same common impedance noise sources are present.

All voltage input modes are compatible with amplified pressure transducers. In some cases, the lower costs of the less capable single-ended measurements system (Fig. 1a) may outweigh the added costs and better measurement accuracy of differential inputs, but the extra cost of amplified transducers often offsets any measurement system savings and should be factored into the cost-benefit analysis.

Input Filter Electronics

The classic EMI/RFI filter applied to the front-end differential electronics is shown in Figure 2.[4] This circuitry is one of the more useful solutions for restoring the original analog signal content from a noisy input signal. Radiated noise originating from pulse-width modulated controlled (PWM) motors or heaters common to ground test facilities occurs at frequencies greater than 1 MHz. This unwanted high-frequency input can appear as any of the interference categories. This interference can overload the input amplifier of the data acquisition system to the point that no usable data are collected or may appear as an unstable low-frequency measurement due to DC rectification. Often, there is no presence of high-frequency content as seen by the measurement system if the front-end amplifier is followed by a low pass filter.

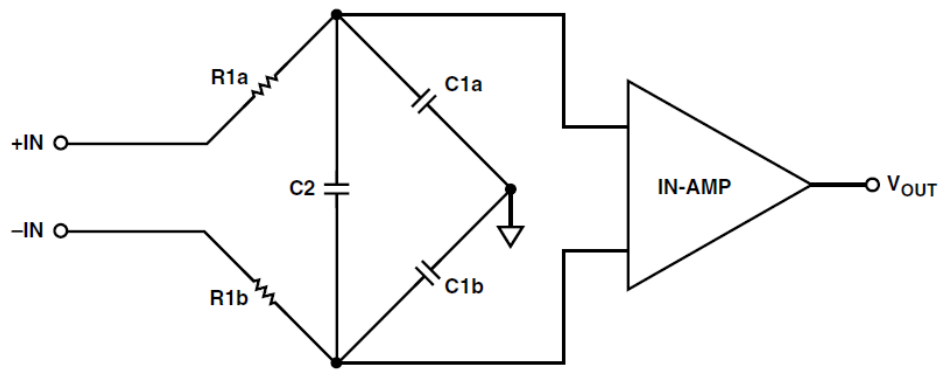

Figure 2: Common-Mode, Differential-Mode Low Pass Filter

It is important to select signal conditioning and measurement systems with EMI/RFI rejection components to prevent the unwanted rectification of common-mode voltage spikes of frequency higher than the bandwidth of interest. The values of the individual passive resistor/capacitor pairs (R1a/C1a and R1b/C1b) must be precisely matched to maintain common-mode rejection at high frequencies. The shunt capacitor, C2, is selected specifically to reduce the common-mode error resulting from any component mismatch of the R1/C1 pairs. The value of C2 is also selected to establish a similar slew rate for both rising and falling waveforms at the amplifier output to ensure that any remaining high-frequency noise averages to 0 volts.[5]

Power Input Filter Electronics

The quality and stability of the incoming AC power is an often-overlooked element of the dynamic data acquisition system. It is best to block all high-frequency signals present on the local AC power distribution system. Many test facilities utilize an isolation transformer with EMI suppression of the incoming line voltage for the instrumentation systems as well as a heavy-gauge copper grid to provide a low-noise ground return. The power distributed to the measurement systems is often assumed to be of high quality if control systems requiring a large amount of current are powered by another AC source with a separate earth ground. Periodic power quality checks within the measurement system are prudent as noise can be reflected to the individual circuits by inadequately designed equipment fed from the instrument power distribution system. Measurement system hardware designed with internal power line filters (Fig. 3) will prevent equipment-generated EMI from conducting to the test cell instrument power system.[6]

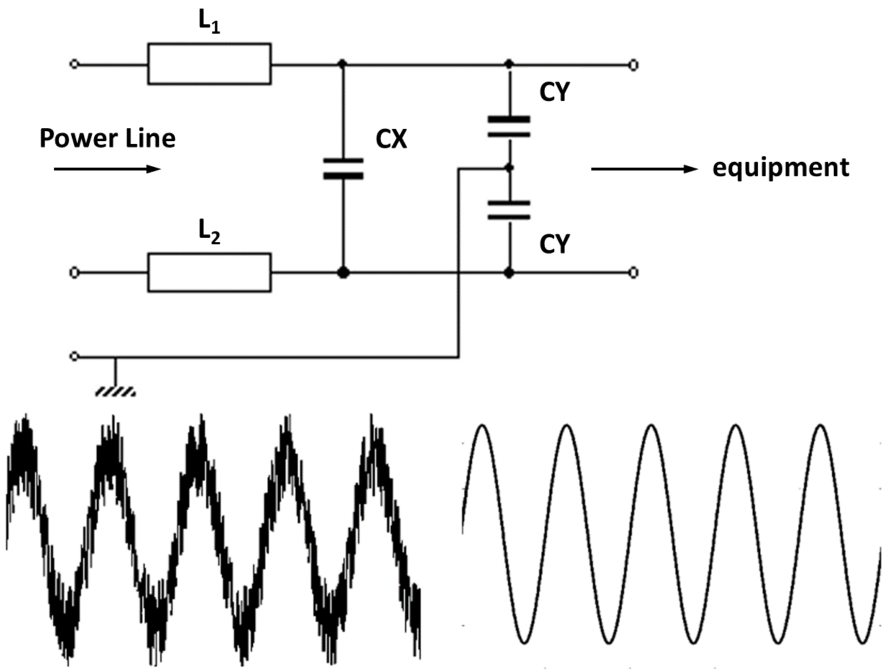

Figure 3: Line Power Suppression Filter to Prevent Outgoing EMI

Ideally, the measurement system power would be supplied as a sine wave with the amplitude and frequency given by national standards with an impedance of zero ohms at all frequencies. Instrument-grade power systems are intended to provide a test cell or facility with stable input power free from grounding issues and noise above the line frequency. These power distribution systems are important to protect equipment and to ensure good data quality. There are good options, including AC power line conditioners, for researchers having low quality or suspect power. Line conditioners are readily available for a few hundred dollars or less that offer several beneficial features including the following.[7]

1. Internal isolation transformer to galvanically transfer AC power from the local AC power source for the elimination of ground loops and to provide a low noise reference ground
2. Input EMI filter to eliminate variations in the wave shape caused by line frequency harmonics
3. Automatic transformer tap switching to maintain nominal power during brownout/surge events
4. Internal surge protection to protect from electrical transients generally caused by large inductive loads being turned off as well as lightning strikes
5. Individual EMI/RFI filters on each AC outlet minimize interference generated by measurement system components such as switching power supplies; the higher the suppression in dB, the lower the reflected output noise component

Signal Conditioner/Amplifier Diagnostics

The quality and embedded features of a stand-alone signal conditioner/amplifier (SCA) system oftentimes greatly aids in the troubleshooting and repair of noisy measurements. The Kulite SCA product line fully supports differential voltage measurements with a high CMRR. The input is protected against high-frequency noise using input EMI/RFI filtering. Very low noise signal amplification and excitation output circuitry provides for a signal-to-noise ratio (SNR) of 90 dB and higher for most measurements. Also, the Kulite SCA product line includes three features that greatly aid the test engineer in ensuring the acquisition of valid pressure data: overload detection, amplifier zero check, and intrinsic noise check.

Overload Detection: The SCA architecture of Figure 4 distributes the gain and places the low pass anti-alias filter between the two amplifier stages. The 1st-stage amplifier is immediately preceded by the EMI/RFI filter (Fig. 2, not shown). The 1st-stage (Amp) increases the input signal to a level within ±10.2 volts. This level will not saturate the low pass filter (LP6F or LP6P) causing a nonlinear filter response and erroneous data. Voltages beyond ±10.2 volts are indicated as an input overload requiring a reduction of the 1st-stage amplifier gain. The low pass filter attenuates the out-of-band signal and ringing at the natural frequency of the pressure transducer prior to the 2nd-stage amplifier which then boosts the "clean" signal in accord with the A/D converter input range. Other designs that allow for prefilter amplifier saturation without notification can give the appearance of proper system operation. The output overload monitor is fully programmable to pass a range of voltages from ±0.1 volts to ±10.0 volts

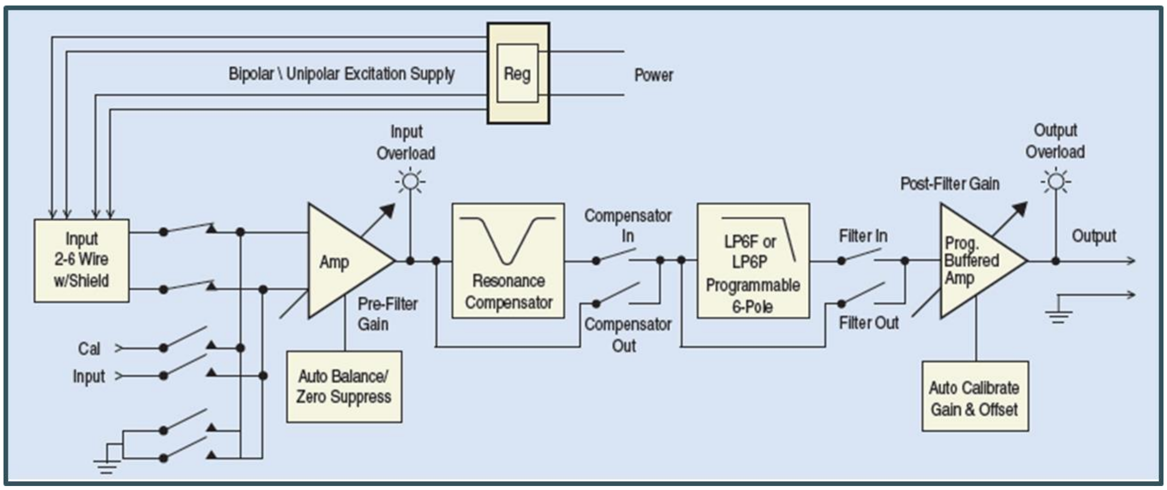

Figure 4: Kulite Signal Conditioner/Amplifier Architecture

Amplifier Zero Check: Kulite SCAs are provided with a circuit to short the input signal and remove any suppression voltage. Activation of the amplifier zero check should result in a low-noise voltage output very close to 0 mV. The resulting signal may be recorded as the baseline noise present in the data acquisition system for that gain/range configuration. Regular checks showing repeatable levels improve measurement system confidence and provide a convenient indication of properly functioning hardware.

Baseline Noise Check: Kulite SCAs are provided with a feature that zeroes excitation with no alteration of the transducer wiring. Activation of the excitation zero function results in an excitation voltage output very close to 0 mV. Any significant noise remaining is systematic noise from external electrical interference or grounding/cabling issues. The resulting signal may be treated as the baseline noise found in the sensor installation. This approach may also be utilized to provide a placebo transducer.

Intrinsic Noise Sources

The measurement threshold is primarily a function of the thermal noise generated by the source resistance of the SOI pressure sensor. This threshold establishes the baseline noise for any dynamic pressure reading. The nominal output impedance of an unamplified Kulite transducer is 1 kΩ. Thermal noise, also known as Johnson noise, is the electronic noise generated by a resistor as the charged carriers become increasingly agitated with higher temperature. Thermal noise is also bandwidth dependent and has a spectral density increasing predictably across the frequency spectrum.[8] This "white noise" is present at the input to the amplifying electronics and is independent of the transduced signal performance.

Bandwidth dependent resistive thermal noise is typically expressed as V_{N-R} in nanovolts (nV) per square root Hz. From equation 1 the thermal noise attributed to a typical unamplified transducer at room temperature is 4 $nV/\sqrt{Hz}$. This source impedance noise is presented to the SCA or data acquisition system prior to any amplification and is characterized as "referred to input" or RTI noise.

Equation 1: $V_{N-R} = \sqrt{4kTR}\ (nV/\sqrt{Hz})$

Equation 2: $V_{N-R} = \sqrt{4kTRB}\ (rms)$

k = Boltzmann's constant 1.38E-23 joule/°K
T = Temperature in degrees Kelvin
R = Resistance in Ohms, 1,000 Ω, typical
B = Bandwidth of interest (f2 – f1) or Δf

Equation 2 is used to provide an estimate of the thermal noise over the bandwidth of interest. The root-mean-square (rms) noise for a typical unamplified Kulite transducer for a frequency range from DC to 20 kHz is 569 nV. This level would be considered the intrinsic noise baseline for the measurement. The figure of merit known as signal-to-noise ratio (SNR) is typically the comparison of the signal at the full-scale input pressure to the sensor noise in decibels and is calculated using equation 3. The SNR for the previous example is 104.9 dB and is regarded as the dynamic range of the typical Kulite piezoresistive transducer.

Equation 3: $Transducer\ SNR\ (dB) = 20 * log_{10}\ (FSO/V_{N-R})$

Amplifier Noise

The other predominant RTI noise source present in all dynamic pressure measurements is current noise originating in the SCA or data acquisition system front-end input amplifier. It is not trivial to identify electronics allowing one to measure the full dynamic range of a Kulite pressure transducer as current noise of many amplifier topologies tends to be larger than the thermal noise originating in the sensor. The bandwidth-dependent amplifier noise, V_{N-Amp}, of the high-quality KSC-2 programmable SCA is 7 $nV/\sqrt{Hz}$. The RMS noise for a KSC-2 SCA for a frequency range from DC to 20 kHz is 990 nV. The built-in amplifier zero check offers a convenient means to measure V_{N-Amp} over the frequency range of interest.

The thermal noise and amplifier noise are both characterized as random sources which may be combined in a root-mean-square fashion to estimate the systematic noise floor (equation 4). An SCA with a built-in zero excitation check offers a convenient means to estimate the combined sensor and amplifier noise over the frequency range of interest. The SNR for the 1 kΩ SOI pressure sensor root-mean-squared with a KSC-2 signal conditioner is 98.8 dB and is regarded as the baseline dynamic range of the installed Kulite piezoresistive transducer and a KSC-2. This dynamic range exceeds that of an ideal 16-bit A/D converter and should meet the performance requirements of most dynamic pressure measurements.

Equation : $Baseline\ SNR\ (dB) = 20 * log_{10}\left(FSO/\sqrt{{V_{N-R}}^2 + {V_{N-Amp}}^2}\right)$

Conclusion

This technical document has introduced the noise coupling mechanisms and interference categories that apply to dynamic pressure measurements. The companion document will cover the best practices for the field installation of wiring and cabling. Specialized input electronics, input power conditioning, and features of best-in-class signal conditioner/amplifier systems have been discussed. The dynamic data system design that includes these elements will effectively mitigate most undesirable EMI and RFI. Incorporating these features in the system design will provide a capability to measure high-bandwidth dynamic pressure signals with minimal noise.

References

[1] "The Importance of Quality Signal Conditioning for Pressure Measurements," Kulite Semiconductor Products Technical Document TD-1008, 2020

[2] "Selecting the Appropriate Analog Output for Pressure Applications," Kulite Semiconductor Products Technical Document TD-1010, 2020

[3] "Noise Reduction and Isolation," Measurement Computing, 2012

[4] Charles Kitchin, et. al, "AN-671 Application Note: Reducing RFI Rectification Errors in In-Amp Circuits," Analog Devices Incorporated, 2003

[5] Al Szary and Doug Firth, "Signal Conditioning Perspectives on Pyroshock Measurement Systems," Sound & Vibration, 2013

[6] "The Importance of Filtering for Power Supplies," Kemet Corporation, July 2020

[7] "Line Conditioners Brochure," Tripp-Lite Corporation, 2016

[8] Tyler Noyes and Tamara Alani, "Understanding Op Amp Noise in Audio Circuits," Texas Instruments, June 2021