

TN-42

Load Cell & Torque Sensor Technical Information

LOAD CELL TECHNICAL INFORMATION

PRINCIPAL OF OPERATION

PCB® manufactures a wide variety of load cells whose output voltage is proportional to the applied force produced by a change in resistance in strain gages which are bonded to the load cell's structure. The magnitude of the change in resistance corresponds to the deformation of the load cell and therefore the applied load.

The four-arm Wheatstone bridge configuration shown in **Figure 1** depicts the strain gages used in our load cells. This configuration allows for temperature compensation and cancellation of signals caused by forces not directly applied to the axis of the applied load.

A regulated 5 to 20 volt DC or AC rms excitation is required and is applied between A and D of the bridge. When a force is applied to the transducer structure, the Wheatstone bridge is unbalanced, causing an output voltage between B and C which is proportional to the applied load.

Most all PCB® load cells follow a wiring code established by the Western Regional Strain Gage committee as revised in May 1960. The code is illustrated in **Figure 2**.

AXIS DEFINITION

Our load cells comply with the Axis and Sense Definitions of NAS-938 (National Aerospace Standard-Machine Axis and Motion) nomenclature and recommendations of the Western Regional Strain Gage committee.

These axes are defined in terms of a "right handed" orthogonal coordinate system as shown in Figure 3.

A tensile load exhibits a positive (+) polarity going output, while a compressive load exhibits a negative (-) polarity going output.

The primary axis of rotation or axis of radial symmetry of a load cell is the z-axis.

PRINCIPAL OF OPERATION

PCB® manufactures load cells under two classifications. They are general purpose and fatigue-rated.

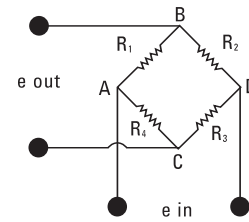


Figure 1
Wheatstone Bridge

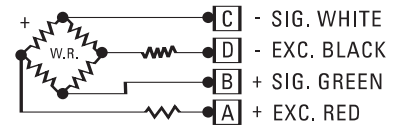


Figure 2
Load Cell Wiring Code

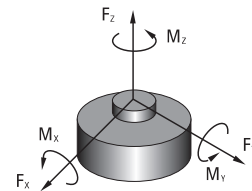


Figure 3
Right-handed Orthogonal Coordinate System

GENERAL PURPOSE

General purpose load cells are designed for a multitude of applications across the automotive, aerospace, and industrial markets. The general purpose load cell, as the name implies, is designed to be utilitarian in nature. Within the general purpose load cell market there are several distinct categories. They are: precision, universal, weigh scale, and special application. PCB® primarily supplies general purpose load cells into the universal and special application categories. Universal load cells are the most common in industry. Special application load cells are load cells that have been designed for a specific unique force measurement task.

FATIGUE-RATED LOAD CELLS

Fatigue-rated load cells are specially designed and manufactured to withstand millions of cycles. They are manufactured using premium fatigue-resistant steel or aluminum and special processing to ensure mechanical and electrical integrity, as well as accuracy. Fatigue-rated load cells manufactured by PCB® are guaranteed to last 100 million fully reversed cycles (full tension through zero to full compression). An added benefit of fatigue-rated load cells is their extreme resistance to extraneous bending and side loading forces.

TYPICAL APPLICATION EXAMPLES:

- Hydraulic Actuators
- Quality Control
- Torque Arm
- Life Cycle Testing
- Material Fatigue Testing
- Tank Weighing

ERROR ANALYSIS

PCB® typically supplies accuracy information on its products in the form of individual errors. They are: non-linearity, hysteresis, non-repeatability, effect of temperature on zero, and effect of temperature on output.

The customer can combine individual errors to establish the maximum possible error for the measurement, or just examine the applicable individual error. If the temperature remains stable during the test, the temperature related errors can be ignored. If the sensor is used for increasing load measurement only, ignore the hysteresis error. If the load measurement is near the full capacity, the linearity error can be ignored. If the capability exists to correct the data through linearization-fit or a look-up table, the error in the measurement can be minimized. A sophisticated user can get rid of all the errors except for the non-repeatability error in the measurement.

Often overlooked by the customer is the error due to the presence of non-measured forces and bending moments. Even though the single axis of measurement sensors are designed and built to withstand these non-measured forces and bending moments (extraneous loads), the errors due to them are present. PCB® engineers can design the set-up to eliminate or minimize these extraneous loads. However, if these extraneous loads are present, the errors due to them should be considered.

Due to cost restraints, PCB®, as with its competition, does not typically measure or compensate for errors due to extraneous loads. If the presences of these extraneous loads are known, the user should request the transducer manufacturer to run a special test, at extra cost, to define and quantify the extraneous load errors. These errors are defined as cross-talk errors.

APPLICATION QUESTIONNAIRE

Determine the capacity required

- A. What is the maximum expected load?
- B. What is the minimum expected load?
- C. What is the typical expected load?
- D. What are the dynamics of the system, i.e. frequency response?
- E. What are the maximum extraneous loads to which the load cell will be subjected?

How will the load cell be integrated into the system?

- A. What are the physical constraints, e.g. height, diameter, thread?
- B. Will the load cell be in the primary load path or will the load cell see forces indirectly?

What type of environment will the load cell be operating in?

- A. Maximum temperature?
- B. Minimum temperature?
- C. Humidity?
- D. Contaminants, (e.g. water, oil, dirt, dust)?

What accuracy is required?

- A. Non-linearity?
- B. Hysteresis?
- C. Repeatability?
- D. Cross-talk?

TORQUE SENSOR TECHNICAL INFORMATION

PRINCIPAL OF OPERATION

All torque sensors manufactured by PCB® are strain gage based measuring instruments whose output voltage is proportional to applied torque. The output voltage produced by a resistance change in strain gages that are bonded to the torque sensor structure. The magnitude of the resistance change is proportional to the deformation of the torque sensor and therefore the applied torque.

The four-arm Wheatstone Bridge configuration shown in **Figure 1** depicts the strain gage geometry used in the torque sensor structures. This configuration allows for temperature compensation and cancellation of signals caused by forces not directly applied about the axis of the applied torque.

A regulated 5 to 20 volt excitation is required and is applied between points A and D of the Wheatstone bridge. When torque is applied to the transducer structure the Wheatstone bridge becomes unbalanced, thereby causing an output voltage between points B and C. This voltage is proportional to the applied torque.

Series 2300 reaction torque sensors have the wiring code illustrated in **Figure 2**. Series 4100 rotary transformer torque sensors have the wiring code illustrated in **Figure 3**.

AXIS DEFINITION

PCB® torque sensors comply with the Axis and Sense Definitions of NAS-938 (National Aerospace Standard-Machine Axis and Motion) nomenclature and recommendations of the Western Regional Strain Gage committee.

Axes are defined in terms of a “right-handed” orthogonal coordinate system, as shown in **Figure 4**.

The principal axis of a transducer is normally the z-axis. The z-axis will also be the axis of radial symmetry or axis of rotation. In the event there is no clearly defined axis, the following preference system will be used: z, x, y.

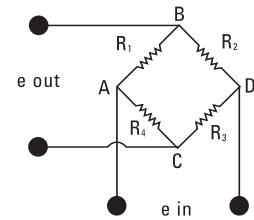


Figure 1
Wheatstone Bridge

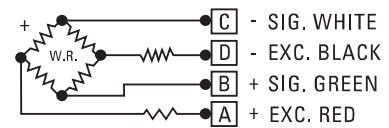


Figure 2
Series 2300 Reaction Torque Sensor Wiring Code

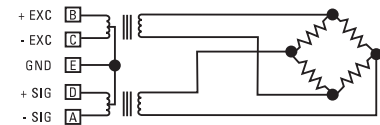


Figure 3
Series 4100 Rotary Transformer Torque Sensor Wiring Code

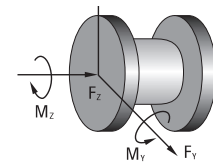


Figure 4
Right-handed Orthogonal Coordinate System

INTRODUCTION TO TORQUE SENSORS

The principal axis of a transducer is normally the z-axis. The z-axis will also be the axis of radial symmetry or axis of rotation. In the event there is no clearly defined axis, the following preference system will be used: z, x, y.

Figure 5 shows the axis and sense nomenclature for our torque sensors. A (+) sign indicates torque in a direction which produces a (+) signal voltage and generally defines a clockwise torque.

TORQUE SENSOR STRUCTURE DESIGN

Torque sensor structures are symmetrical and are typically manufactured from steel (SAE 4140 or 4340) that has been heat-treated Rc 36 to 38. Common configurations are solid circular shaft, hollow circular shaft, cruciform, hollow cruciform, solid square, and hollow tube with flats.

The solid square offers advantages over the solid circular design, especially in capacities greater than or equal to 500 in-lb (55 N-m). The solid square offers high bending strength and ease of application of strain gages. Torque sensors with capacities less than 500 in-lb (55 N-m) are usually of the hollow cruciform type. The hollow cruciform structure produces high stress at low levels of torque, yet has good bending strength. Common configurations are shown in **Figure 6**.

A variety of end configurations are available, including: keyed shaft, flange, and spline. (See below).



Keyed Shaft



Spline Drive

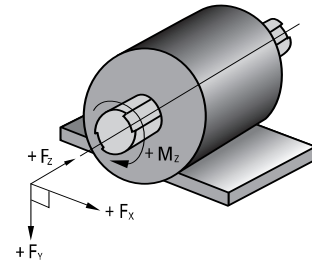


Figure 5

Axis and Sense Nomenclature for Torque Sensors

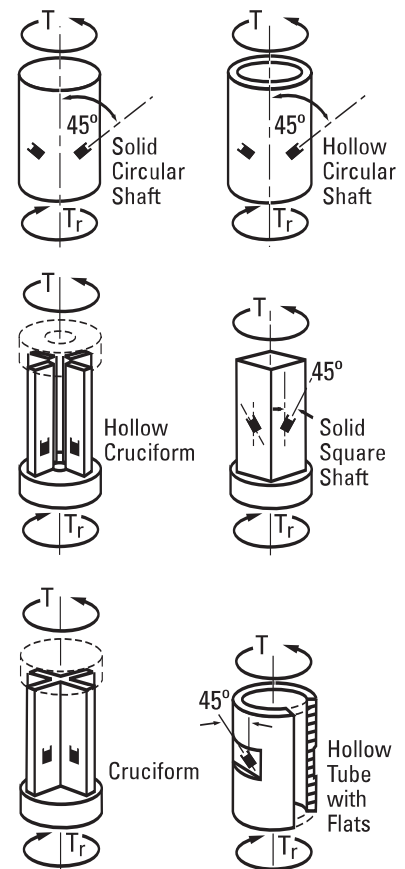


Figure 6

Common Torque Sensor Configurations

REACTION TORQUE SENSORS

Typical reaction torque sensor applications include:

- Bearing friction
- Automotive brake testing
- Starter testing
- Axle torsion test
- Stepping switch torque

Reaction torque is the turning force or moment, imposed upon the stationary portion of a device by the rotating portion, as power is delivered or absorbed. The power may be transmitted from rotating member to stationary member by various means, such as the magnetic field of a motor or generator, brake shoes or pads on drums or rotors, or the lubricant between a bearing and a shaft. Thus, reaction torque sensors become useful tools for measuring properties such as motor power, braking effectiveness, lubrication, and viscosity.

Reaction torque sensors are suitable for a wide range of torque measurement applications, including motor and pump testing. Due to the fact that these sensors do not utilize bearings, slip-rings, or any other rotating elements, their installation and use can be very cost effective. Reaction torque sensors are particularly useful in applications where the introduction of a rotating inertia due to a rotating mass between the driver motor and driven load is undesirable. An example of this can be found in small motor testing, where introduction of a rotating mass between the motor and load device will result in an error during acceleration. For these applications, the reaction torque sensor can be used between the driver motor, or driven load, and ground. An added benefit is that such an installation is not limited in RPM by the torque sensor. PCB® manufactures reaction torque sensors with capacities ranging from a few inch ounces to 200k in-lb (22.5k N-m), in configurations including keyed shaft and flange.

ROTARY TORQUE SENSORS

Typical rotary torque sensor applications include:

- Chassis dynamometer
- Blower or fan testing
- Clutch testing
- Efficiency testing
- Engine dynamometer
- Small motor / pump testing

Rotating torque sensors are similar in design and in application to reaction torque sensors, with the exception that the torque sensor is installed in-line with the device under test. Consequently, the torque sensor shaft rotates with the device under test. In PCB® Series 4100 models, the rotating torque sensor shaft is supported in a stationary housing by two bearings. Signal transfer between the rotating torque sensor shaft and the stationary housing is accomplished by means of rotary transformers.

ROTARY TRANSFORMERS

Rotary Transformers provide a non-contact means of transferring signals to and from the rotating torque sensor structure. Rotary transformers are similar to conventional transformers, except that either the primary and secondary winding is rotating. For rotating torque sensors, two rotary transformers are used. One serves to transmit the excitation voltage to the strain gage bridge, while the second transfers the signal output to the non-rotating part of the transducer. Thus no direct contact is required between the stationary and rotating elements of the transducer (see **Figure 7**).

Rotary transformers are made up of a pair of concentrically wound coils, with one coil rotating within or beside the stationary coil. The magnetic flux lines are produced by applying a time varying voltage (carrier excitation) to one of the coils (see **Figure 8**).

Figure 9 depicts a typical rotary transformer torque sensor:

Transmission of energy through any transformer requires that the current be alternating. A suitable signal conditioner with carrier excitation in the range of 3,200 to 5,000 Hz is required to achieve this.

MECHANICAL INSTALLATION OF KEYED SHAFT TORQUE SENSORS

Proper installation must be observed when assembling a torque sensor into a driveline. Careful selection of components must be made so that problems are not created which could lead to part failure or danger to personnel.

SHAFT MISALIGNMENT

Provision must be made to eliminate the effects of bending and end loading on the torque sensors shaft due to parallel offset of shafts, angular misalignment, and shaft end float. The proper use of couplings can reduce these problems to a negligible level.

All shafts must first be aligned mechanically, as accurately as possible, to lessen the work the couplings must do. Alignment within 0.001 inch per inch of shaft diameter is normally satisfactory, however, for some critical applications such as high speed, this level of alignment is not acceptable, and a tighter tolerance must be achieved. Please contact our factory, or your coupling vendor, for information regarding your application.

TORQUE SENSOR WITH FOOT-MOUNTED HOUSING INSTALLATION

A foot-mounted torque sensor has a plate on its housing, which can be securely attached to a machine base or bedplate. This installation reduces the mass in suspension on the couplings and can increase the shaft's critical speed, if the torque sensor is within its speed rating. Normally, if both the driving and load sources are fully bearing-supported in foot-mounted housings, and the torque sensor housing is foot-mounted, double-flex couplings should be used on each shaft end. Double-flex couplings provide for two degrees of freedom, meaning they can simultaneously allow for angular and parallel misalignment, and reduce the effects of bending on the torque sensor shaft. Half of each coupling weight is supported on the torque sensor's shaft, and the other half is carried by the driving and load shafts.

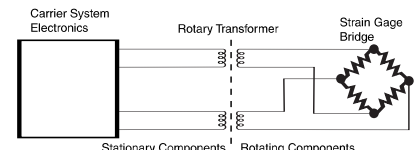


Figure 7

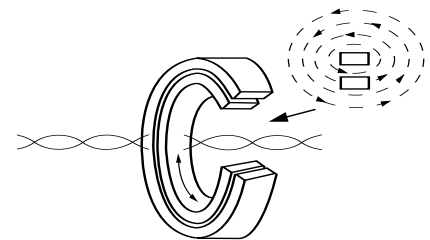


Figure 8

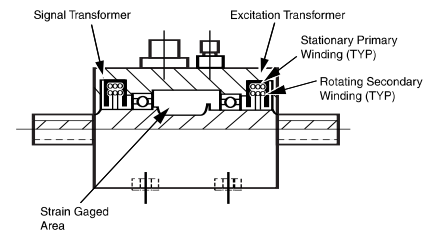


Figure 9

Rotary Transformer Torque Sensor Diagram

TORQUE SENSOR WITH FLOATING SHAFT INSTALLATION

A floating shaft torque sensor does not have a foot-mount plate on the housing, nor is the housing affixed to a bedplate in any other fashion. It depends on being carried by the driver and load shafts for its support. The housing, which is meant to remain stationary and not rotate with the shaft, must be restrained from rotating with a conductive flexible strap. Tapped threaded holes are provided on the side of the housing for this purpose. The other end of the strap is bolted to a bedplate or other stationary-grounded member, which will electrically ground the torque sensor housing to the electrical system ground.

Therefore, with the floating shaft, there is just one degree of freedom between each shaft end of the torque sensor and the adjacent mating shaft, which is bearingsupported (driver and load shafts) on the bedplate. Consequently, a single flex coupling is required at each end of the torque sensor.

ERROR ANALYSIS

PCB® typically supplies accuracy information on its products in the form individual errors. They are non-linearity, hysteresis, non-repeatability, effect of temperature on zero unbalance, and effect of temperature on output.

The customer can combine these individual errors to establish the maximum possible error for the measurement, or just examine the applicable individual error. If the temperature remains stable during the test, the temperature related errors can be ignored. If the sensor is used for increasing load measurement only, ignore the hysteresis error. If the load measurement is near the full capacity, the linearity error can be ignored. If the capability exists to correct the data through linearization-fit or a look-up-table, the error in the measurement can be minimized. A sophisticated user can get rid of all the errors except for the non-repeatability error in the measurement.

Often overlooked by the customer is error due to the presence of non-measured forces and bending moments. Even though the single axis of measurement sensors are designed and built to withstand these non-measured forces and bending moments(extraneous loads), the errors due to them are present. The user can design the set-up to eliminate or minimize these extraneous loads. However, if these extraneous loads are present, the errors due to them should be considered.

APPLICATION QUESTIONNAIRE

Determine the capacity required

- A. What is the maximum expected torque, including transients?
- B. What is the minimum expected torque?
- C. What is the typical expected torque?
- D. What are the dynamics of the system, (i.e. frequency response?)
- E. What are the maximum extraneous loads to which the torque sensor will be subjected?

How will the torque sensor be integrated into the system?

- A. What are the physical constraints, (e.g. length, diameter)?
- B. Will the torque sensor be foot-mounted or floated?
- C. Couplings, torsionally stiff, or torsionally soft?

What type of environment will the load cell be operating in?

- A. Maximum temperature?
- B. Minimum temperature?
- C. Humidity?
- D. Contaminants, (e.g. water, oil, dirt, dust)?

What speed will the torque sensor be required to rotate?

- A. What length of time will the torque sensor be rotating, and at what speed?

GLOSSARY OF TERMS

Accuracy	<p>Stated as a limit tolerance, which defines the average deviation between the actual output versus theoretical output.</p> <p>In practical transducer applications, the potential errors of non-linearity, hysteresis, non-repeatability and temperature effects do not normally occur simultaneously, nor are they necessarily additive.</p> <p>Therefore, accuracy is calculated based upon RMS value of potential errors, assuming a temperature variation of ± 10 °F (± 5.5 °C), full rated load applied, and proper set-up and calibration. Potential errors of the readout, cross-talk, or creep effects are not included.</p>
Ambient Conditions	<p>The conditions (humidity, pressure, temperature, etc.) of the medium surrounding the transducer.</p>
Ambient Temperature	<p>The temperature of the medium surrounding of transducers.</p>
Calibration	<p>The comparison of transducer output against standard test loads.</p>
Calibration Curve	<p>A record (graph) of the comparison of transducer output against standard test loads.</p>
Combined Error (Non-linearity and Hysteresis)	<p>The maximum deviation from a straight line drawn between the original no-load and rated load outputs expressed as a percentage of the rated output and measured on both increasing and decreasing loads.</p>
Compensation	<p>The utilization of supplementary devices, materials, or processes to minimize known sources of error.</p>
Creep	<p>The change of transducer output occurring with time, while under load, and with all environmental conditions and other variables remaining constant.</p> <p>Note: Usually measured with rated load applied and expressed as a percent of rated output over a specific period of time.</p>
Creep Recovery	<p>The change in no-load output occurring with time, after removal of a load, which has been applied for a specific period of time.</p>
Cross-Talk	<p>With one component loaded to capacity, and the other unloaded, the output of the unloaded component will not exceed the percentage specified of its full-scale capacity.</p>
Deflection	<p>The change in length along the primary axis of the load cell between no-load and rated load conditions.</p>
Drift	<p>A random change in output under constant load conditions.</p>
Error	<p>The algebraic difference between the indicated and true value of the load being measured.</p>
Excitation, Electrical	<p>The voltage or current applied to the input terminals of the transducer.</p>
Fatigue Capacity	<p>Capacity as percentage of the nominal load limit capacity, and based on 100×10^6 cycles (minimum) from zero to full fatigue capacity and 50×10^6 cycles (minimum) from full fatigue capacity tension to full fatigue capacity compression load.</p>

Hysteresis	<p>The maximum difference between the transducer output readings for the same applied load, one reading obtained by increasing the load from zero and the other by decreasing the load from rated load.</p> <p>Note: Usually measured at half rated output and expressed in percent of rated output. Measurements should be taken as rapidly as possible to minimize creep.</p>
Insulation Resistance	<p>The DC resistance measured between the transducer circuit and the transducer structure.</p> <p>Note: Normally measured at 50 Volts DC and under standard test conditions.</p>
Natural Frequency	<p>The frequency of free oscillations under no-load conditions.</p>
Nominal Load Limit Capacity	<p>It is the designed normal maximum capacity of a transducer. Output sensitivity of the transducer is based on this capacity unless specified.</p>
Non-linearity	<p>The maximum deviation of the calibration curve from a straight line drawn between the no load and rated load output, expressed as a percentage of the rated output and measured on increasing load only.</p>
Output	<p>This signal (voltage, current, etc.) produced by the transducer.</p> <p>Note: Where the output is directly proportional to excitation, the signal must be expressed in terms of volts per volt, volts per ampere, etc., of excitation.</p>
Output, Rated	<p>The algebraic difference between the outputs at no-load and at rated load.</p>
Overload Rating	<p>The maximum load in percent of rated capacity, which can be applied without producing a permanent shift in performance characteristics beyond those specified.</p>
Primary Axis	<p>The axis along which the transducer is designed to be loaded; normally its geometric centerline.</p>
Rated Capacity (Rated Load)	<p>The maximum axial load that the transducer is designed to measure within its specifications.</p>
Repeatability	<p>The maximum difference between transducer output readings for repeated loading under identical loading and environmental conditions.</p>
Resolution	<p>The smallest change in mechanical input, which produces a detectable change in the output signal.</p>
Sensitivity	<p>The ratio of the change in output to the change in mechanical input.</p>
Shunt Calibration	<p>Electrical simulation of transducer output by insertion of known shunt resistors between appropriate points within the circuitry.</p>
Shunt-to-load Correlation	<p>Electrical simulation of transducer output by insertion of known shunt resistors between appropriate points within the circuitry.</p>

Standard Test Conditions	<p>The environmental conditions under which measurements should be made, when measurements under any other conditions may result in disagreement between various observers at difference times and places. These conditions are a follows:</p> <p>Temperature 72 °F ± 3.6 °F (23 °C ± 2 °C) Relative Humidity: 90% or less Barometric Pressure: 28 to 32 inch Hg</p>
Static Extraneous Load Limits	<p>Static Extraneous Load Limits are calculated such that only one extraneous load (Fx or Fy or Mx or My or Mz) can be applied simultaneously with 50% of the nominal load limit applied.</p>
Temperature Effect on Output	<p>Temperature Effect on Output — The change in output due to a change in transducer temperature.</p> <p>Note: Usually expressed as a percentage of load reading per degree Fahrenheit change in temperature.</p>
Temperature Effect on Zero Balance	<p>The change in zero balance due to a change in transducer temperature.</p> <p>Note: Usually expressed as the change in zero balance in percent of rated output per degrees Fahrenheit (change in temperature).</p>
Temperature Range, Compensated	<p>The range of temperature over which the transducer is compensated to maintain rated output and zero balance within specified limits.</p>
Temperature Range, Usable	<p>The extremes of temperature within which the transducer will operate without permanent adverse change to any of its performance characteristics.</p>
Terminal Resistance	<p>The resistance of the transducer circuit measured at specific adjacent bridge terminals at standard temperature, with no-load applied, and with the excitation and output terminals open-circuited.</p>
Terminal Resistance, Excitation	<p>The resistance of the transducer circuit measured at the excitation terminals, at standard temperature, with no-load applied, and with the output terminals open-circuited.</p>
Terminal Resistance, Signal	<p>The resistance of the transducer circuit measured at the output signal terminals, at standard temperature, with no-load applied, and with the excitation terminals open-circuited.</p>
Traceability	<p>The step-by-step transducer process by which the transducer calibration can be related to primary standards.</p>
Zero Balance	<p>The output signal of the transducer with rated excitation and with no-load applied, usually expressed in percent of rated output.</p>
Zero Return	<p>The difference in zero balance measured immediately before rated load application of specified duration and measured after removal of the load, and when the output has stabilized.</p>
Zero Shift, Permanent	<p>A permanent change in the no-load output.</p>
Zero Stability	<p>The degree to which the transducer maintains its zero balance with all environmental conditions and other variables remaining constant.</p>



3425 Walden Avenue, Depew, NY 14043 USA

pcb.com | info@pcb.com | 800 828 8840 | +1 716 684 0001

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