Technical Information

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INTRODUCTION TO QUARTZ FORCE SENSORS

Quartz Force Sensors are well suited for dynamic force measurement applications. They are not interchangeable with strain gage load cells used for static force measurements.

Measurements of dynamic oscillating forces, impact or high speed compression/tension under varying conditions may require sensors with special capabilities. Fast response, ruggedness, high stiffness, extended range and the ability to also measure quasi-static forces are standard features associated with PCB quartz force sensors.

The following information presents some of the design and operating characteristics of PCB quartz force sensors to help you better understand how they function, which in turn, will "help you make better dynamic measurements".

Types of Quartz Force Sensors

This catalog describes two modes of operation for quartz force sensors manufactured by PCB. ICP® (IEPE, or voltage mode type) feature built-in microelectronic amplifiers, which convert the high impedance electrostatic charge signal from the crystals into a low impedance voltage output signal. (ICP® is a registered trademark of PCB Piezotronics). The other type are charge mode force sensors, which directly output a high impedance electrostatic charge signal.

Sensor Construction

Both modes of operation for PCB force sensors feature similar mechanical construction. Most are designed with thin quartz crystal discs that are "sandwiched" between upper and lower base plates. An elastic, beryllium-copper stud holds the plates together and preloads the crystals. (Preloading assures parts are in intimate contact to ensure linearity and provide the capability for tensile force measurements.) This "sensing element" configuration is then packaged into a rigid, stainless-steel housing and welded to assure the internal components are sealed against contamination.

Fig. 1 illustrates the cross-section of a typical quartz force sensor. This particular sensor is a General Purpose 208 Series compression/tension model with built-in electronics.

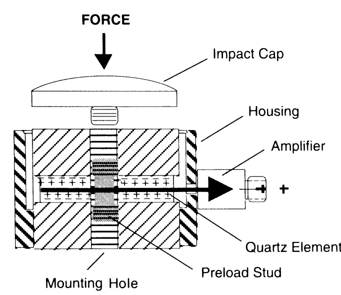


Figure 1. Compression-Tension-Impact Series 208

When force is applied to this sensor, the quartz crystals generate an electrostatic charge that is proportional to the input force. This charge output is collected on electrodes that are sandwiched between the crystals. It is then either routed directly to an external charge amplifier or converted to a low impedance voltage signal within the sensor. Both these modes of operation will be examined in the following sections.

Conventional Charge Mode Sensors

A charge mode piezoelectric force sensor, when stressed, generates an electrostatic charge from the crystals. For accurate analysis or recording purposes, this high impedance charge must be routed through a special "low noise" cable to an impedance converting amplifier such as a laboratory charge amplifier or source follower. Connection of the sensor directly to a readout device such as an oscilloscope is possible for high frequency impact indication, but is not suitable for most quantitative force measurements.

The primary function of the charge or voltage amplifier is to convert the high impedance charge output to a usable low impedance voltage signal for analysis or recording purposes. Laboratory charge amplifiers provide added versatility for signal normalization, ranging and filtering. PCB's "electrostatic" charge amplifiers have additional input adjustments for quasi static measurements, static calibration and drift-free dynamic operation. Miniature in-line amplifiers are generally of fixed range and frequency.

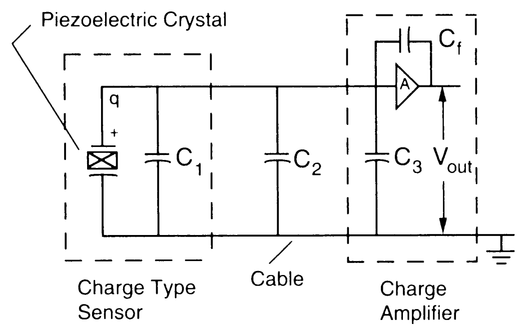
Quartz charge mode force sensors can be used at operating temperatures up to 400°F (204°C).

When considering the use of charge mode systems, remember that the output from the crystals is a pure electrostatic charge. The internal components of the force sensor and the external electrical connector maintain a very high (typically >10^{12} ohm) insulation resistance so that the electrostatic charge generated by the crystals does not "leak away". Consequently, any connectors, cables or amplifiers used must also have a very high insulation resistance to maintain signal integrity.

Environmental contaminants such as moisture, dirt, oil, or grease can all contribute to reduced insulation, resulting in signal drift and inconsistent results.

The use of special, "low noise" cable is required with charge mode force sensors. Standard, two-wire or coaxial cable when flexed, generates an electrostatic charge between the conductors. This is referred to as "triboelectric noise" and cannot be distinguished from the sensor's crystal electrostatic output. "Low noise" cables have a special graphite lubricant between the dielectric shield which minimizes the triboelectric effect.

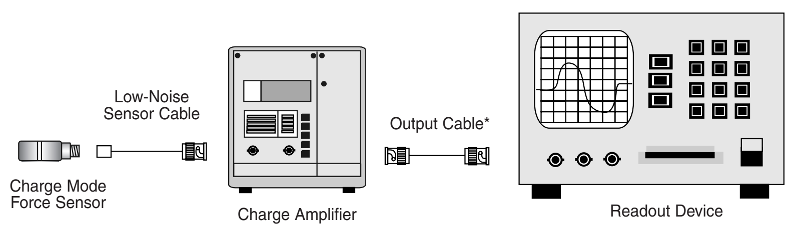
Fig. 2 shows a typical charge mode sensor system schematic including: sensor, low noise cable, and charge amplifier.

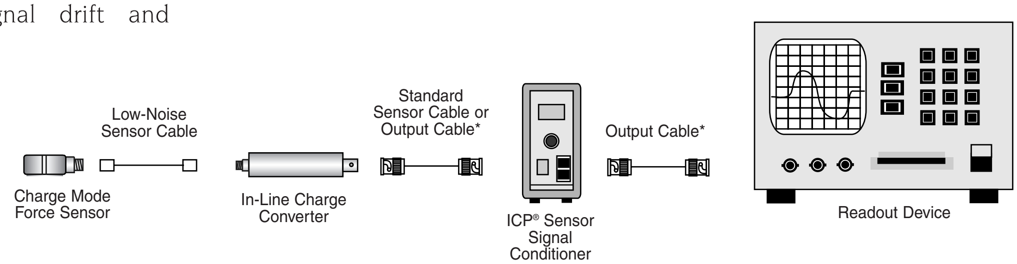


q = charge signal
C_1 = sensor capacitance
C_2 = cable capacitance
C_3 = amplifier input capacitance
C_1 = amplifier feedback capacitor

Figure 2. Charge Mode Sensor System Schematic

If the measurement signal must be transmitted over long distances, PCB recommends the use of an in-line charge converter, placed near the force sensor. This minimizes the chance of noise. In-line charge converters can be operated from the same constant-current excitation power source as ICP® force sensors to minimize system cost. **Fig. 3** shows two typical charge mode systems and their components.





* Low noise cable is required to maintain CE conformance.

Figure 3. Charge Mode Systems

ICP® Low Impedance Quartz Force Sensors

ICP® force sensors incorporate a built-in MOSFET microelectronic amplifier. This serves to convert the high impedance charge output into a low impedance voltage signal for analysis or recording. ICP® sensors, powered from a separate constant current source, operate over long ordinary coaxial or ribbon cable without signal degradation. The low impedance voltage signal is not affected by triboelectric cable noise or environmental contaminants.

Power to operate ICP® sensors is generally in the form of a low cost, 24-27 VDC, 2-20 mA constant current supply. **Fig. 4** schematically illustrates a typical ICP® sensor system. PCB offers a number of AC or battery-powered, single or multi-channel power/signal conditioners, with or without gain capabilities for use with force sensors. (See Signal Conditioners Section of this catalog for available models). In addition, many data acquisition systems now incorporate constant current power for directly powering ICP® sensors. Because static calibration or quasi-static short-term response lasting up to a few seconds is often required, PCB also manufactures signal conditioners that provide DC coupling.

Fig. 5. summarizes a complete 2-wire ICP® system configuration.

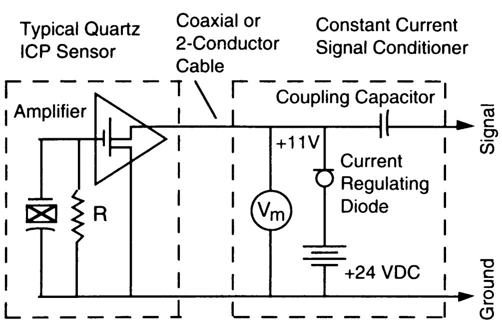
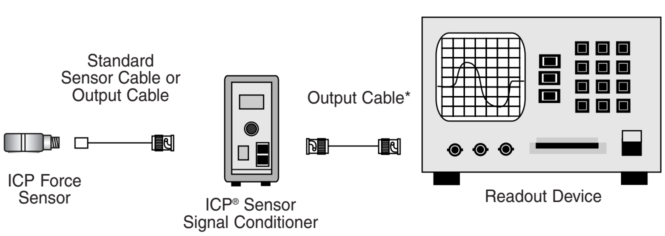


Figure 4. ICP® Sensor System Schematic



* Low noise cable is required to maintain CE conformance.

Figure 5. Typical ICP® Sensor System

In addition to ease of operation, ICP® force sensors offer significant advantages over charge mode types. Because of the low impedance output and solid-state, hermetic construction, ICP® force sensors are well suited for continuous, unattended force monitoring in harsh factory environments. Also, ICP® sensor cost-per-channel is substantially lower, since they operate through standard, low-cost coaxial cable, and do not require expensive charge amplifiers.

Polarity

The output voltage polarity of ICP® force sensors is positive for compression and negative for tension force measurements. The polarity of PCB charge mode force sensors is just opposite: negative for compression and positive for tension. This is because charge output sensors are usually used with external charge amplifiers that exhibit an inverting characteristic. Therefore, the resulting system output polarity of the charge amplifier system is positive for compression and negative for tension; same as for an ICP® sensor system. (Reverse polarity sensors are also available.)

Why Only Dynamic Force Can be Measured with Piezoelectric Force Sensors

The quartz crystals of a piezoelectric force sensor generate an electrostatic charge only when force is applied to or removed from them. However, even though the electrical insulation resistance is quite large, the electrostatic charge will eventually leak to zero through the lowest resistance path. In effect, if you apply a static force to a piezoelectric force sensor, the electrostatic charge output initially generated will eventually leak back to zero.

The rate at which the charge leaks back to zero is dependent on the lowest insulation resistance path in the sensor, cable and the electrical resistance/capacitance of the amplifier used.

In a charge mode force sensor, the leakage rate is usually fixed by values of capacitance and resistance in the low noise cable and external charge or source follower amplifier used.

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Introduction to Force Sensors

In an ICP® force sensor with built-in electronics, the resistance and capacitance of the built-in circuitry normally determines the leakage rate.

When a rapid dynamic force is applied to a piezoelectric force sensor, the electrostatic charge is generated quickly and, with an adequate discharge time constant, does not leak back to zero. However, there is a point at which a slow speed dynamic force becomes quasi-static and the leakage is faster than the rate of the changing force. Where is the point at which the force is too slow for the piezoelectric force sensor to make the measurement? See the next section on Discharge Time Constant for the answer.

Discharge Time Constant (DTC)

When leakage of a charge (or voltage) occurs in a resistive capacitive circuit, the leakage follows an exponential decay. A piezoelectric force sensor system behaves similarly in that the leakage of the electrostatic charge through the lowest resistance also occurs at an exponential rate. The value of the electrical capacitance of the system (in farads), multiplied by the value of the lowest electrical resistance (in ohms) is called the Discharge Time Constant (in seconds).

DTC is defined as the time required for a sensor or measuring system to discharge its signal to 37% of the original value from a step change of measurand. This is true of any piezoelectric sensor, whether the operation be force, pressure or vibration monitoring. The DTC of a system directly relates to the low frequency monitoring capabilities of a system and, in the case of force monitoring, becomes very important as it is often desired to perform quasi-static measurements.

DTC Charge Mode System

In a charge mode system, the sensors do not contain built-in amplifiers, therefore, the DTC is usually determined by the settings on an external charge amplifier. A feedback resistor working together with a capacitor on the operational amplifier determines the time constant. PCB's laboratory-style charge amplifiers feature short, medium and long time constant selections. It is assumed that the electrical insulation resistance of the force sensor and cable connecting to the charge amplifier are larger than that of the feedback resistor in the charge amplifier; otherwise, drift will occur. Therefore, to assure this, the force sensor connection point and cable must be kept clean and dry.

Low Frequency Response of ICP Systems

With ICP® force sensors, there are two factors which must be considered when making low frequency measurements. These are:

1. The discharge time constant characteristic of the ICP® force sensor.
2. The discharge time constant of the AC coupling circuit used in the signal conditioner. (If DC coupling is used, only the above (1) need to be considered.)

It is important that both factors be readily understood by the user to assure accurate low frequency measurements.

DTC In ICP® Force Sensors

The DTC is fixed by the components in the ICP® sensor's internal amplifier. Specifications for the ICP® force sensors shown in this catalog list the DTC for each force sensor.

When testing with ICP® sensors, there are two time constants that must be considered for low frequency determination, one being that of the sensor which is a fixed value, and the other being that of the coupling electrical circuit used in the signal conditioner.

When an ICP® sensor is subjected to a step function input, a quantity of charge, q, is produced proportional to the mechanical input. According to the law of electrostatics, output voltage is $\Delta V = \Delta q/\Delta C$ where C is the total capacitance of the sensing element, amplifier, and ranging capacitor.

This voltage is then amplified by the MOSFET amplifier to determine final sensor sensitivity. After the initial step input, the charge signal decays according to the equation

$$q = Qe^{-t/RC}$$

where:

q = instantaneous charge (C)
Q = initial quantity of charge (C)
R = bias resistor value (ohms)
C = total capacitance (F)
e = base of natural log (2.718)
t = time elapsed since t_0 (sec)

This equation is also graphically represented in **Fig. 6** below:

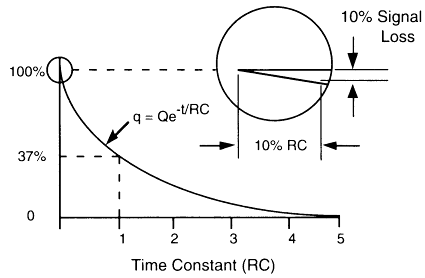

Figure 6. Standard DTC Curve

The product of R and C represents the DTC (in seconds) of the sensor. Sensor time constants vary from just a few seconds to >2000 seconds for standard sensors. Special time constants can be supplied by altering the resistor value, R, in the sensor's built-in circuitry.

Most readout instruments have a high input impedance of >1 megohm. For these systems, the sensor DTC as previously discussed becomes the dominant value and can be used in determining signal discharge rate. However, for signals coupled to low impedance readout devices, generally <1 megohm, it is necessary to determine the system time constant. This will be explained further in the following section.

Signal Conditioner and Readout Time Constants

The external power supply used with an ICP® force sensor may also have a DTC associated with it. In some ICP® signal conditioners, which feature internal buffer amplifiers or gain amplifiers, the time constant is fixed by various internal components and may be shorter, or longer, than the sensor DTC. In signal conditioners with capacitive-coupled outputs, the DTC is not fixed. In this case, a capacitor used to decouple an ICP® force sensor bias voltage acts with the input impedance of the readout device to create another time constant.

Check the specifications of the signal conditioner to determine if it has a fixed internal DTC, which sets the low frequency response, or if it has a capacitive-coupled output. If the output is capacitive-coupled, the time constant, when fed into the input of the readout can be calculated as follows:

$$DTC = RC$$

where:

R = input impedance of readout device (ohms)
C = value of coupling capacitor at output of signal conditioner (F)

Note that the output of some capacitive-coupled ICP® sensor power conditioners feature a shunt resistor that overrides the effects of the input resistance of the readout device if it is 1 Megohm or greater.

AC coupling in the readout device is also an additional type of DTC. Check specifications for the power conditioners and readout instrument to be sure they are suitable for your particular dynamic measurement. If you have more than one DTC in the system, a time constant that is significantly shorter than the others will usually dominate. Determination of the system DTC for oscillating and transient inputs can be calculated from these equations:

Oscillating inputs: $$DTC = \frac{(R_1C_1)(R_2C_2)}{\sqrt{(R_1C_1)^2 + (R_2C_2)^2}}$$

Transient inputs (lasting up to 10% of smaller DTC): $$DTC = \frac{(R_1C_1)(R_2C_2)}{(R_1C_1) + (R_2C_2)}$$

To avoid potential problems, it is recommended to keep the coupling time constant at least 10 times longer than the sensor time constant. The system discharge time constant determines the low frequency response of the system. It is analogous to a first-order high pass RC filter. The system's theoretical low frequency roll-off is illustrated in **Fig. 7** below, and can be calculated from the following relationships:

3 dB down: $0.16/DTC = f_c$
10% down: $0.34/DTC = f_{-10\%}$
5% down: $0.5/DTC = f_{-5\%}$

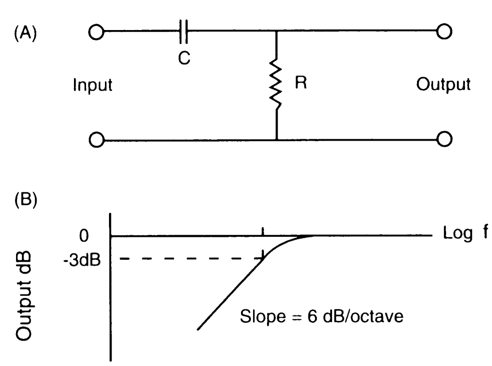

Figure 7. Low Frequency Characteristic of a First-Order, High-Pass Filter