



# Guide to Dynamic Force Sensors

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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. (also offered by PCB)

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

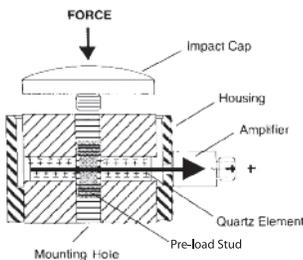
This paper describes two modes of operation for quartz force sensors manufactured by PCB®. ICP® (voltage output type sensors) feature built-in microelectronic amplifiers, which convert the high-impedance electrostatic charge signal from the crystals into a low-impedance voltage output signal. The other type are charge output 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 pre-loads the crystals (pre-loading 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.

**Figure 1** illustrates the cross-section of a typical quartz force sensor. This particular sensor is a general purpose Series 208 compression/tension model with built-in electronics.

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 an electrode that is 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.



**Figure 1. Compression-Tension-Impact Series 208**

## Conventional Charge Output Sensors

A charge output 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 electro-static 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 output force sensors can be used at operating temperatures up to +400 °F (+204 °C).

When considering the use of charge output 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<sup>12</sup> 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.

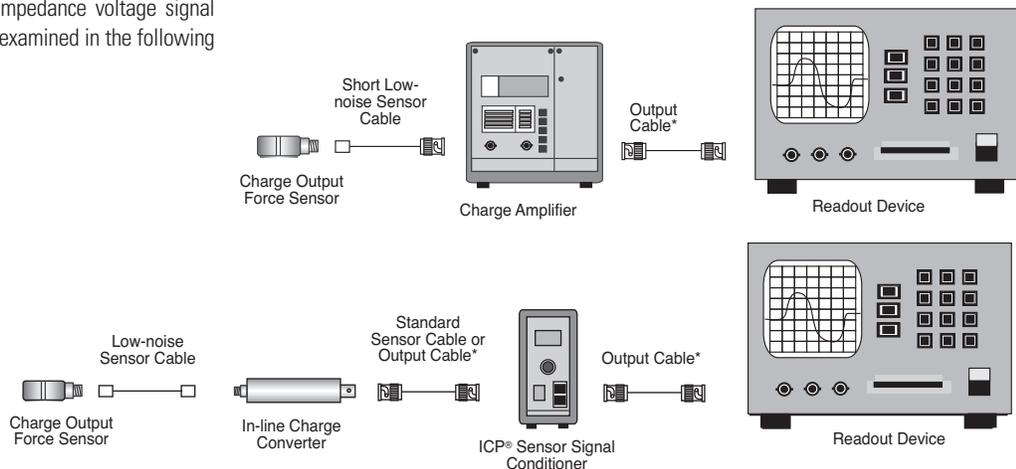
Environmental contaminants such as moisture, dirt, oil, or grease can all contribute to reduced insulation, resulting in signal drift and inconsistent results.

The use of special, low- noise cable is required with charge output 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.

**Figure 2.** shows a typical charge output sensor system schematic including: sensor, low-noise cable, and charge amplifier.

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.

**Figure 2.** shows two typical charge output systems and their components.



A fixed in-line charge converter may be utilized to simplify setup or to make use of an existing ICP® sensor signal conditioner.

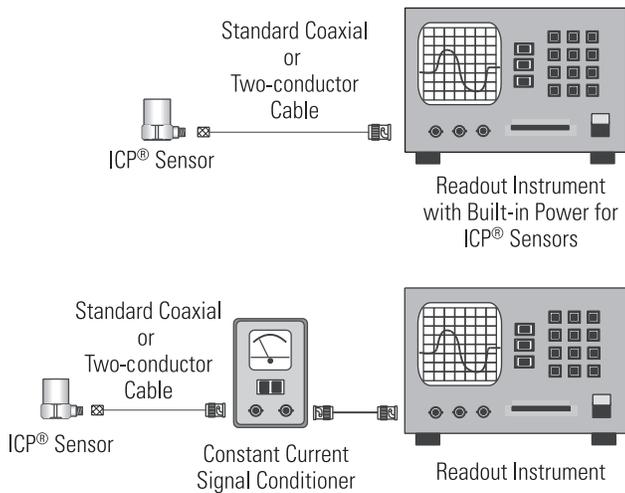
**Figure 2. Typical Charge Amplified System**

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## 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 to 27 VDC, 2 to 20 mA constant current supply. **Figure 3** 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. 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.

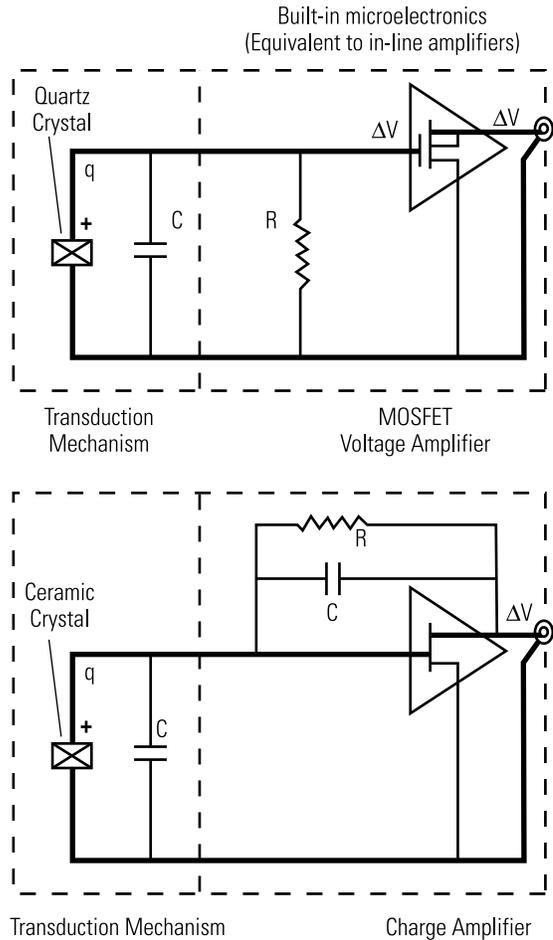


**Figure 3. Typical ICP® Sensor Systems**

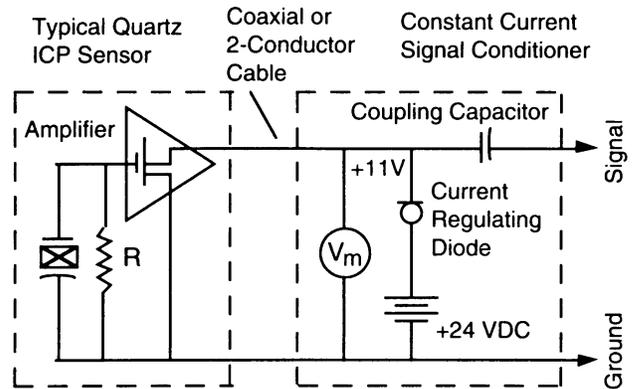
**Figure 5** summarizes a complete 2-wire ICP® system configuration. In addition to ease of operation, ICP® force sensors offer significant advantages over charge output types. Because of the low-impedance output and solid-state, hermetic construction, ICP® force sensors are well-suited for continuous, 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. ICP® strain sensors have the opposite polarity. The polarity of PCB® charge output force sensors is the 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).



**Figure 4. Basic Quartz and Ceramic ICP® Sensors**



**Figure 5. Typical 2-wire ICP® Sensor System**

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## Why Can Only Dynamic Force 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 output 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.

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 ohm) 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 Output System

In a charge output 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 (1) above needs 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 an 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.

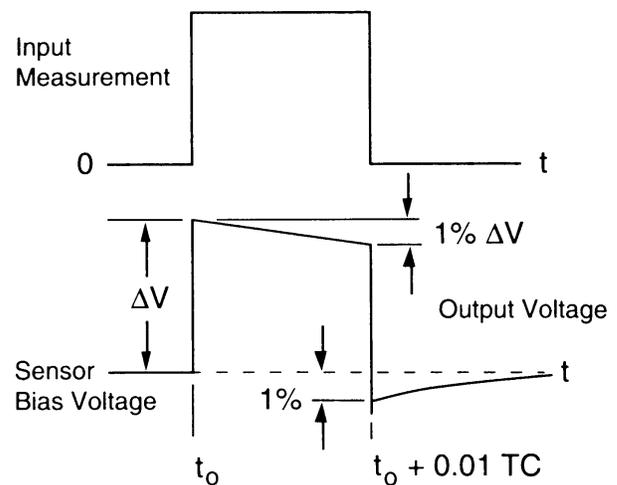


Figure 6. Step Function Response

## Long Duration Events and DTC

It is often desired to measure an input pulse lasting a few seconds in duration. This is especially true with force sensor applications where static calibration or quasi-static measurements take place. Before performing tests of this nature, it is important to DC couple the entire monitoring system to prevent rapid signal loss. PCB®'s AC/DC mode signal conditioners are designed for such applications.

The general rule of thumb for such measurements is that the output signal loss and time elapsed over the first 10% of a DTC have an approximate one to one relationship. If a sensor has a 500 second DTC, over the first 50 seconds, 10% of the original input signal will have decayed. For 1% accuracy, data should be taken in the first 1% of the DTC. If 8% accuracy is acceptable, the measurement should be taken within 8% of the DTC, and so forth. **Figure 6** graphically demonstrates this event.

Left unchanged, the signal will naturally decay toward zero. This will take approximately 5 DTC. You will notice that after the original step impulse signal is removed, the output signal dips below the base line reference point ( $t_0 + 0.01 TC$ ). This negative value is the same value as has decayed from the original impulse (shown as 1% in **Figure 6**). Further observation will reveal that the signal, left untouched, will decay upwards toward zero until equilibrium in the system is observed.

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Series 208 force sensors are supplied with a convex curved impact cap to help spread the forces over the entire surface of the force sensor.

One other consideration when mounting force sensors is to minimize unnecessary mechanical high frequency shock loading of the sensors. **The high frequency content of direct metal-to-metal impacts can often create short duration, high "g" overloads in structures and sensors. This problem can be minimized by using a thin damping layer of a softer material on the interface surface between the structure and sensor being impacted (it should be considered beforehand whether the slight damping of the high frequency shock is critical to the force measurement requirements).** The impact surface on Series 200 and the impact caps on Series 208 force sensors are supplied with thin layers of damping material.

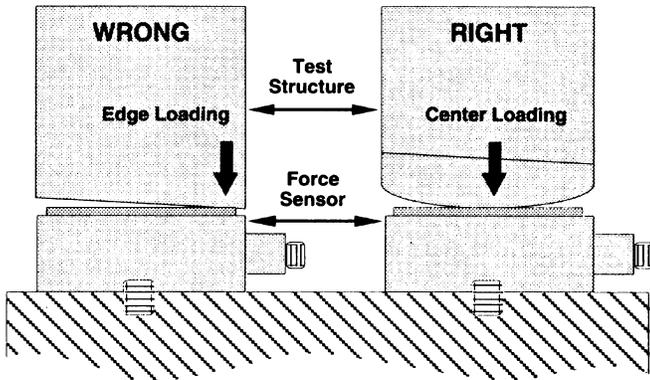


Figure 7. Edge vs. Central Loading

## Force Sensor Natural Frequency

Unlike the low frequency response of the sensor, which is determined electrically through the  $DTC = RC$  equation, the high frequency response is determined by the sensor's mechanical configuration (unless electrical low-pass filtering has been added). Each force sensor has an upper frequency limit specification which should be observed when determining upper linear limits of operation.

## Installation

Proper installation of quartz force sensors is essential for accurate dynamic measurement results. Although rugged PCB® quartz force sensors are forgiving to some degree, certain basic procedures should be followed.

Since most PCB® force sensors are designed with quartz compression plates to measure forces applied in an axial direction, aligning the sensor and contact surfaces to prevent edge loading or bending moments in the sensor will produce better dynamic measurement results.

Having parallelism between the sensor and test structure contact surfaces minimizes bending moments and edge loading. Flatness of mounting surfaces will also affect the quality of the measurement. Using a thin layer of lubricant on mounting surfaces during installation creates better contact between sensor and mounting surface.

The mounting surfaces on PCB® force sensors are lapped during their manufacture to ensure that they are flat, parallel and smooth. Ring-style force sensors are supplied with anti-friction washers to minimize shear loading of the sensor surface when torquing between two surfaces.

Loading to the entire force sensor sensing surface is also important for good measurements. However, this can be difficult if the surface being brought into contact with the force sensor is flat but not parallel to the sensor mounting surface. In this case, an intermediate curved surface can lessen edge loading effects (See Figure 7).

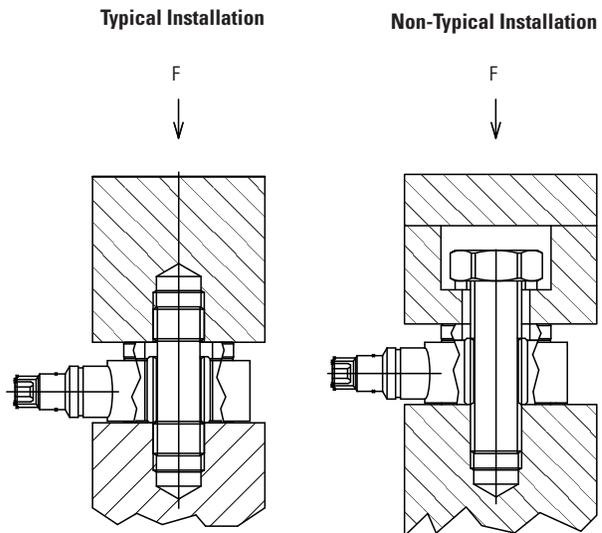


Figure 8. Force Ring Sensor Installations

## Pre-Loading Force Rings and 3-Component Force Sensors

PCB® ring-style 1-component and 3-component force sensors are generally installed between two parts of a test structure with the supplied elastic beryllium-copper stud or customer-supplied bolt. The stud or bolt holds the structure together, and applies pre-load to the force ring as shown in Figure 8. In the typical installation, shown on the left side in Figure 8, part of the force between the two structures is shunted through the mounting stud. The amount of force shunted may be up to 7% of the total force for the beryllium-copper stud supplied with the sensor, and up to 50% for steel studs. This typical installation setup is used by PCB® during standard calibrations.

A non-typical installation is shown on the right side in Figure 8. In this non-typical installation, the stud or bolt used to apply the pre-load does not shunt part of the applied force. The plate on top of the sensor has a clearance hole that the stud or bolt passes through. In this installation, the stud or bolt is not directly connected to the top plate by its threads, as it is in the typical installation, so it does not shunt any force.

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**NOTE:** If any of the following conditions apply to the pre-loading of the force ring in the application, the sensitivity and linearity performance of the sensor will not match the standard PCB® calibration values.

1. Use of a stud or bolt other than the supplied beryllium-copper stud
2. Use of no stud or bolt
3. Use of an amount of pre-load other than the recommended amount
4. Use of the non-typical installation setup shown below

In these cases, please contact a PCB® application engineer to discuss your special calibration requirements.

PCB® in-house calibration procedure requires the installation of a force ring with beryllium-copper stud, in the typical installation setup above, in series with a NIST traceable reference sensor. Generally, a pre-load of 20% (full-scale operating range of the force ring) is applied before recording of measurement data. Contact a PCB® application specialist for proper pre-load requirements. Allow the static component of the signal to discharge before calibration.

Three-component force sensors must be pre-loaded to achieve proper operation, particularly for the shear x-, and y-axis. The recommended applied pre-load for three-component force sensors is 10 times their x or y axes measurement range. This pre-load provides the sensing crystals with the compressive loading required to achieve an output in response to shear direction input forces. As with force rings, the sensitivity achieved from a 3-component force sensor is dependent upon the applied pre-load and the elasticity characteristics of the mounting bolt or stud used. If the unit is to be installed with a stud or bolt other than the supplied elastic, beryllium-copper stud, a calibration using the actual mounting hardware must be performed. Errors in sensitivity of up to 50% can result by utilizing studs or bolts of different materials.

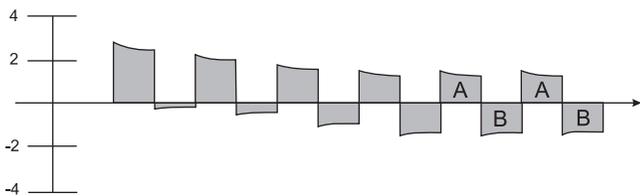


Figure 9. Repetitive Pulse, AC Signal

## Typical Piezoelectric System Output

The output characteristic of piezoelectric sensors is that of an AC coupled system, where repetitive signals will decay until there is an equal area above and below the original base line. As magnitude levels of the monitored event fluctuate, the output will remain stabilized around the base line with the positive and negative areas of the curve remaining equal. Figure 9 represents an AC signal following this curve (output from sensors operating in DC mode following this same pattern, but over an extended time frame associated with sensor time constant values).

**Example:** Assuming a 0 to 3 volt output signal is generated from an AC coupled force application with a one second steady-state pulse rate and one second between pulses. The frequency remains constant, but the signal quickly decays negatively until the signal centers around the original base line (where area A = area B). Peak-to-peak output remains the same.

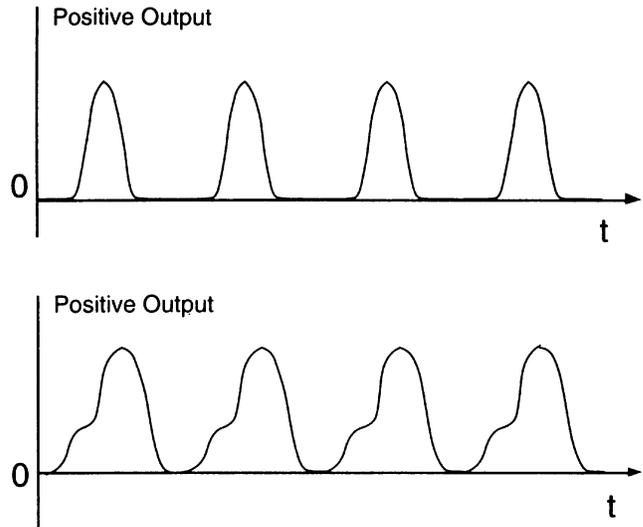


Figure 10. Positive Polarity, Zero-based AC Output

## Repetitive Pulse Applications

In many force monitoring applications, it is desired to monitor a series of zero-to-peak repetitive pulses that may occur within a short time interval of one another. This output signal is often referred to as a “pulse train”. As has been previously discussed, the AC coupled output signal from piezoelectric sensors will decay towards an equilibrium state, making it look like the positive force is decreasing. In this scenario, it would be difficult to accurately monitor a continuous zero-to-peak output signal such as those associated with stamping or pill press applications. With the use of special ICP® sensor signal conditioning equipment it becomes possible to position an output signal positive going above a ground-based zero. Operating in drift-free AC mode, PCB®’s Model 484B02 or a Model 410B01 ICP® sensor signal conditioner provides the constant current voltage excitation to ICP® force sensors and has a zero-based clamping circuit that electronically resets each pulse to zero. As outlined in Figure 10, this special circuitry prevents the output from drifting negatively, and provides a continuous, positive polarity signal.



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## ICP® 3-Component Force Measurement System

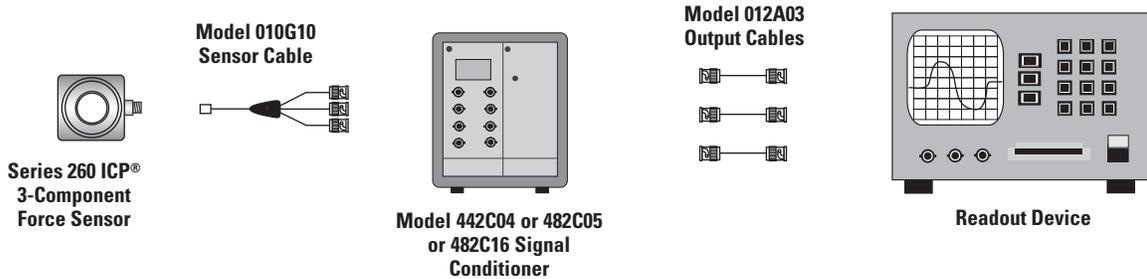


Figure 11. System Utilizing a ICP® Sensor Signal Conditioner

## Charge Output Force Measurement System

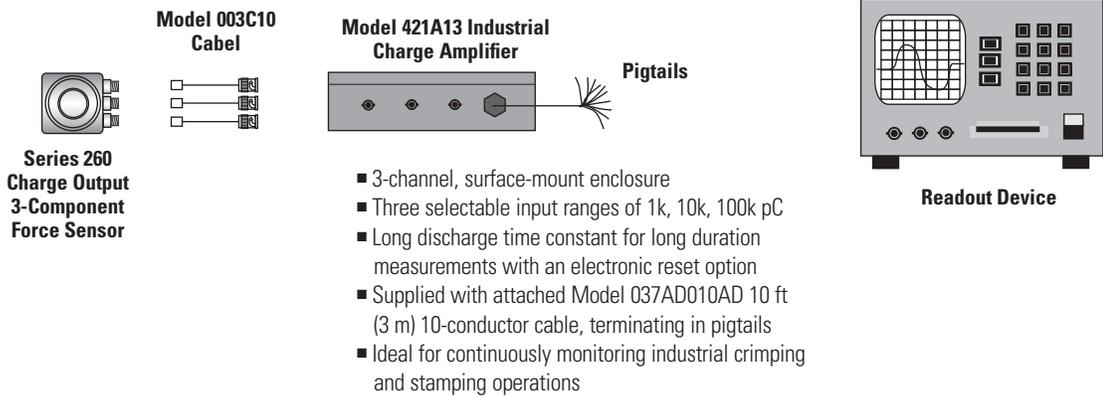


Figure 12. Low-cost System Utilizing 3-Channel Industrial Charge Amplifier





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