Automotive Component Durability Testing

Using Quartz Piezoelectric Force Sensors

Abstract

Although strain gage load cell technology has its place for DC (static) force measuring and measurements requiring accuracy better than 1.0% of full scale, quartz piezoelectric force sensors offer many advantages. Qualities such as long-term stability and durability are particularly important for automotive component durability testing. This paper is intended to acquaint instrumentation engineers, who may not be familiar with quartz piezoelectric force sensors characteristics, with the benefits of the technology and how to take advantage of these benefits in automotive testing applications.

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1. Introduction

Automotive component durability applications include compression, tension, impact and fatigue testing of latches, doors, hoods, trunks, seats, springs, actuators, suspensions, chassis, brackets and other automotive accessories and components. Most automotive durability testing, such as the power door lock actuator test pictured in Figure 1 below, that requires a force measurement has traditionally used strain gage load cell technology. This may, in part, be due to a lack of knowledge of the technical benefits of ICP® and charge mode quartz piezoelectric force sensors when used in these applications.

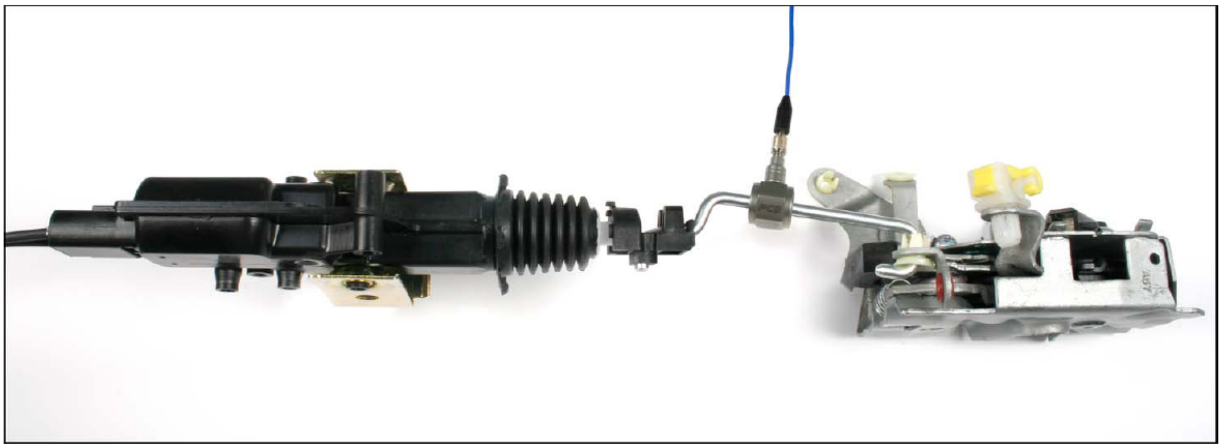


Figure 1
Door Lock Actuator Durability Testing

This paper will describe the quartz piezoelectric force sensor features and the benefits for dynamic testing as compared to strain gage technology, to help the automotive test engineer make the best technical selection for a given application. Table 1, on Page 5, is a summary of the features that will be described within the paper.

Table 1 Quartz Piezoelectric Compared with Strain Gage Technology		
Feature	**Technology Advantage**	**Benefit**
Stiffness	Piezoelectric	Typically an order of magnitude more stiff
Dynamic Response	Piezoelectric	Typically ten times higher frequency response than strain gage
Accuracy, static	Strain gage	“True DC” (static) accuracy for weighing
Size	Piezoelectric	Piezoelectric sensors are smaller than strain gage load cells of equivalent range
Multiple Ranges	Piezoelectric	Wide dynamic range. One quartz force sensor covers the linear range of several strain gage load cells. Zoom in the working range 10,000 times or more.
Electrical Output	Piezoelectric	ICP® output is a full 5 volts. Full-scale strain gage output is a mere 20 mV.
Overload Protection	Piezoelectric	Due to high stiffness, piezoelectric technology has several hundred percent overload without difficulty
Sensitivity Stability	Piezoelectric	Long-term stability, no aging effects with time, solid-state construction and moving parts. Less frequent calibration.
Temperature Effects	Piezoelectric	Piezoelectric up to 400 °F (204 °C). Common strain gage load cells limited to 200 °F (93 °C). Quartz Piezo sensitivity stability 0.01 to 0.03%/°F. Strain gage requires temp compensation electronics.
Cost	Similar	Piezoelectric and strain gage systems similar
Life-cycle cost	Piezoelectric	Less frequent calibration, increased sensor life due to stiffness vs. strain gage

2. Discussion

During the discussion, there are some concepts unique to quartz piezoelectric force sensor technology that shall be referred to frequently. These concepts are expounded upon in detail in the forthcoming discussion, but it would be best to define them at the beginning of the discussion. The concepts are:

Piezoelectric - from the Greek word for “squeeze electricity,” it is a natural phenomenon where electric output is produced when compressing certain crystals. It is an active sensing material that produces its own electrical output.

Charge Output – a quartz piezoelectric force sensor with sensitivity in pC/lb or pC/N. It requires an external charge amplifier to convert pico-Coulombs (pC) to volts.

ICP® Output – a quartz piezoelectric force sensor with sensitivity in mV/lb or mV/N. The sensor contains a built in hybrid amplifier circuit that converts pC to mV. A constant current power supply of approximately 2 to 20 mA at 18 to 30 VDC powers the sensor.

Discharge Time Constant – time in seconds required for an electrical signal to discharge exponentially to 37% of the original value.

Drift Rate – a nearly linear function that defines a leakage current inside of a charge amplifier. It is approximately 0.03 pC/sec. It is similar to a very long DTC beyond 10,000 sec.

2. a. Stiffness

Sensitivity of a strain gage load cell is fixed by the stiffness of the deflecting structure, called a flexure, which must be sized for the desired measurement range. Foil strain gages are bonded to the flexure and an electrical resistance change occurs as they deflect, or strain, under load. For example, most strain gage load cells require a deflection of at least 0.001 to 0.003 inches in order to reach full-scale output. This equates to a stiffness of only 0.03 to 6.7 lbs/μin for a 100 lb and 10k lb full-scale range respectively.

Quartz (Silicon Di-Oxide, SiO_2) piezoelectric force sensors are typically an order of magnitude stiffer than strain gage load cells of an equivalent full scale measuring range. A piezoelectric charge output is produced as a result of stress on a crystal lattice as opposed to deflection (strain) of a bonded foil strain gage. The unit of charge output is the pico-Coulomb (pC). Quartz sensing elements typically have the same charge sensitivity of 18 pC/lb (4 pC/N) for any size force sensor that is manufactured for measuring compression or tension.

A quartz piezoelectric force sensor reacts to stress, resulting in a miniscule strain, to produce its charge output. Depending on the physical shape of the sensor, it has stiffness on the order of 6 to 100 lbs/μin. The stress causes the crystal lattice to be polarized, which is an asymmetric arrangement of the lattice at rest. As shown in Figure 2 below, the molecule on the left is at rest while the molecule on the right is electrically polarized from the resulting asymmetry caused by the force. Figure 2 may appear to show a deflection under load, but this is magnified on an atomic level. Actual deflection is on the order of millionths of an inch (0.05 μm).

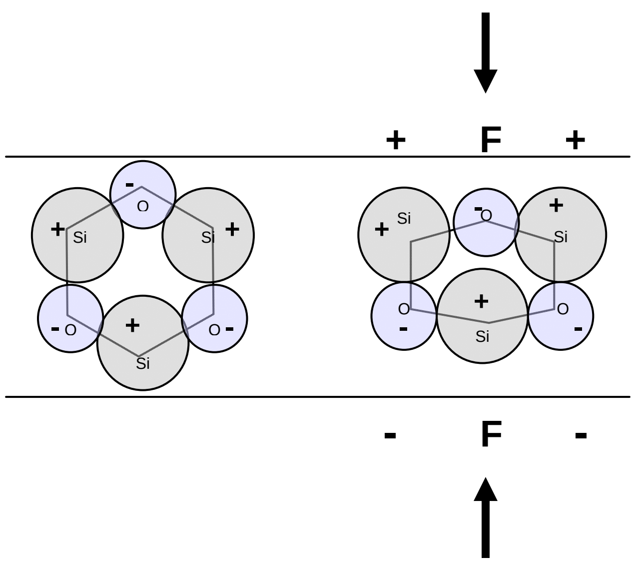


Figure 2
Quartz Molecule

Molecule at rest is pictured on left. When force is applied, the lattice polarizes under the resulting stress.

2. b. Dynamic Response

The frequency response of a quartz piezoelectric force sensor is approximated by a second order system with unique resonant frequency and low damping factor[1], and has up to ten times higher frequency response than a strain gage load cell. The high frequency response of quartz piezoelectric force sensors is determined by the mechanical characteristics of mass and stiffness, while the low frequency response is an electrical characteristic, which acts as a high-pass filter. Piezoelectric sensors can measure from near DC (quasi-static) to several kHz, while strain gage load cells are limited from “true DC” (static) to only several tens of Hz[2]. Many applications fall into an overlapping zone.

High frequency response is a mechanical property of quartz piezoelectric force sensors. We learned in section 2.a. above, that a quartz piezoelectric force sensor is stiffer and doesn’t require deflection to produce an output like a strain gage load cell. Thus, they achieve higher frequencies since frequency is proportional to the square root of stiffness.

Mass factors into the frequency calculation because frequency is also proportional to the square root of the inverse of the mass. Most strain gage load cell specifications list a ringing frequency. The ringing frequency is a calculated value using ½ of the mass. This is done because most load cells are used in a mounted configuration, where approximately ½ of the mass is supported and the center of the load cell acts as a diaphragm. The ringing frequency is the natural frequency of this diaphragm.

An experiment for natural frequency was conducted by testing two equivalent measuring range sensors of the quartz piezoelectric and strain gage load cell type. The sensors were selected with the same measuring range and were mounted and impacted as shown in Figure 3a and 3b.

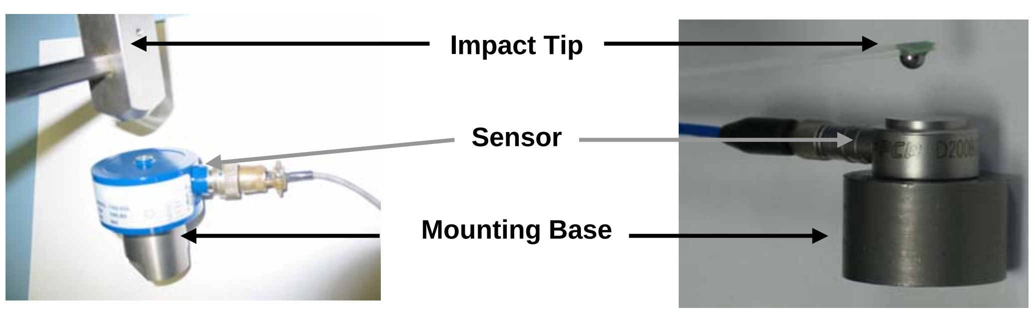


Figure 3a
Strain Gage Load Cell Set-up
PCB Load & Torque, Inc.
Model 1102-02A

Figure 3b
Piezoelectric Force Sensor Set-up
PCB Piezotronics
Model 200B02

Chart 1a and 1b below show a power spectrum of the mounted natural frequency for the strain gage load cell and the quartz piezoelectric force sensor. Note the lower resonant frequency of the load cell (2.3 kHz) compared to the piezoelectric force sensor (87.1 kHz). We may conclude that because of the high stiffness, the quartz piezoelectric force sensor may be mounted in a structure without changing the frequency characteristics of the structure with respect to stiffness.

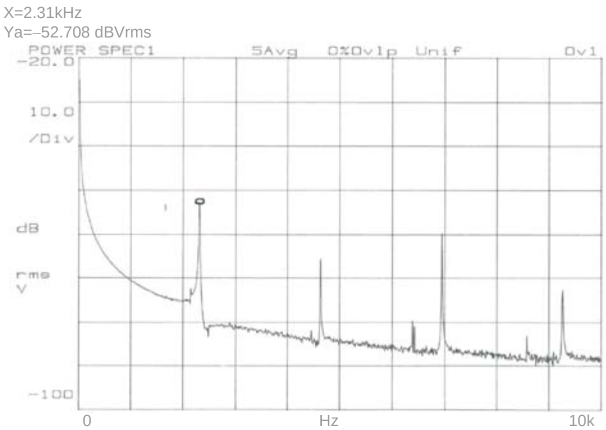


Chart 1a - PCB Load & Torque, Inc.
Model 1102-02A

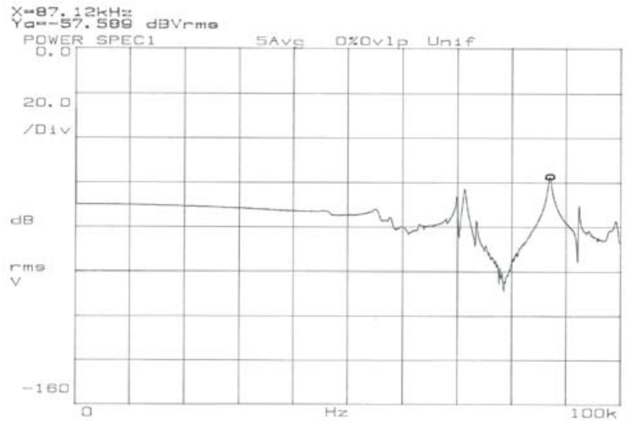


Chart 1b – PCB Piezotronics
Model 200B02

Natural Frequency of Piezoelectric Force Sensor Versus Strain Gage Load Cell

The natural frequency of a sensor may be calculated from the following equation:

f_n in kHz = $1/2\Pi * \sqrt{k/m}$ where k = stiffness in N/m and m = mass in kg[3]

The test engineer should take special note with respect to the mounted frequency response. Whenever a quartz piezoelectric force sensor or strain gage load cell is mounted, the mass of the system is increased and a new spring constant is introduced. Therefore, a bump test should be performed on the test setup in order to determine the system resonant frequency. Because the quartz piezoelectric force sensor has a lower mass and higher stiffness, it will help maintain to a higher system resonant frequency of the automotive component under test.

We present a summary of the relevant specifications for comparison in Table 2.

Table 2
Comparison of Equivalent Measuring Ranges

	PCB Piezotronics Model 200B02 quartz piezoelectric	**PCB Load & Torque, Inc. Model 1102-02A strain gage load cell**
Range lbs. (N)	100 (445)	100 (445)
Stiffness (kN/µm)	2.1	0.0056
Mass (kg)	0.01	0.304
Calculated fn (kHz)	72.9	3.8 (using ½ mass method)
Measured fn (kHz)	87.12	2.3

Low frequency response is determined by the electrical characteristics of the quartz piezoelectric force sensor. A static limitation is set by the system Discharge Time Constant (DTC) for ICP® output or drift rate for charge output sensors. We call the static limit quasi-static operation. DTC, which defines the low frequency response for piezoelectric sensors, should not be confused with “Time Constant” used in strain gage terminology, which defines rise time. DTC is defined as the time required for an electrical signal to discharge exponentially to 37% of the original value, whereas drift rate is a function of leakage current across a transistor in a charge amplifier.

The low frequency response for quartz piezoelectric force sensors therefore looks like a high-pass filter. The point where the frequency response falls off, known as the cut-off frequency, is set by the system DTC. Points at -3 dB, -10%, and –5% in the frequency response curve may be calculated as shown in Figure 4. Within this low frequency end of the sensor response is where quasi-static measurements can be made with a sufficiently long DTC.

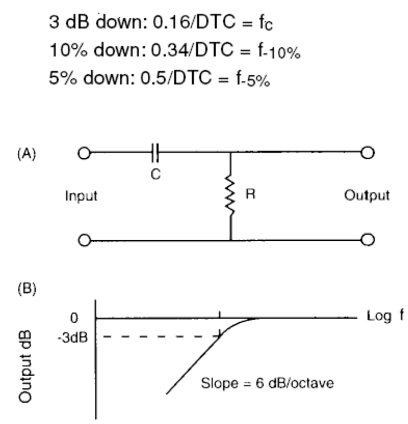


Figure 4
Low Frequency Characteristic of a First-Order, High-Pass Filter

Chart 2 below shows the response of two quartz piezoelectric force sensors when a steady state load is applied and maintained. It becomes clear that the signal from a lower DTC value of 10 seconds dissipates faster than a signal with a higher DTC of 500 seconds.

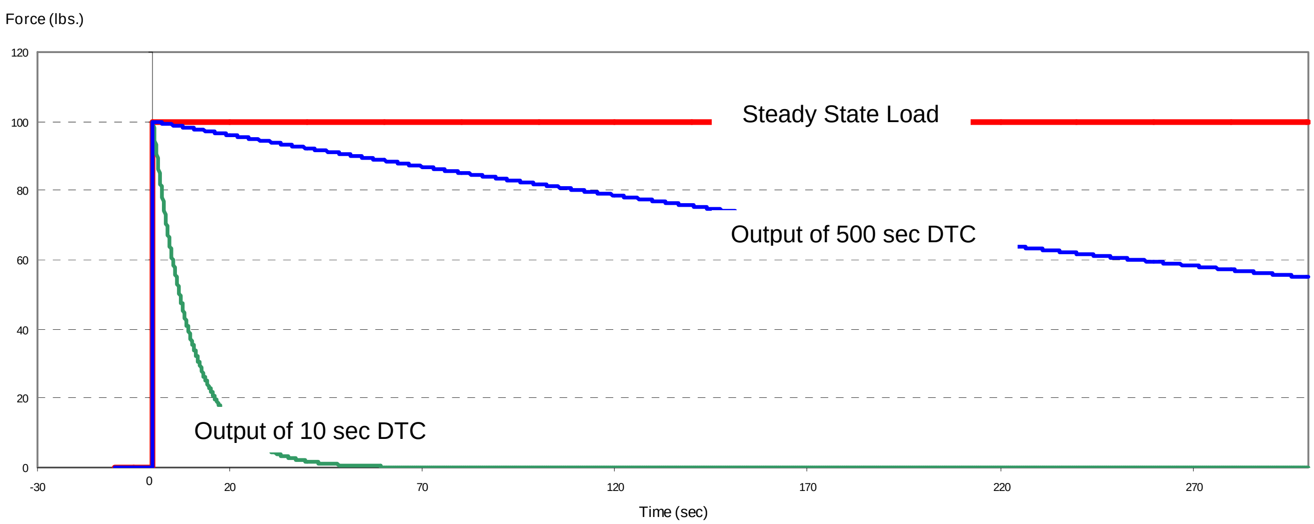


Chart 2
Discharge Time Constants

2. c. Static Accuracy

Herein lies the greatest advantage of strain gage load cell technology since true DC (static) accuracy for weighing applications may be achieved. As mentioned in section 2.b., low frequency response for quartz piezoelectric force sensors is limited, as they cannot monitor static, true DC response.

When using ICP® output sensors for quasi-static measurements or static calibration, DC coupled signal conditioners, such as the PCB model 484 series, and a DC coupled readout device should be used. They allow the sensor's DC bias voltage to be zeroed and do not apply any additional high-pass filter effects to the system. A general rule of thumb for such quasi-static measurements is that the output signal loss and time elapsed over the first 10% of a DTC have a linear, one-to-one relationship, as depicted in Figure 6a and 6b on Page 13. Thus, in the first one-hundredth of the DTC, there will be only 1% signal loss. If a sensor has a 2,000 second DTC, over the first 20 seconds, 1% of the original input signal will decay.

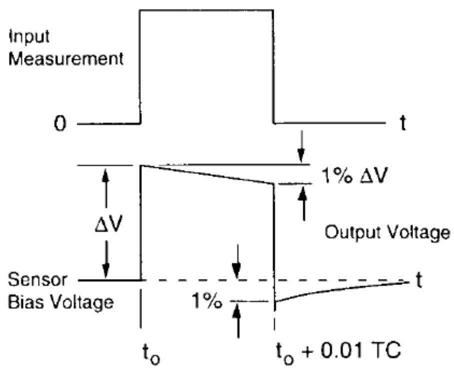


Figure 6a
DC Coupled Piezo Response
to a Static Step Input

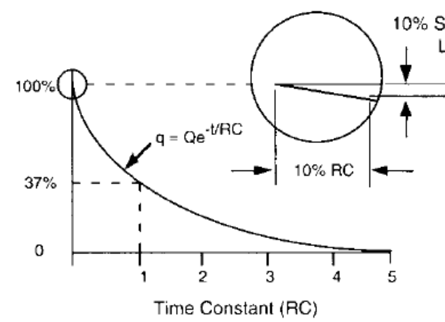


Figure 6b
Linear Portion of a DC Coupled
Discharge Time Constant

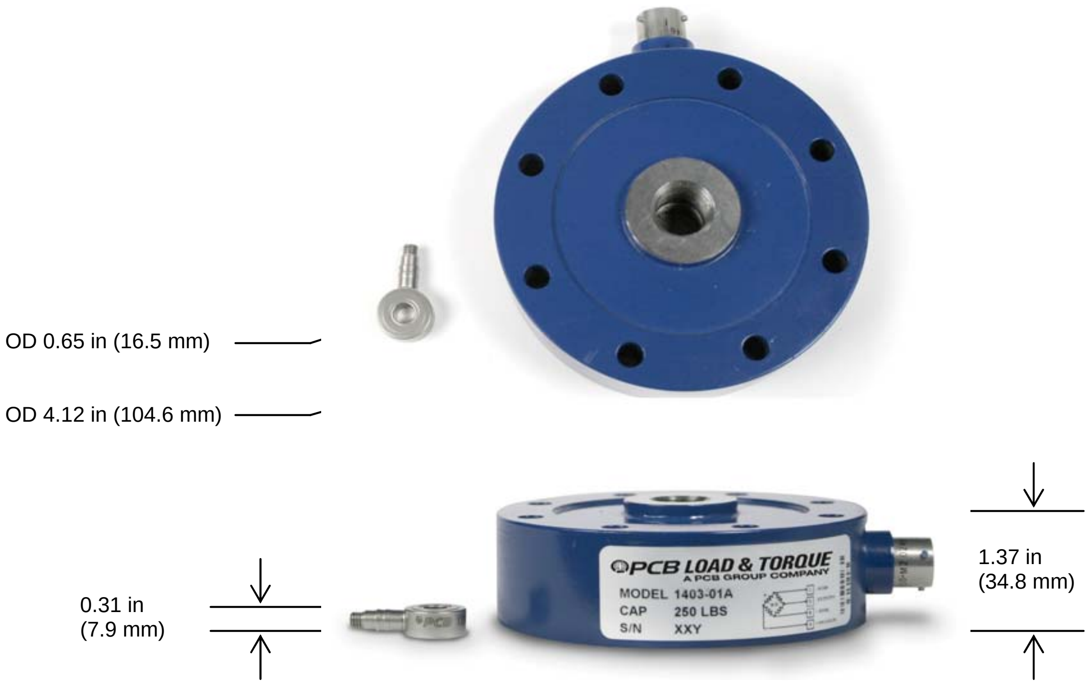
For example, when a 1,000 lb static load is applied to a DC coupled force sensor that has a 2,000 second system DTC, within the first 20 seconds (1% of 2,000) the force output signal would decay 1%, or less than 10 lbs. So for 1% accuracy, the reading must be taken in 1% of the DTC, or 20 seconds.

Final Note on Static Accuracy: The entire system must be DC coupled, which means the sensor has a long DTC, the signal conditioner is DC coupled and the readout device is DC coupled. The most common use for DC coupled operation is for calibration.

2. d. Size

Size is often an important consideration when selecting a force sensor. Quartz piezoelectric force sensors are smaller than strain gage load cells of equivalent range. This is a distinct advantage since the quartz piezoelectric types take up minimal space and do not add significant mass loading for dynamic tests.

A visual comparison is shown in Figure 5. The unit on the left is a PCB Piezotronics model 201B03 force ring, with 500 lb (2.2 kN) full-scale range. It has a 0.65 in (16.5 mm) diameter and 0.31 inch (7.9 mm) height. The unit to the right is a PCB Load & Torque, Inc. model 1403-01A fatigue-rated strain gage load cell, with 250 lb full-scale range. This unit has a 4.12 in (104.6 mm) diameter and 1.37 in (34.8 mm) height.



PCB Piezotronics
Model 201B03

PCB Load & Torque, Inc.
Model 1403-01A

Figure 5
Range Size Comparison

2. e. Multiple Ranges

Quartz piezoelectric force sensors with charge output have active sensing elements and generate a linear charge output proportional to the applied force[4]. They may be used for multiple measuring ranges without removing the force sensor from the test fixture. By the simple formula V=Q/C, where V is the voltage output, Q is the charge produced, and C is the system capacitance, multiple output ranges may be selected by adjusting the value of C[5]. The value of C may be adjusted internally in ICP® output sensors and externally in a charge amplifier for charge output sensors. This feature allows lower ranges to be measured while the sensor is experiencing much higher static loading. The test engineer can zoom in the working range from full scale 10,000 times or more. The same charge output quartz piezoelectric force sensor used at 0 to 10k lb may also be used to measure 0 to 10 lb.

By comparison, a strain gage load cell of a specific measuring range must be purchased for each desired measuring range required in a test. For example, suppose a test engineer desires to use a 10k lb strain gage load cell, with 0.05% linearity to measure both 10 klb and 100 lb dynamic loads on the same unit under test, and the test specification calls for 1% linearity error. The engineer would require two separate load cells and would have to set up the test two times to complete the work, because for the 100 lb load range, the 10 klb strain gage load cell would have a 5 lb linearity error. The maximum allowable error for the 100 lb load range is only 1 lb according to the test requirement.

When using a charge output quartz piezoelectric force sensor, the linearity remains at less than 1% of the working range (versus 1% of full-scale for strain gage load cells). If the engineer from the example in the previous paragraph would use a charge output quartz piezoelectric force sensor, the same sensor may be used for both tests. The linearity specification for a charge output quartz piezoelectric force sensor is 1% of the full scale working range. So, for the 10k lb test, the linearity error is 100 lb (1%) and when the associated charge amplifier range is changed, the 100 lb test error is only 1 lb (1%).

2. f. Electrical Output

Another benefit of an ICP® output quartz piezoelectric force sensor, is a high 5 or 10 volt output, whereas the full scale strain gage output may only be up to 20 mV when using a 2 mV/V strain gage and a 10 Volt DC power supply.[6] The high voltage output of the piezoelectric sensors provides a significant benefit in terms of signal to noise ratio, especially when the test is remote and requires a long cable run.

2. g. Overload Protection

The most common failure mode of a strain gage is the application of force beyond the yield point of the strain gage flexure (overload range). A typical 1,000 lb (4.45 kN) strain gage fatigue-rated load cell has an overload limit of 2,000 lb (8.9 kN), equivalent to 200%. Overloading the load cell may cause permanent damage to the flexure, which could lead to a zero shift, non-linearity and a general fatigue of the metal flexure, reducing the load cell's life.

Quartz piezoelectric force sensors react to stress, not strain, meaning there is virtually no deflection during measurement. Most have a compressive strength of 3.0×10^8 Pa (4.351×10^4 psi), which allows massive overloading without risk of crushing the sensor. Even when the sensor is overloaded beyond its stated measuring range, they suffer no ill effects, zero-shift, fatigue or linearity change. For the PCB model 201B03, with a measuring range of 500 lb and a diameter of 0.65 in, this means a maximum compression of 3,000 lb equivalent to 600% over-range protection.

An astute reader may notice that some lower ranged ICP® output quartz piezoelectric force sensors have a lower overload limited specified. This is an electrical limitation and not a mechanical limit.

Most ICP® output force sensors are designed to provide a full-scale 5 volts output at rated measuring range. However, the circuit typically provides output without damage to 30 volts and beyond. Several ICP® sensors have a built-in circuit that protects the electronics up to 100 volts impact induced shock overload. This electrical overload is typically six times or more of the rated capacity. For example, the PCB model 208C01, rated for 10 lb at 5 volts, has an overload rating of 100 lb at 50 volts. The mechanical overload for this force sensor is 6,000 lb by design, much higher than its electrical limit. Assume the test engineer electrically overloads the sensor beyond the 50 volts (100 lb) limit with a large impacting force with a microsecond pulse width. The resulting load could blow the electronic circuit. However, the force sensor's electronic circuit may be replaced as a module and the unit put back into service.

2. h. Sensitivity Stability

In durability testing of automotive components or structures, long-term sensor stability is an important consideration. Fatigue cycling of the flexure in strain gage load cells can cause sensitivity changes, often detected as a lower sensitivity in the compression direction[7]. Depending on the longevity of a particular test, the engineer should be aware of this fatigue life limit and calibrate the strain gage load cell on a regular basis.

Quartz force sensors excel in this characteristic since they are of solid-state construction and quartz, a natural piezoelectric sensing element, has no aging effects. Since they do not deflect under load like strain gage load cells, there is little chance for sensitivity change and frequent calibration is not required. This equates to time and cost savings.

Suppose a test engineer desires to perform a 50 Hz durability test in tension and compression for 1 month. This would equate to a total of 129.6 million cycles. Using a fatigue rated load cell, rated for 100 million cycles, the test would have to be interrupted at least once to replace the load cell because it exceeds its rated lifetime limit. With a quartz piezoelectric force sensor, the test would not have to be interrupted. It has in fact been demonstrated in one dynamic space application where the quartz piezoelectric force sensor continued to perform beyond 4-billion cycles, at which point the test was completed.

2. i. Temperature Effects

Quartz piezoelectric force sensors may be operated from –100 °F to 400 °F (-73 °C to 204 °C). Commonly available strain gage load cells have a useful temperature range limited from –65 °F to 200 °F (-54 °C to 93 °C), although upon special request, strain gage load cells may be manufactured with operating temperature up to 350 °F. This limited operating temperate range of strain gage load cells is due to the combination of solder melting point, the backing material of the strain gage and bonding agents used to attach the gages to the metal flexure[2]. Additionally, at elevated temperatures, the insulation resistance of stain gage load cell insulation materials can degrade significantly, leading to sensor non-linearity.

Because of the effect of temperature on the strain gage resistance, the mismatch between coefficient of expansion of the strain gage and the flexure, and bridge out-of-balance condition, these load cells require a temperature compensation circuit in order to provide a stable output. The various temperature-related measuring errors include thermal expansion, point response, thermal sensitivity change and electrical loading.

Quartz piezoelectric force sensors have one thermal error characteristic, which is a thermal coefficient of approximately 0.01 to 0.03 %/°F. This is a soaking temperature specification that will affect the sensor's sensitivity. It is inversely related to temperature. For example, if the temperature increases by 100 °F from calibration temperature, the sensitivity decreases 1% to 3%.

2. j. Cost

Quartz piezoelectric force sensor and strain gage load cell systems have a similar acquisition cost when considering sensor, cable and signal conditioning. A representative comparison of a quartz piezoelectric force sensor to a general-purpose strain gage load cell and fatigue rated load cell may be found in Table 3 below. The comparison includes a 10 ft cable and signal conditioner that provides analog voltage output.

Table 3
System Cost Comparison

	PCB Piezotronics General purpose quartz piezoelectric	**PCB Load & Torque, Inc. Typical strain gage pancake load cell**	**PCB Load & Torque, Inc. Typical strain gage fatigue rated load cell**
Range (lbs)	5,000	5,000	5,000
System cost	$862.00	$1,230.00	$1,385.00

Referring to section 2.d., when a quartz piezoelectric force sensors is used in charge mode with a slightly more expensive but fully adjustable charge amplifier we can take advantage of their wide linear dynamic measuring range and high voltage output. The same sensor may be used at full scale, 10% of full scale, or anywhere in between, thus magnifying the cost savings across multiple strain gage load cells.

The high stiffness and durability of quartz piezoelectric force sensors offer additional economic benefits of increased life and less frequent calibration. As mentioned in section 2.g. above, they are not susceptible to fatigue over billions of cycles or sensitivity changes because there are no moving parts. As an example, fatigue rated load cells are rated for 100-million cycles before the material used in its construction weakens to such a degree that the load cell cannot maintain its specifications. In certain automotive durability applications, quartz piezoelectric force sensors may offer performance and cost advantages compared to the more expensive fatigue-rated load cells.

3. Conclusions

Although strain gage technology is commonly taught and widely used, comparisons indicate that quartz force sensors can provide both technical and cost advantages in certain applications. Many applications fall into an overlapping zone, as depicted in Figure 6 below.

Quartz piezoelectric sensors measure from near DC (quasi-static) to several kHz, while strain gage load cells are limited from “true DC” (static) to only several tens of Hz. Quartz piezoelectric force sensors excel in dynamic applications requiring high frequency response, long-term stability and durability, while strain gage load cells are well suited for static and low frequency measurements.

Additional benefits of quartz piezoelectric technology include; small size, low mass, extended measuring range, overload protection, high voltage output, extended operating temperature range, low acquisition cost and low life-cycle cost.

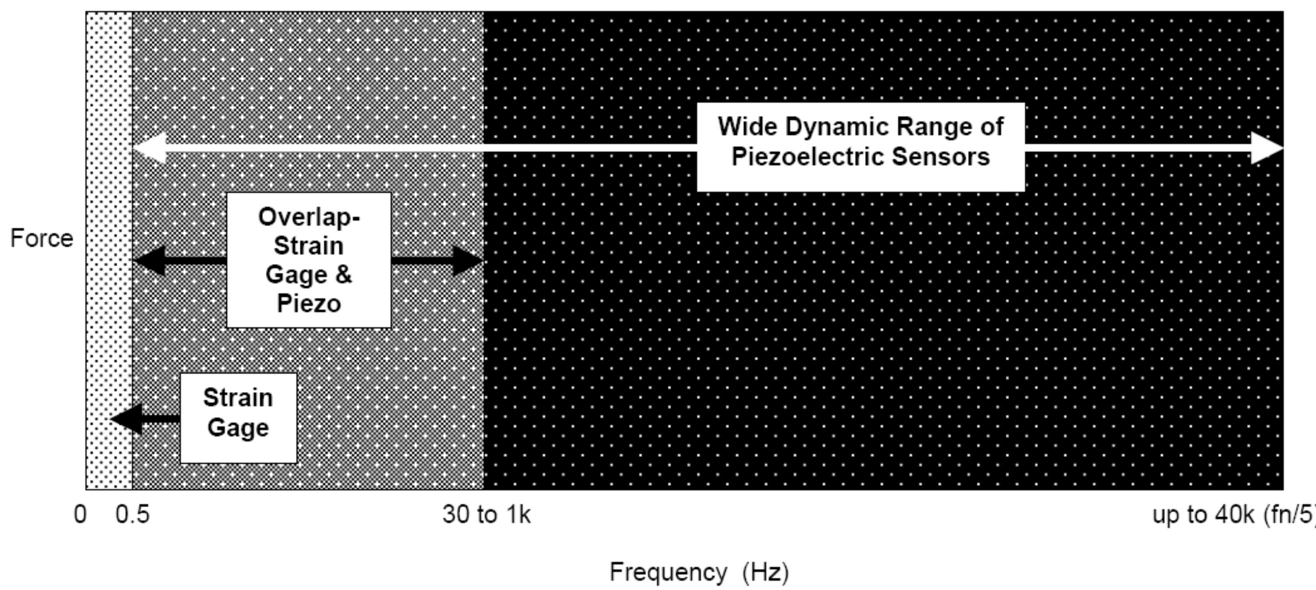


Figure 6
Technology Overlap – Quartz Piezoelectric versus Strain Gage

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