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Kulite TD 1012
Understanding the Pressure Transducer Datasheet: Total Error Band vs. Accuracy

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The pressure transducer/transmitter specification sheet is one of the more common and one of the least understood documents encountered by engineering and science professionals. Interpreting how the reported datasheet performance translates to performance in the field is not always a straightforward process. Critical environmental specifications are sometimes omitted and the performance that should be anticipated is often misrepresented. The manufacturers that do include thermal effects in the specifications will frequently include confusing formulas inclusive of range, span, and percent of reading with no explanation for combining the various sources of error into a total error band estimation. This technical document will address the primary factors that may lead to an increase in measurement uncertainty and define the error terminology found on the typical transducer specification sheet.

The first datasheet parameter to review is the method of reporting electrical performance with regards to pressure measurement uncertainty. According to ISA-S37.1-1975 "*Use of the term Accuracy should be limited to generalized descriptions of characteristics. It should not be used in specifications. The term Error is preferred in specifications and other specific descriptions of transducer performance.*" [1] Yet, nearly all manufacturers of general-purpose transducers highlight the "Accuracy" or "Static Accuracy" of their pressure transducers on the datasheet. Accuracy is typically reported as a best-fit straight line under laboratory conditions and is more correctly known as the static error band. This figure is usually a small percentage of the overall total error band for most practical installations. Accuracy is meant to convey the potential measurement performance of a thermally stable transducer with no external physical stimuli and not what will be encountered in a test application or industrial environment with dynamic environmental conditions.

Kulite pressure measurement products are shown with one of two specifications. Test, measurement, and product development transducers typically include the static error band figure. Production aerospace and digitally-compensated pressure transducers will generally report a total error band (TEB) as seen in figures below. Total error band specifications are meant to convey the installed performance when any combination of realistic environmental factors may be present. TEB is often presented as a bowtie error band over temperature for transducers with passive compensation, Figure 1a. Improved TEB may be obtained using active digital temperature compensation using embedded integrated circuitry, Figure 1b.

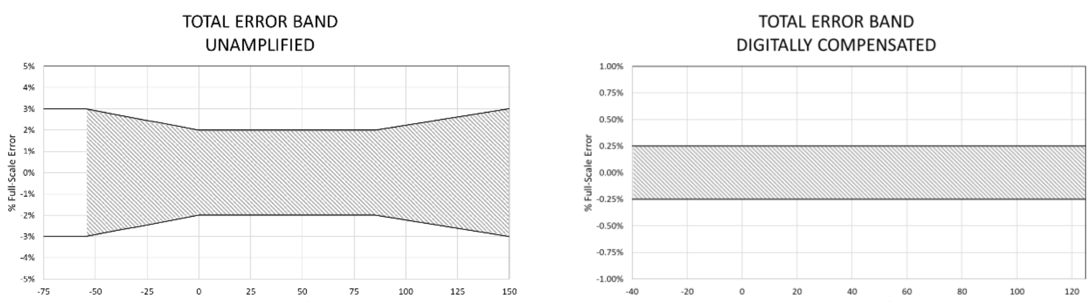

Figure 1a/1b: Typical Total Error Band for Kulite Transducers

Static Error Band

Total error band is inclusive of the static error band. The non-temperature dependent root sum squared (RSS) of non-linearity, hysteresis, and repeatability is the transducer static error band.[2] Other components of the TEB are shown in Figure 2.

Equation1: $$\boldsymbol{Static\ Error\ Band} = \sqrt{\boldsymbol{nonlinearity}^2 + \boldsymbol{hysteresis}^2 + \boldsymbol{repeatability}^2}$$

Static error band is mistakenly used interchangeably with the term "accuracy" by many transducer manufacturers. A description of the static error band components follows.

Non-Linearity

Non-linearity (sometimes called linearity) is defined as the maximum deviation of any calibration point on a specified straight line, during any one calibration cycle expressed as "within ±X.XX percent of full scale, (%FSO)." See Figure 3 for a graphical representation.

Full scale output is the algebraic voltage difference between the operating pressure end points. This is typically the highest value of the pressure measurand voltage minus the lowest value pressure measurand voltage. Full range is the measurand increment between the lowest pressure, such as the highest negative numerical value (differential mode), to the highest value pressure.

Hysteresis

Hysteresis is defined as the maximum difference between output readings, at any pressure value within the specified range, when the value is approached first with increasing and then with decreasing pressure. The points are taken on the same calibration cycle. It is expressed as the maximum difference between pressure readings as "within ±X.XX percent of full scale." See Figure 4 for a graphical representation.

Repeatability

Repeatability (sometimes called non-repeatability) is defined as the ability of a transducer to reproduce output readings when the same pressure value is applied to it consecutively, under the same conditions, and in the same direction. It is expressed as the maximum difference between pressure readings as "within ±X.XX percent of full scale." See Figure 5 for a graphical representation.

Two data sets are needed to determine hysteresis and repeatability. The overall contribution of hysteresis and repeatability to the transducer error is typically less than 10% of the static error band for a Silicon on Insulator (SOI) transducer.

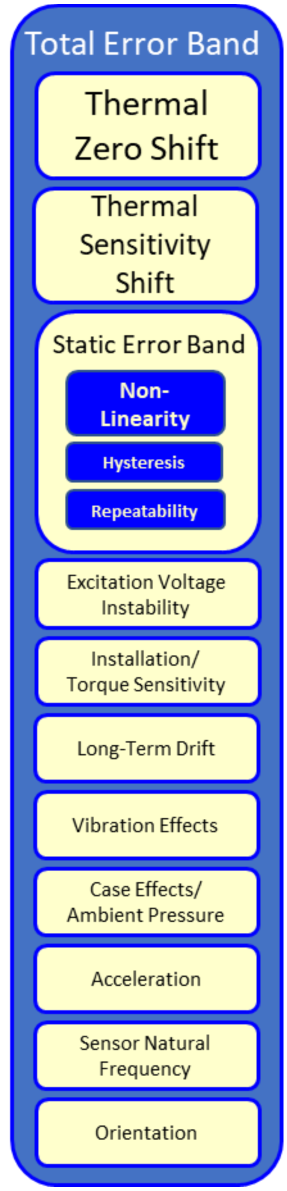

Figure 2: Components of Total Error Band

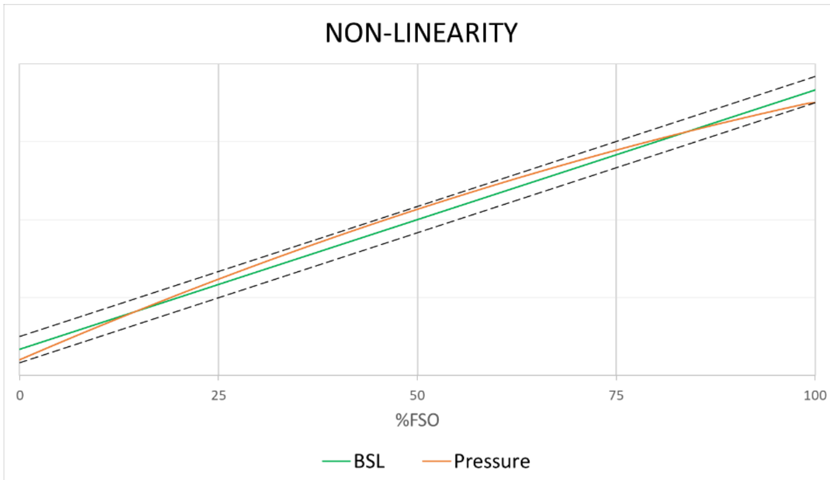

Figure 3: Pressure Transducer Best Straight-Line Non-Linearity

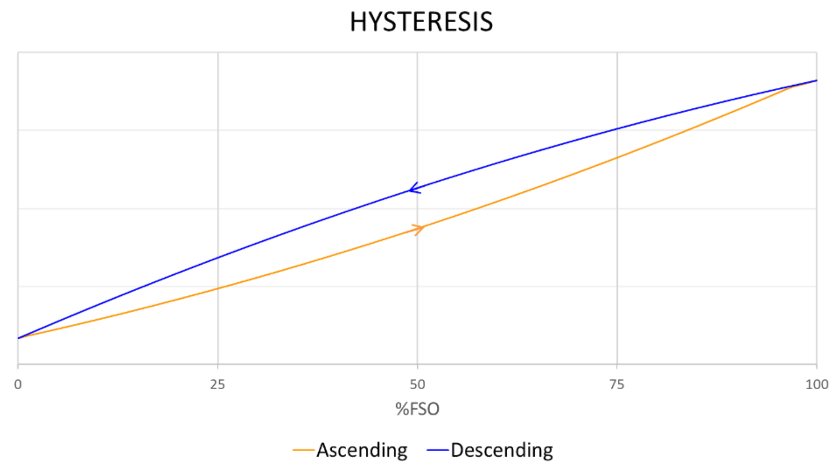

Figure 4: Pressure Transducer Hysteresis

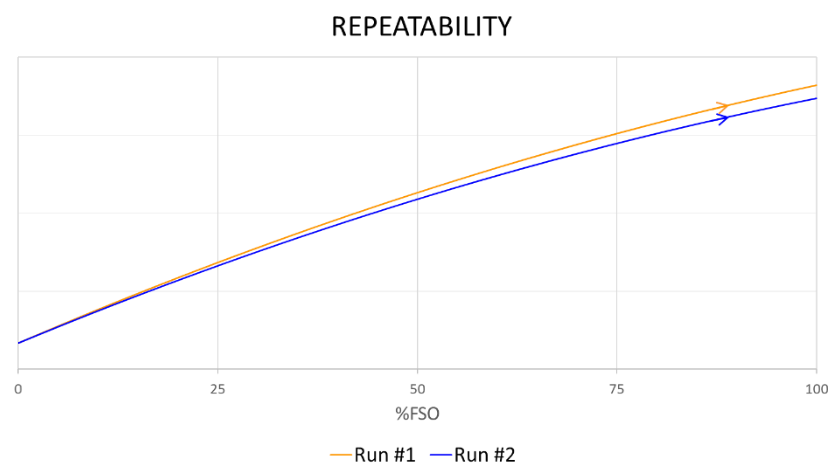

Figure 5: Pressure Transducer Repeatability

 (TD 1012 Rev. 12/6/2021)

Final Thoughts on Static Error Band

The static error band of a Kulite SOI pressure transducer is typically ±0.1 % FSO of the transducer or lower as compared to a best fit straight line (BFSL) for most pressure ranges. A best straight line (BSL) is a line midway between the two parallel straight lines (dashed lines in Figure 3) closest together and enclosing all output versus measurand values on a calibration curve. Non-linearity is the largest contributing component of the static error band. Fortunately, non-linearity errors may be minimized during post-processing using simple polynomial curve fitting. Curve fitting the transducer to a 2nd-order polynomial is most beneficial for very high-pressure ranges (>10,000 PSIA), low pressure sealed-gage ranges (<25 PSISG), and pressure sensors that are recalibrated to be operated outside their specified range.

Curve fitting cannot correct any error due to hysteresis and repeatability. Fortunately for users of SOI pressure transducers, hysteresis and repeatability are seldom measurable errors due to the nearly perfectly elastic nature of the monocrystalline silicon pressure sensor combined with the low level of stress applied at full scale. Figures 4 and 5 show exaggerated hysteresis and repeatability plots to illustrate each undesirable effect. A typical static error plot for a microminiature pressure probe is shown below in Figure 6. To quote a ±0.1% FSO BFSL combined non-linearity, hysteresis, and repeatability (CNLHR) figure, a pressure calibration standard and a precision voltmeter having a system calibration uncertainty of ±0.025% or better at the full-scale output of the transducer is needed. This provides the desired test accuracy ratio (TAR) of 4X as the RSS of the calibration standard uncertainties is four times more accurate than the device under test. The failure of the transducer to return to the starting voltage on the hysteresis check is well within the system calibration uncertainty and should not be assumed to be hysteresis.

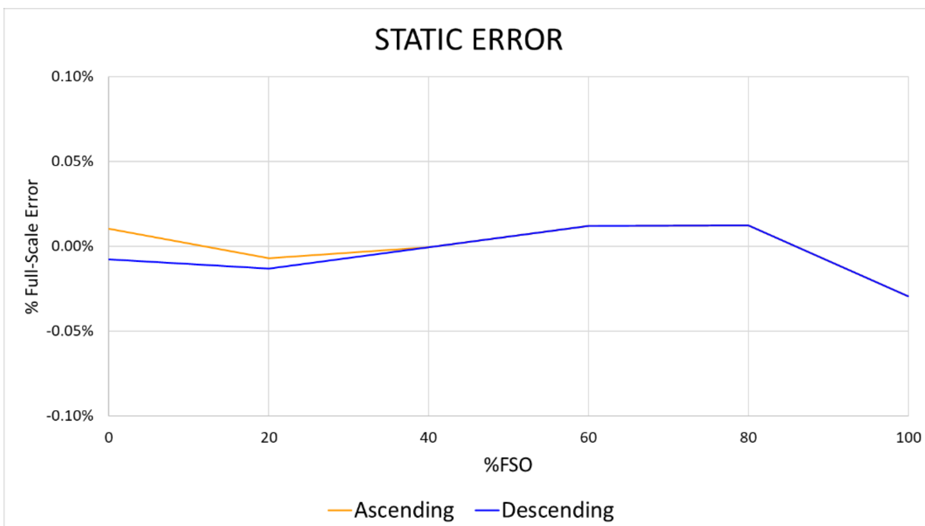

Figure 6: Pressure Transducer Static Error (Typical)

Thermal Zero Errors

Thermal zero shift is normally the single largest error source in general-purpose pressure transducers. This is the zero shift due to changes of the ambient temperature from room temperature to the specified limits of the operating temperature range. See Figure 7 for the output change at 0 PSIA attributed to a 100° F temperature rise from 80° F to 180° F. This may be treated as a bias and periodically tared if provisions for in-place zeroes at operational temperature have been designed into the system. The same transducer demonstrated to easily meet the ±0.1 % FSO BFSL (Figure 6) was shown to possess a -0.44% FSO/100° F zero shift due to temperature. The specification for this product is ±1% FSO/100° F (typical).

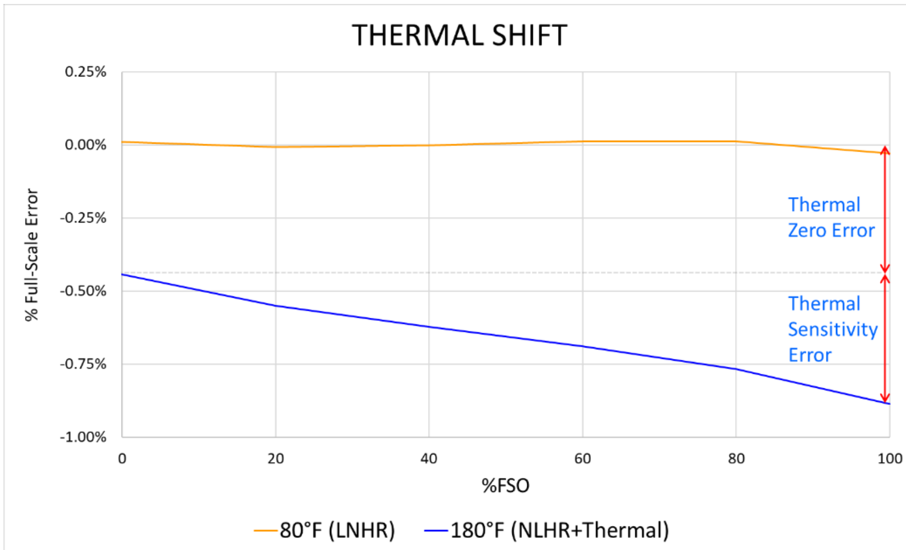

Figure 7: Pressure Transducer Thermal Zero and Sensitivity Shift

Thermal Sensitivity Errors

Thermal sensitivity shift is normally the second largest error source in general-purpose pressure transducers. Thermal sensitivity shift is the sensitivity shift due to changes of the ambient temperature from room temperature to the specified limits of the operating temperature range. Thermal sensitivity shifts increase with pressure and must be treated as a percent of reading error, % RDG. The additional error attributed to thermal sensitivity shift for this transducer is approximately -0.42% RDG/100° F. The specification for this product is also ±1% RDG/100° F (typical) thermal sensitivity shift. Kulite pressure scanners support provisions for in-situ calibration to minimize thermal sensitivity errors during operation.

Thermal Gradient Errors

Thermal effects due to temperature gradients are never found on pressure transducer datasheets. The user must be aware that certain pressure measurement technologies are prone to provide exaggerated inaccuracies when subjected to temperature gradients.[3] The dual capacitive cell design found in industrial pressure transmitters are especially prone to large measurement errors. The dielectrically isolated SOI pressure sensors manufactured by Kulite are microminiature solid state devices with very low mass and support a much faster thermal response than any competing technology. The force collector and sensing elements are all part of a monolithic silicon crystal structure forming a pressure chip. The strain sensitive elements also produce the thermal response used for compensation. The passive thermal compensation elements are unaffected by temperature and may be housed externally from the transducer. These components control the excitation delivered to the pressure chip while continuously and automatically compensating the transducer sensitivity and electrically cancelling much of the transducer offset voltage.

Excitation Instability Errors

The zero measurand output or residual voltage and full-scale output are determined during production at a specific excitation voltage. Maintaining the accuracy and stability of the bridge excitation voltage, usually 10 VDC, for unamplified transducers should be of utmost concern. Any change from the calibration excitation voltage will result in a proportional change in the full-scale output. The residual voltage also changes with excitation level, but not always in a predictable or linear manner. In-band noise coupled into the transducer excitation leads or generated by the power supply will increase the noise floor.[4]

Amplified pressure transducers usually contain internal voltage regulation circuitry. The bridge excitation and power to the internal electronics are designed for highest stability. Additionally, the electronics and sensor are compensated simultaneously over the operating temperature range of the transducer which helps to minimize thermal error exhibited by amplified pressure transducers. Typical Kulite designs are either optimized for 28 VDC aircraft power systems, 12 VDC automotive systems, or test, measurement, and product development transducers having a variety of excitation options. The input voltage range is generally at least ±4 VDC centered around the design voltage. Most test, measurement, and product development transducers are tolerant of voltages within the range of 8 – 32 VDC. This enables researchers and test engineers to apply both amplified and unamplified transducers using 10 VDC power sources.

Installation/Torque Sensitivity Errors

Mounting error is the error resulting from mechanical deformation of the transducer caused by mounting the transducer and making all measurand and electrical connections. Zero offset can be increased by improper transducer mounting of miniature cylindrical probe or flatpack pressure transducers. Any stresses placed on or near the diaphragm will result in changes in the zero offset. Flatpack transducers can produce a pressure response to stress and/or bending of the mounting structure such as a helicopter blade. Kulite produces a variety of designs to minimize case transfer stress to the pressure sensor.

Threaded transducers are less sensitive to mechanically-induced zero shift output and large zero errors typically occur when overtightening has resulted in physical damage to the threads or the transducer body. Threaded transducers should be installed using the torque ratings highlighted on the datasheet. As with miniature cylindrical probes, the unthreaded area at the front of the transducer should not be in close-fitting contact the surrounding material. Installation guides that include mounting hole dimensions, tolerances, and perpendicularity are available for each threaded style of transducer. It is also important to use the O-rings or crush washers provided or recommended by the manufacturer for a leak-free seal.

Long-Term Drift

Drift is defined as an undesired change in output over a period of time, which change is not a function of the measurand. Most general-purpose pressure transducers utilize several materials in the construction of the pressure diaphragm that serves as the electrical transconduction device. Additionally, the output signal on most general-purpose pressure sensing elements is significantly lower than the output of a Kulite SOI pressure sensor prior to internal or external amplification. This combination of hybrid construction and low sensitivity naturally leads to higher levels of drift following long-term usage, thermal cycling, over-pressure, and bonding agent creep.

Kulite transducers incorporate complex micro-structures of atomically-bonded, single-crystal silicon layers to form a monolithic pressure sensor. The construction exhibits a very high degree of stability even when used in challenging test cell environments. Much of the Kulite pressure transducer inventory managed by the US Air Force have been statistically determined to possess minimal long-term drift resulting in the assignment of the maximum allowable calibration interval for this instrument class.

Vibration Effects

Vibration error is the maximum change in output, at any measurand value within the specified range, when vibration levels of specified amplitude and range of frequencies are applied to the transducer along specified axes. The miniscule mass and monolithic, single crystal construction of Kulite pressure sensors translates to very high natural frequencies with extremely low damping ratios. The sympathetic vibration of a Kulite transducer to its surrounding environment is only measurable when the test subject is excited to frequencies higher than 50 kHz.

Case/Ambient Pressure Effects

Case/Ambient pressure errors occur due to changes of the ambient pressure of the medium surrounding the transducer housing. A stress analysis is performed for every Kulite design such that the mounting of Kulite pressure sensors inside the transducer housing is isolated from ambient pressure as dictated by the application requirements. Except for the lowest range transducers, the microminiature SOI pressure sensor lends itself to designs having a high degree of mechanical isolation from the transducer housing. Kulite has decades of experience manufacturing and verifying the accuracy of sub-sea control module transmitters during required hyperbaric acceptance testing to case pressures as high as 2000 bar.

Acceleration and Orientation Errors

Acceleration error is the maximum difference, at any measurand value within the specified range, between output readings taken with and without the application of specified constant acceleration along specified axes. The response of a Kulite transducer to acceleration is only measurable in cases of extreme shock. Recent independent studies completed by Army Research Lab and Air Force Research Lab personnel selected high-pressure Kulite transducers as the pressure measurement device least sensitive to levels of mechanical shock encountered during high-energy weapons systems development.

Orientation errors are essentially the same as acceleration errors, but the external stimulus is limited to ±1 g. When a reorientation of the transducer relative to the direction in which gravity acts upon the transducer causes an output response, the transducer must be calibrated and installed with the same orientation relative to gravity. Many lower pressure, general-purpose transducers will respond with changing attitude. The microminiature Kulite SOI pressure sensors typically do not exhibit this behavior.

Sensor Natural Frequency

The sensor natural frequency is the frequency of free (not forced) oscillations of the sensing element of a fully assembled transducer. This value known as the resonant frequency and is the measurand frequency at which a transducer responds with maximum output amplitude. Kulite SOI pressure transducers respond with minimal amplification errors to pressure signals in the audible spectrum. The frequency response of a flush-mounted, unscreened 15 PSID Kulite pressure transducer is shown in Figure 8 below. Experimental shock tube results confirm expected damping ratio of 0.007 and a sensor natural frequency of approximately 200 kHz. Due in part to both its high natural frequency and the very low damping ratio, the potential usable frequency of this 15 PSID transducer is approximately 90 kHz (1 dB error).

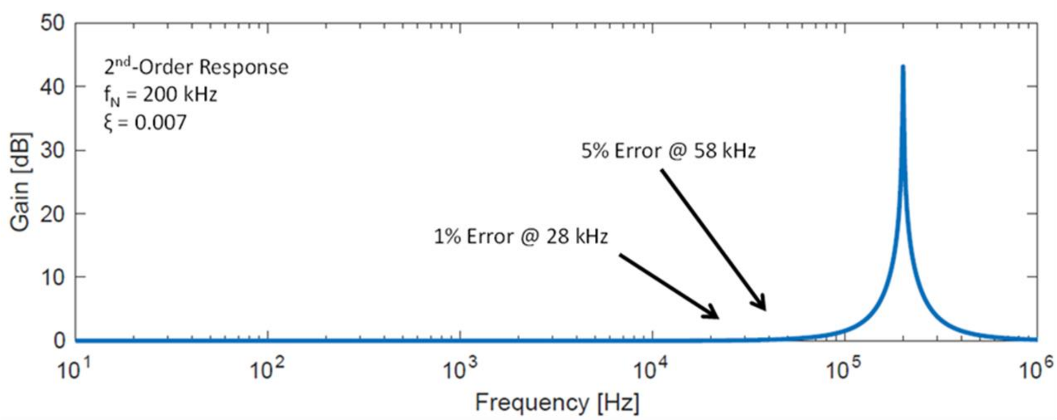

Figure 8: Shock Tube Characterization of XTEL-190-15D

The output voltage of all other general-purpose pressure technologies in the 15 PSID range could increase to saturation due to the mechanical amplification of the relatively large diaphragm in the lower audible frequency range. A resonant frequency of 2 kHz is typical of most general-purpose metal-foil, thin film, and capacitive pressure transducer designs. The rather low resonant pressure therefore compels most manufacturers to limit the usable bandwidth to less than 20% of the resonant frequency to avoid saturation of any internal electronics. The common response specification for these technologies is rise time (or response time). A rise time of 1 mS corresponds to a transducer frequency response of 350 Hz.[5]

End Point Errors

Kulite datasheets include the full-scale (or net) output and residual unbalance performance specifications. The methods applied and components selected to minimize the static error band often produce a small residual or uneven full-scale output voltages. The variability of the residual output voltage levels is normally less than ±5% of the full-scale output. Typically, these voltages are not precisely controlled as that would unnecessarily increase production costs.

Many customers prefer a “live offset” such as 500 mV ±25 mV when using amplified transducers for two reasons: 1) the output voltage never goes negative, so users can specify a unipolar A/D converter to increase measurement resolution and 2) the presence of 500 mV “live offset” is a good indication that the transducer is properly wired, supplied with sufficient excitation voltage, and providing an expected output to the measurement system. A nominal zero pressure voltage of 0 VDC simply does not provide as much device health information.

The advanced manufacturing processes developed by Kulite permit customers to request tighter tolerance on the full-scale output and residual unbalance performance specifications when necessary to meet system requirements. This does add cost and complexity to the transducers without improving the static error band. Similarly, improvements can be made on the thermal zero and sensitivity performance either with the use of a more complex compensation network of the inclusion active digital circuitry.

Typical and Nominal Datasheet Terms

Pressure transducer datasheets include non-deterministic terms applicable to an entire product family. Example of these terms also include a “nominal” full scale output of 100 mV and a “typical” residual imbalance of ±5 mV. A precise output impedance specification is not critical to maintain optimum performance unless high-frequency transmission is required.[6] However, all these specifications may be controlled to specific levels and ranges for individual transducers – at additional cost to the end user. The measured room temperature input and output impedance of each transducer as well as and the calibrated sensitivity and full-scale pressure range are provided to the customer on the calibration certificate.

Thermal zero and thermal sensitivity shifts will include “typical” performance characteristics and they can be critical to the attainable measurement uncertainty in many applications. Kulite offers several means to limit the deleterious effects of thermal shifts on pressure transducers. Each solution does increase the cost of the transducer and must be specified at the time of order. It is always best to contact factory personnel to discuss these special cases listed below.

1. Digitally-compensated transducers or in-line KEA-DC-1B amplifiers (for frequencies below 10 kHz).
2. 5^{th}-wire transducers (requires a 2^{nd} data channel for temperature channel input and polynomial fit).[7]
3. Custom temperature range thermal compensation (smaller ranges can lessen shifts).
4. Pressure calibration data at multiple temperature points (requires external temperature sensor).
5. Narrow thermal performance error bands (with test data) are also available on some models.

Confidence Interval

It is not possible to develop a confidence interval for most test, measurement, and product development transducers without conducting a measurement uncertainty analysis in the operating environment. The static error band figure may only be used as an element of the measurement system uncertainty at lab conditions. Even then, the entire family of transducers should be analyzed with a large enough number of calibration cycles to realize a normal distribution with a 95% confidence interval, 2-σ. The number of calibration cycles required may be lowered if the repeatability and hysteresis of each transducer under test remains small compared to its non-linearity.

Production aerospace and digitally-compensated pressure transducers reporting total error band may be treated differently as these specifications are meant to convey the installed performance under normal operating conditions. Kulite will not pass a transducer falling outside the TEB specification when examined over several pressure/temperature cycles. These environmental tests coupled with the long-term stability of the SOI pressure sensor permit Kulite to report a 99.7%confidence interval, 3-σ, for both the production aerospace and digitally-compensated pressure transducers when used within the operating limits presented on the datasheet.

Conclusion

The complete understanding of pressure transducer datasheets will continue to present challenges to research and test engineers because the device performance during its intended use is nearly impossible to quantify without independent and costly testing.[8] Products that continue to use accuracy terminology without the identification and contribution of all error sources should be reviewed with caution. The performance of these products in a typical installation will be significantly worse than in lab-like conditions. Instructions for estimating performance are seldom provided by transducer or transmitter manufacturers. When the individual error sources are annotated by the manufacturers, the complexity of the equations used to determine the error often causes engineers within the same organization to develop different expected performance estimates.

Kulite pressure transducers may be viewed in a different light because most of the error sources outside of thermal shifts may be considered negligible in all but the most physically challenging installations. For many applications, Kulite will quantify all error sources and present the measurement uncertainty in the total error band specification. Test data over the full operating temperature and pressure ranges are available with each transducer. Kulite understands and regularly evaluates the performance of the SOI pressure sensing products for some of the galaxy's most extreme conditions and demanding applications. Individual testing at simulated operating conditions is available on most of the Kulite product line.

The highly engineered Kulite SOI pressure sensor allows test engineers and researchers to ignore many common measurement error sources. The miniscule mass and high natural frequency of these MEMS devices coupled with their chemically pure and stable monolithic transduction elements is unmatched for general-purpose pressure sensing. Understanding the transducer thermal characteristics and how they may be leveraged into very precise pressure measurements to high frequencies, when required, is the principal task remaining for maintaining low measurement uncertainty for test article research and development activities.

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