

Calibration Considerations for Six Sigma™ Accuracy and Precision in Combustion Pressure Measurement

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ABSTRACT

Precise and accurate internal-combustion engine pressure measurements are typically built upon extremely low level piezoelectric sensor signals acquired in the laboratory. In turn, these minute signals must be accurately conditioned using electronic charge amplifiers and then processed for meaningful analysis.

Laboratory standard operating procedures often overlook the importance of timely and rigorous calibration of the equipment, or perform them without using sufficient environmental controls. In some facilities, years have been allowed to pass between metrology-quality calibrations, introducing the potential for significant out-of-tolerance conditions and non-compliance when compared to accredited measurement standards. Environmental, aging and operator factors influencing calibration metrology and in-use accuracy are presented in this paper, along with a method and example for estimating the calibration interval needed to specify calibration frequency for charge amplifiers.

Accurate and timely calibration of combustion analysis or “indicating” equipment supports the validity of using engine incylinder pressure data for engineering design decisions. Quality calibrations, for example those which are done to ISO 17025 standards, help avoid the complications and costs of development program timing delays. These delays can often be the result when additional unplanned testing becomes necessary due to out-of-tolerance measurement equipment and laboratory non-compliance to requirements.

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INTRODUCTION

Internal combustion engines are designed for producing mechanical power by releasing the chemical energy in their fuel. [1] Engineering personnel conducting powertrain research and engine development have suggested that combustion pressure indicating measurements provide the most valuable input for making well informed design decisions. [2] These indicating measurements obtain their name from the indicated work per cylinder per cycle [1], and additional details about selected indicating measurements are included in a later section.

The quality and accuracy of the indicating measurements made in the laboratory are limited by the tolerance and calibration uncertainty of the equipment utilized. This report is meant to collect and assess the major process points needed for a methodology that ensures the highest quality indicating measurements can be made. Following these considerations, measurements can be made approaching some of the limits of intrinsic equipment specifications, and an example of Six Sigma™ process benchmarking is included.

This paper is also meant to augment the work of others, in several specific areas.

- Characterize the often subtle, but extremely important, factors influencing measurement uncertainty.
- Addressing the systemic effects of laboratory environmental conditions, along with considerations for quantifying the impact of these factors on measurement uncertainty.
- Overview of the effects of out-of-tolerance, or incorrectly calibrated equipment on basic indicating analysis calculations.

Relative magnitudes of factors affecting measurement uncertainties are discussed, along with best practice recommendations.

DESCRIPTION OF INDICATING EQUIPMENT STUDIED

Figure 1 illustrates a simplified engine combustion indicating system.

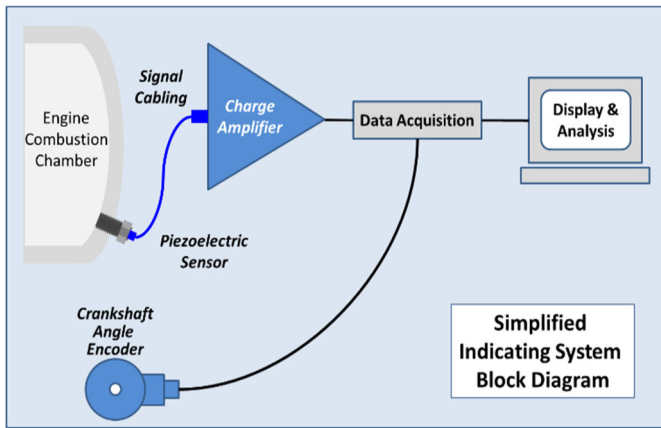


Figure 1. Simplified Indicating System-Block Diagram

Combustion Indicating Overview

Crankshaft angular position is acquired using an encoder of typically one crank angle degree (1 CA°) resolution or finer. The changes in engine combustion chamber pressure are measured using a piezoelectric sensor device, which may be mounted in one or more of the cylinder heads or walls (as shown), or by means of a spark-plug or glow-plug mounted device. The sensor signal or signals are routed to charge amplifiers using signal cabling, then amplified for transmission to a data acquisition and analysis system for engineering unit conversions and data reduction for displays, summary and/or reporting. More details follow on the parts of the system which have particularly important effects on accurate and precise combustion pressure measurement. The focus of this paper is on the factors related to the sensor, cabling and charge amplifier portions of the system, as they have the dominant effects.

Charge Amplifiers

These high-gain electronic devices are used to convert low-level piezoelectric sensor charge signals into high-level output voltage or current signals. The charge to voltage or current conversions are required to make the signals suitable for transmission and use with measurement instruments for thermodynamic analysis, commonly referred to collectively as combustion indicating equipment. [3]

The charge amplifier units of interest are subjected in-use to many application conditions which have an impact on the accuracy and repeatability of the laboratory measurements. These factors are directly related to the extremely low-level, pico-coulomb signals generated by the piezoelectric sensors themselves. Detailed in later sections, the individual factors which may affect in-use charge amplifier accuracy include:

- Charge Amplifier Technology Level
- Operating and Calibration Temperature
- Environmental Humidity
- Post Burn-In Component Aging
- Mechanical Vibration and Shock

Piezoelectric Combustion Sensors

The piezoelectric combustion pressure sensors used for indicating systems are devices which convert a mechanical deformation due to pressure into an electrical charge. The device itself contains a type of crystalline material, and through use of the piezoelectric effect, it generates an electrical charge proportional to the mechanical deformation of this piezoelectric material. [3]

Piezoelectric sensors from any manufacturer are subjected to application factors which will have an impact on the accuracy and repeatability of measurements made in the laboratory. As mentioned earlier, the conditioning of the extremely low level, pico-coulomb sensor signals is critical to measurement accuracy. Covered later in depth in subsequent sections, the individual factors which may significantly affect sensor measurement accuracy include:

- Ambient & Amplifier Operating Temperatures
- Sensor Operating Temperature
- Conductor Resistance
- Signal Transmission and Cabling
- Environmental Humidity
- Operator Skill Level and Training
- Installation Torque

FACTORS AFFECTING EQUIPMENT ACCURACY

Charge Amplifier Technology Level

Amplifier designs may contain electronic components, for example capacitors, that have thermal or aging drift; drift values of 0.1 percent (0.1%) or more may be common, to as much as 0.5% or more, in less contemporary designs. [4]

Thermal effects can be reduced in modern designs by specifying components with improved temperature or thermal coefficients. An example of the importance of capacitor selection for thermal performance is described in a later section on ambient operating temperature effects. Performing a new equipment burn-in of a sufficient time duration can reduce some of the initial aging-related effects that are seen in practice. However, once stabilized, these effects typically continue at a much reduced level throughout the useful life of the equipment, until the equipment ultimately wears out. [5] These relative effects of aging are described and shown graphically in a later section which focuses on component aging.

Ambient Operating Temperature

Available thermal data indicates that it is important to ensure the environment in which amplifiers are operated has a consistent temperature which does not vary more than several degrees Celsius (°C), for example ± 5 °C. This thermal stability is especially important when calibrating amplifiers, for example maintaining ± 3 °C, and ideally the amplifiers will be both calibrated and operated at or near the same temperature. Newer amplifier designs benefit from updated components which have improved the thermal coefficients.

The following graph shows the thermal performance envelope data, shaded in gray crosshatch, for a Class I, temperature compensating capacitor with temperature coefficient of ± 30 PPM (Parts Per Million), or $\pm 0.003\%$, per $^{\circ}\text{C}$.

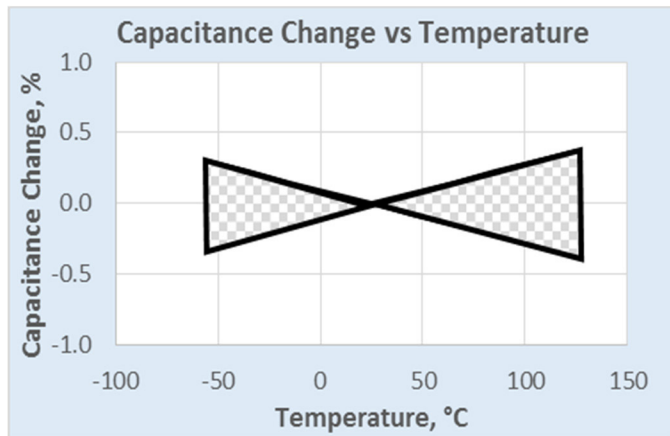


Figure 2. Temperature Effect on Capacitance [6]

This component type, with a low thermal coefficient, better minimizes the variations observed during thermal transients. Designs using these components are an improvement over earlier charge amplifier designs. Earlier designs could have used a more typical ± 80 to ± 270 PPM per $^{\circ}\text{C}$ thermal coefficient component [7], exhibiting up to an order-of-magnitude (factor of ten) increased variation for a given amount of temperature change.

Sensor Operating Temperature

Available thermal data indicate that it is not only important to provide an environment in which charge amplifiers are operated at a consistent temperature, but also one which does not vary by more than a few degrees during calibration. Modern amplifier designs benefit from updated components, such as those shown with reduced thermal coefficients in Figure 2. These amplifier designs better minimize the variation observed during operation in the presence of thermal transients.

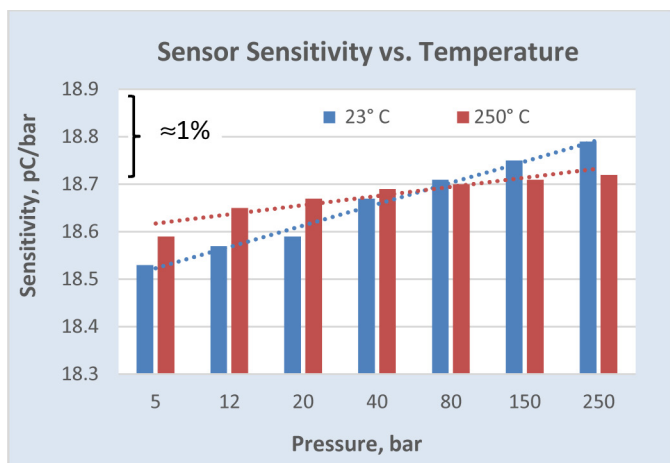


Figure 3. Sensor Thermal Effects [8]

Additionally, sensor operating temperature can have an effect that is typically 1% or less. If this is of significance to the laboratory measurement study, it can be addressed via a calibration performed at elevated temperature. An example of sensor thermal performance data is given as follows in Figure 3, showing applied Pressure, in bar, versus sensor Sensitivity for two temperatures, in pico-coulombs per bar (pC/bar). [8]

Humidity

Another important factor is the humidity of the laboratory where an amplifier is calibrated or operated. When an ideal environment is not available, parasitic losses in the sensor-to-amplifier cabling may contribute to an increase in measurement uncertainty.

A high relative humidity condition can temporarily reduce the effective resistance of the sensor cable conductors or amplifier connections, and is influenced by the porosity of the material. This can cause a measurement uncertainty of several percent or more, as will be described in a following section.

The effect of relative humidity on some typical capacitive components is shown by the following data in Figure 4.

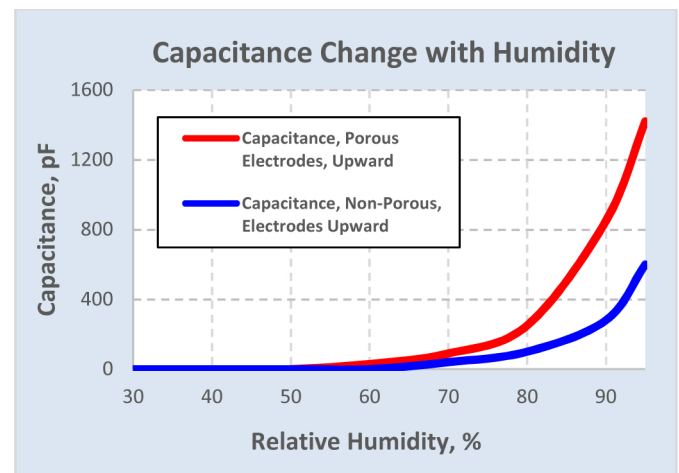


Figure 4. Humidity Effect on Capacitance [9]

Though use of non-porous electrode capacitors can reduce the effect of humidity, capacitor orientation (positioning downward) can also reduce the effect by up to 25%. [9] From Figure 4, a rapid increase in capacitance is seen to occur with both electrode types in the 60% to 70% RH range. However, component tolerance selections and usage need to allow for measurement uncertainties of less than 1.0%, as this is often preferred or required in charge amplifier designs.

Changes in feedback capacitance typically have a proportional effect on gain, and a charge amplifier might commonly use 200 pF to 400 pF capacitors in the gain network for a particular design. In the typical case for the data shown in Figure 4, relative humidity values must be controlled to below 50% to maintain specified capacitance to within the desired 1% or tighter tolerance values, at nominal ambient temperatures.

Proper warm-up of amplifier electronics and laboratory temperature control helps to reduce the relative humidity effects on capacitance. The elevated temperature allows the internal relative humidity to decrease in proximity to the capacitor components enclosed in the amplifier unit. A best practice to mitigate the humidity effect in the laboratory is to maintain a fully warmed-up, 24 hour, 7 day a week powered-on condition for charge amplifiers that are used daily.

Conductor Effective Resistance

With a sensor signal of such low amplitude, parasitic losses in the sensor-to-amplifier cabling and connections may contribute to an increase in measurement uncertainty. Loss of accuracy is exacerbated by environmental conditions, such as humidity and temperature of the air, [10] and in particular when effective cable insulation resistance drops to a value below one hundred teraohms ($100 \times 10^{12}\Omega$). A minimum insulation resistance of least 5 teraohms ($5 \times 10^{12}\Omega$) for charge acquisition is recommended when sensing charges below 1000 pC. [3]

An example of humidity effects on resistance (or its reciprocal value, conductivity) is shown in Figure 5. This information originates from oceanographic atmospheric condition studies. [11] Though not typically operated near or in the ocean, the potential major variation effect of relatively high humidity on air resistance must be considered when estimating sensor measurement uncertainty. Other factors (pollution, contaminants, etc.) affect ion-content in the air, provide scatter in the data, and can significantly change the slope of the air resistance relationship shown in the figure that follows. [10]

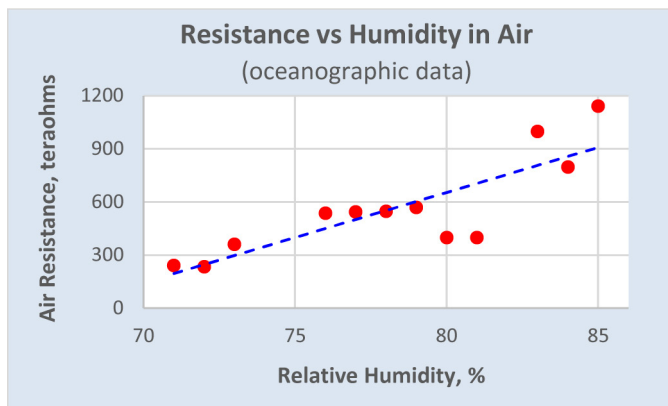


Figure 5. Humidity Effect on Air Resistance [11]

As a best practice due to the high variation in the effects of air resistance to humidity, and also due to the capacitance effect shown earlier, relative humidity (RH) values below 50% are the preferred operating environment. This is particularly important for best measurement accuracy, especially during metrology level calibration of charge amplifier modules.

Signal Transmission and Cabling

Often reported sensor issues can actually be attributed to the signal cabling subsystem. Very high quality, clean, and dry cables are required to optimize data integrity. The individual cylinder piezoelectric signal cables may also be mishandled during installation. Careful selections of

both the cable types and lengths are critical as well, since longer conductors decrease the signal amplitude and increase the opportunity for introducing noise into the measurement.

Common mode currents or “ground loops” must also be avoided, especially at any exposed connectors or junctions, if extension cables are used. It is imperative that long cable lengths use special low-noise materials in order to maintain the very high signal integrity that is required for accurate acquisition and analysis. Also, cabling must be carefully strain relieved in order to avoid mechanical stress at the terminals to the point of intermittent signal interruption or failure.

Cabling must also not be too loose as to be susceptible to noise from vibration induced triboelectric effects. These effects occur when cable subcomponents move or vibrate relative to each other, creating friction. This friction in turn results in electrical discharge being introduced into the cable system, corrupting the transmitted signal with noise. Special low noise cables are made with internal construction which helps to mitigate this unwanted triboelectrical discharge. As a best practice, these effects can also be minimized or avoided through the use of appropriate cabling with properly installed and strain relieved mountings. [3]

Component Aging

Variations due to aging of key components, such as feedback capacitors, may be as low as 0.1% or less over equipment life, but these can be up to 5% in older (or lower rated) electronic component designs. [6] Some component variation or failure is typical during new equipment burn-in, and less frequent failures may continue at a reduced but measureable level throughout the life of the equipment.

The low level of failures continues until failures increase somewhat more abruptly due to wear-out, as shown in the figure that follows. “

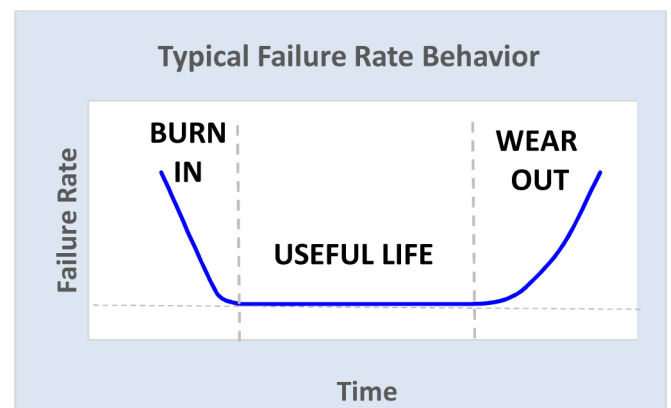


Figure 6. Electronic & Electrical Failure Rates [5]

Mechanical Shock

In-laboratory vibration and mechanical shocks from rough handling will also be reflected in changes to key electronic components. Over time, the fatigue effects of frequent, repeated shocks can accumulate, increasing a potential for out-of-tolerance conditions and other failure mechanisms in some of the electronic components. [12]