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 1010
Selecting the Appropriate Analog Output for Pressure Applications

Prepared by Steve Carter

The system design engineer or test engineer must evaluate the complete signal chain with the measurement conditions and performance requirements in mind before selecting the optimum electrical interface for the application. There are instances when the utmost accuracy is required and serial digital communications such as Ethernet or RS-485 would be warranted. Otherwise, the electronic output would likely take the form of an unamplified voltage, an amplified voltage, or a 4 to 20 mA current output. Special thermal compensation methods that are particular to piezoresistive sensors may offer very high accuracy with any of the analog interfaces. Each electrical pressure transducer interface has both advantages over the others as well as potential shortcomings. The tradeoffs of each are examined in this application note.

Unamplified Voltage Output

The low-level signal from a Kulite SOI pressure transducer is typically 0 mV (± 5 mV) for a zero pressure input and 100 mV at full scale (absolute, gage, sealed gage), ±100 mV for low pressure differential. High-sensitivity pressure transducers having a full scale of 150 mV to 200 mV are available to 50 PSI. The highly sensitive silicon strain gages allow Kulite to design the pressure chip for relatively low levels of mechanical stress over the operational pressure range.[1] The SOI sensor signal level easily surpasses the full-scale signal of bonded-foil and thin-film transducers exhibiting 20 mV to 30 mV at full scale while demonstrating better linearity with negligible hysteresis and non-repeatability.

Pressure transducers supplied with an unamplified output offer the highest potential bandwidth capability of all common electrical interfaces. The minimum resonant frequency of any Kulite SOI pressure sensor is 150 kHz. In order to maintain a high bandwidth the transducer must be connected to the measurement system with low capacitance wiring. Close-coupled signal conditioning with low source impedance is often used to support high bandwidth installations.[2] Rise times of 0.8 µs and faster have been observed in oil-filled and leadless RTV-coated blast-pressure transducers when configured in either manner.

Acceleration-Compensated Output

Leadless acceleration-compensated pressure sensors utilize two strain gages that are sensitive to pressure and two strain gages that are sealed under vacuum and cannot respond to input pressure.[3] The pressure-insensitive strain gages respond to acceleration in the same manner as the pressure sensitive strain gages. The bridge is configured such that the output of the pressure-insensitive strain gages is subtracted from the pressure-sensitive strain gages. This circuit design exhibits half the nominal full-scale output signal, but effectively eliminates any error due to extreme levels of acceleration.

Ratiometric Output

Kulite SOI pressure transducers are ratiometric devices. That means the full-scale output level changes in direct proportion to the change in the excitation level. The transducer zero also changes with excitation level, but not always in a predictable or linear manner. Circuits that interface the A/D converter reference and the bridge excitation in a ratiometric configuration produce negligible errors with varying voltage levels in dynamic-only designs.[4] This characteristic permits the use of battery-powered equipment where voltage levels can vary over time. Provisions for transducer zero checks and adjustments must be included in ratiometric designs for Kulite SOI pressure transducers when steady state measurements are required.

Amplified Voltage Output

The inclusion of electronics to power the strain gage bridge and amplify the differential bridge signal can simplify the electrical interface. Amplified pressure transducers typically contain internal voltage regulation that eliminates the need for remote sensing and external bridge conditioning electronics. The higher signal level and lower source impedance of an amplified output signal is less likely to be impacted by radio frequency and electromagnetic interference. Amplified pressure signals are often filtered internally in order to transmit a high-frequency signal without broadband noise outside the frequencies of interest.

Kulite manufactures several styles of internal amplification subassemblies. The most common output is a 3-wire configuration having a nominal "live offset" of 500 mV (Figure 1a). The typical live offset for fully differential transducers is 2.5 volts. The absence of the 500 mV signal (when no pressure is applied) provides immediate indication of a failed transducer, cabling issue, or loss of power. The full-scale outputs of 4.5, 5.0, and 10.0 volts are available in many transducer styles. It is normally acceptable to interface 3-wire transducers to single-ended measurement systems as long as low–impedance cabling is installed. It is a best practice to terminate two wires (power return and negative signal) to the –IN terminal for long cable installations.[5] Using two wires from the transducer to separate terminals on the power source and data system input will eliminate any possibility of a voltage drop in the transmitted pressure signal.

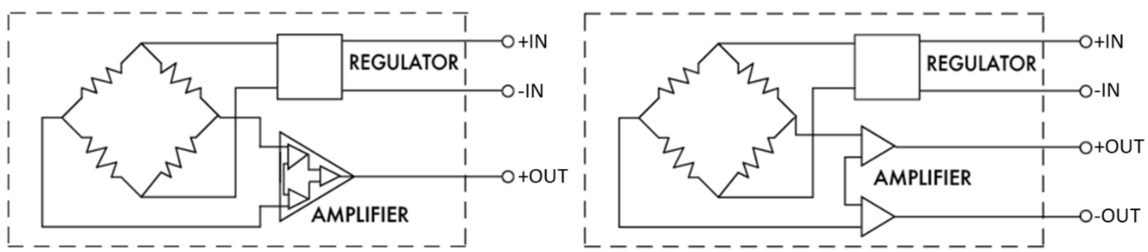


Figure 1a: 3-Wire Amplified Voltage Output 1b: 4-Wire Amplified Voltage Output

The 4-wire output shown in Figure 1b is developed using two amplifiers. The terminal -OUT is supplied by an amplifier having a nominal signal level of 500 mV in most designs. The terminal +OUT is supplied by an amplifier controlled to a level between 500 mV and 5.5 volts. The differential voltage between the +OUT and –OUT terminal will range from 0.0 to 5.0 volts. Grounding either of the output signals will invalidate the pressure reading and may damage the transducer. The use of twisted-pair cabling is recommended for all 4-wire transducers and 3-wire transducers installed with long cables. Dedicating one twisted pair of a 4-conductor cable to power the transducer and the other pair to read the signal into the data system will ensure minimal noise pickup for each balanced, differential function during power/signal transmission.

Amplified AC Only Voltage Output

Wide bandwidth two-channel amplifier assemblies are provided on certain transducers designed for gas turbine installations. The high-temperature SOI pressure sensor is interfaced to an in-line 3-wire amplifier that provides a high-frequency steady-state signal including the dynamic pressure content. The second channel includes a high pass filter with a corner frequency of 10 Hz plus an additional gain of 10. The high pass filter is known as an AC-coupling network. Its function is to remove the steady-state content prior to amplification so that the dynamic signal may be transmitted with a higher degree of resolution. Output 1 (steady state plus dynamic) is configured with a live offset and a full-scale output of 5 volts. Output 2 (dynamic only) is configured with a live offset of 5 volts and a span of ±4.5 volts.

4 to 20 mA Current Output

SOI pressure sensors that include internal amplification and a current output transceiver are known as pressure transmitters. Typically, these devices convert input pressure to a loop current that is linear between 4 mA and 20 mA.[6] There are four specific advantages of pressure transmitters over most amplified pressure transducers.

1. Low cost cabling (2-conductor, twisted/shielded) is often recommended for installation
2. The live offset of 4 mA provides indication of a failed transducer, cabling issue, or loss of power
3. The current loop signal is very insensitive to RF/EMI
4. The 4 to 20 mA current loop is insensitive to varying resistive loads (can drive long cables)

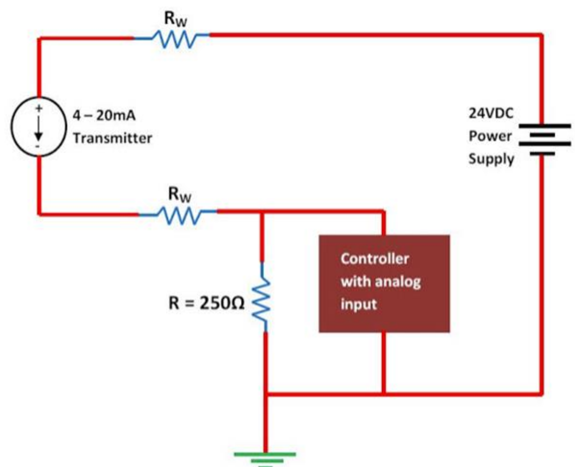


Figure 2: Simple 4 to 20 mA Current Loop Schematic

Additionally, pressure transmitters include low pass filters to ensure they can drive long cables without oscillation or other instabilities. The frequency response of Kulite pressure transmitters ranges from 750 Hz to 1500 Hz. Increasing the loop power supply permits the additional monitoring (typically through a 250 Ω resistor) using a secondary monitoring/control system. Each added resistor will consume 5 volts of the available loop power at full-scale pressure. Kulite conservatively estimates that 9 volts must be available to power the internal electronics of the transmitter. That leaves 750 Ω in total of loop resistance available to the customer for cabling and load resistors with a power supply of 24 VDC.

Thermal Compensation

All silicon strain gages exhibit temperature dependency. The resistance of a typical uncompensated Kulite SOI bridge increases with temperature at approximately 10% per 100° F while its gage factor, or sensitivity, decreases by -2% per 100° F. Temperature stable resistors limit the thermally induced shifts and normalize the transducer full-scale output. The operating temperature and size of the transducer often dictates the location of these passive compensation resistors to be some distance from the pressure sensor. This physical separation does not affect the accuracy. Kulite has minimized the number of external resistors using a combination of on-chip resistance trimming and continued advances in pressure sensor design.

Since the temperature coefficient of the bridge resistance (TCR) is greater in magnitude than the temperature coefficient of gauge factor (TCGF), a span resistor may be selected that acts as a voltage divider in such a way as to increase the voltage at the bridge at a rate equal to the decrease in gage factor over temperature. This compensation approach yields a typical thermal sensitivity shift within ±1% of full scale per 100°F and holds the sensitivity at a nominal 10 mV/V over the compensated temperature range.

The SOI pressure sensor will also exhibit a zero shift with temperature. Any fixed offset is removed using a combination of on-chip laser trimming or adding an external resistor to increase resistance of one arm of the bridge. After the fixed offset is addressed, the sensor will exhibit a predictable response to temperature at zero input pressure as long as the voltage input to the transducer is stable. The slope of this thermal zero shift may be flattened to reduce the error over temperature. Adding a single large value shunt resistor to one of the gages desensitizes its impact on the bridge output. The overall thermal error is typically within ±1% of full scale per 100°F.

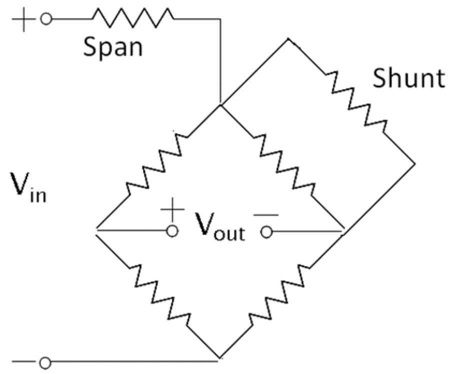


Figure 3: Simple Thermal Compensation of SOI Pressure Sensor

5th Wire Pressure/Temperature Transducers

The SOI resistive bridge and span compensation resistor form a resistive divider that provides a repeatable indication of the SOI pressure chip temperature. Kulite can provide the temperature signal in one of two methods. Figure 4a below shows the 5th wire as V_T. This signal is essentially the bridge excitation voltage required to maintain a stable sensitivity over a specific temperature range. The value is typically 5 volts or more at room temperature and increases at approximately 2 mV/°F. This is the standard 5th wire analog interface available as an option on many Kulite pressure transducers.

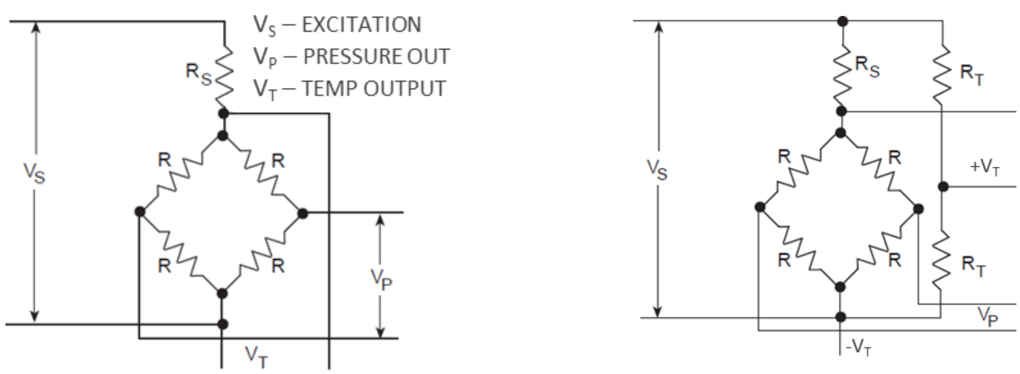
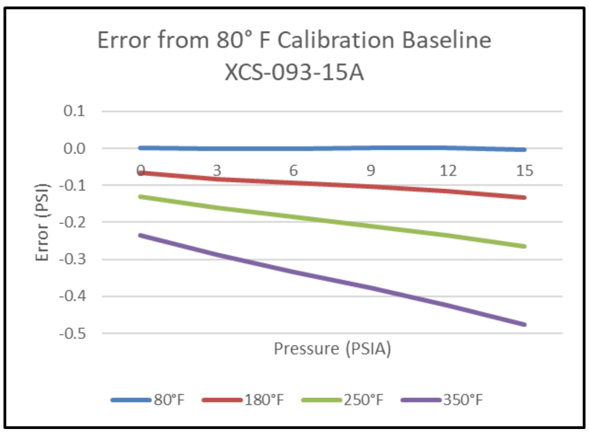


Figure 4a: Bridge Sensor with 5th Wire Voltage Output   4b: Bridge Sensor with 5th Wire mV Output

Two additional resistors (R_T) shown in Figure 4b remove the high-level voltage. These resistors are chosen specifically to form a secondary full bridge having an output close to 0 volts at room temperature or another fixed temperature. The two added resistors do not alter the overall pressure measurement performance. The removal of the high-level signal allows the measurement engineer to set additional system gain on the 2 mV/°F signal for improved temperature resolution. This configuration is more common to physically larger transducers having amplified outputs.

It is important to note the 5th wire signal is not exactly representative of the media temperature – it follows the temperature of the SOI pressure chip. Since the SOI pressure sensor has a predictable offset and sensitivity response to temperature for a given excitation level, knowing the voltage delivered to the full bridge of the pressure sensor permits the measurement engineer to correct for most thermal errors in post processing. Two separate data channels must be made available for 5th wire corrections. The two signals do not have to be interfaced to the same data acquisition system, but time alignment of the high-speed pressure signal with the more slowly changing 5th wire temperature signal is critical. The pressure chip temperature usually changes at a rate of 2 Hz or slower.

Kulite pressure transducers are known for exhibiting excellent static pressure performance. The typical static error band is ±0.1% or better of full scale when fit to a least squares linear regression. The pressure signal remains linear when using the room temperature coefficients regardless of ambient temperature as shown in Figure 5a. The 5th wire temperature signal may be approximated more closely using a 2nd-order function. Embedding the 2nd-order temperature polynomial within a 1st-order pressure curve fit can improve accuracy as shown in Figure 5b. Manufacturers of downhole tooling often apply higher order curve fits to the pressure and temperature response to improve the accuracy quoted in low-voltage, battery powered loggers.



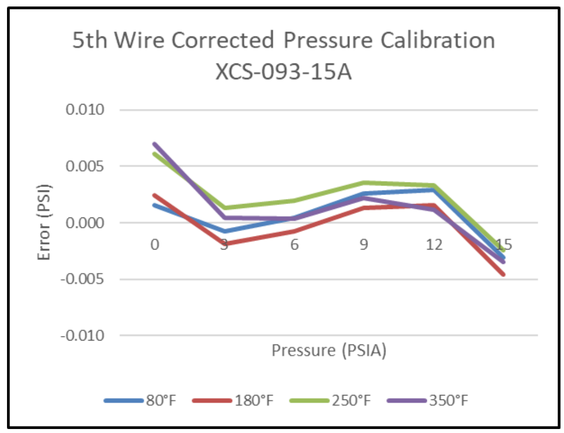


Figure 5a: Typical Thermal Error at Temperature

5b: Corrected Thermal Error Using 5th Wire

Digitally Compensated Output

Digitally compensated transducers have traditionally utilized embedded analog-to-digital converters and microprocessors for pressure conversion. Software commands and embedded firmware configuration settings are required for signal conversion and transmission. Miniaturized application-specific integrated circuits (ASICs) are available that interface directly to SOI pressure sensors. Current ASIC technology supports the temperature compensation and pressure linearization of the signal for enhanced accuracy without any need for a customer-supplied digital interface or software development and maintenance.

ASIC-based pressure transducers convert a low-level, thermally influenced voltage input signal to a high-level, linearized voltage output with no need for logic-based processing in the signal path. Unlike traditional digital designs, the low-level voltage to high-level voltage conversion in ASIC-based designs is time continuous with no discernable steps or signal processing time delays in the 4.5/5 volt output signal (to 10 kHz) or 4 to 20 mA current output signal (to 1 kHz).

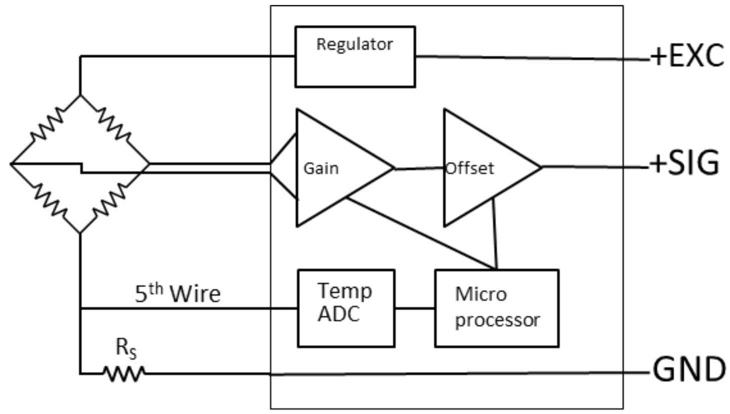


Figure 6: SOI Pressure Sensor Interface to ASIC

ASIC technology incorporates a wide range of analog and digital circuits and functions within a single integrated circuit. The temperature signal is generated in a way very similar as the analog 5th wire signal and input to the internal A/D converter of the ASIC. Immediately following this high-speed conversion, zero offset and sensitivity are continuously adjusted using internal digital to analog converters along an "all-analog" pressure signal circuit. This method of thermal compensation results in a measurement improvement of 10:1 or better over traditional designs using passive analog compensation while requiring a single input to the data acquisition system. This innovation also includes an internal programmable gain amplifier with signal suppression that can be used to span the transducer for different full-scale pressures. Transducer manufacturers may calibrate the transducer for narrow pressure and/or temperature ranges to improve pressure measurement accuracies using the embedded ASIC functions.

The ASIC-based pressure transducers produce the high repeatability and low hysteresis of an "all-analog" signal with the linearity and temperature stability of a "digitally-corrected" 5th wire transducer. This all-analog signal path coupled with the digitally corrected qualities provides the highest available combination of accuracy and bandwidth performance. The analog signal path is less susceptible to noise pickup from radio frequency or electromagnetic interference as both sensor and electronics are close coupled to the SOI pressure sensor – often confined within the stainless steel transducer case. The resulting reliability and stability is exceptional and well suited for critical pressure measurements.

ASIC-based pressure transducers are also suitable for installation in harsh environments. The ambient operating temperature range for amplified capacitive and metal-foil gaged pressure transducers is typically –40 to 85°C. ASIC technology offers improved performance across wider operating temperatures. Commercially available products are available from Kulite that meet performance specifications to temperatures of 125° C and higher. An ASIC incorporating a programmable gain amplifier (PGA) with an auto-zeroing internal network to counter temperature-induced shifts can reduce thermal drift to 10 ppm/°C or less. By comparison, many microprocessor-based pressure transducers drift around 50 ppm/°C for ambient temperature changes.

Kulite ASIC-based pressure transducers incorporating monolithic Silicon on Insulator (SOI) pressure chips support pressure rise times (10% to 90%) in the 35 µs to 100 µs range compared to 80 to 600 ms response time (0 to 63%) for pressure transducers and transmitters utilizing traditional microprocessor-based design approaches. Faster measurements enable more detailed pressure profiles, improved signal-to-noise measurements, and a rapid indication of an unsafe condition.

These devices require fewer components than conventional microprocessor-based transducers. Fewer parts translate to a lower failure probability and higher reliability. ASIC-based pressure transducers can have as few as three major electronic components—the ASIC, EEPROM memory, and a voltage regulator. On-board voltage regulation and power conditioning allows the ASIC-based pressure transducers to share a single unregulated DC power supply. Applying a passive analog filter to the high-level compensated voltage can permit for direct connection to the measurement system input without external signal conditioning and amplification. Adding a current transceiver to this design will result in a pressure transmitter with similar electrical performance to 1000 Hz.

The use of analog interfaces eliminates the possibility of storing digital pressure data inside the transducer. There is a small amount on-board non-volatile memory within the transducer that is used for thermal sensitivity and zero compensation during production activities. Other than this memory containing factory calibration coefficients, there is no memory device within digitally compensated Kulite pressure transducers that is programmable by any external means.

Conclusion

The availability of highly accurate data acquisition systems permits the measurement engineer to make analog-domain pressure measurements with great accuracy and minimal noise providing better insight to the system performance. The specified accuracy and response time of the measurement will dictate the best electronic interface for the application. Other factors such as size, temperature constraints, and transmission distance will factor into the interface decision.

References

[1] "Selecting the Best Sensing Technology for Pressure Applications," Kulite Semiconductor Products Technical Document TD-1009, 2020

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

[3] A.D. Kurtz et. al, "Further Work on Acceleration Insensitive Semiconductor Pressure Sensors for High Bandwidth Measurements on Rotating Turbine Blades," NASA 2003 Propulsion Measurement Sensor Development Workshop, Huntsville, AL, May-2003

[4] Albert O'Grady, "Transducer/Sensor Excitation and Measurement Techniques," Analog Devices, Analog Dialogue 34-5 (2000)

[5] "Maintaining High-Frequency Signal Transmission for Pressure Systems," Kulite Semiconductor Products Technical Document TD-1011, 2020

[6] "Basics of the 4 - 20mA Current Loop," InstrumentationToolbox.com, October 2012