



Load Cell Handbook

A Technical Overview and Selection Guide



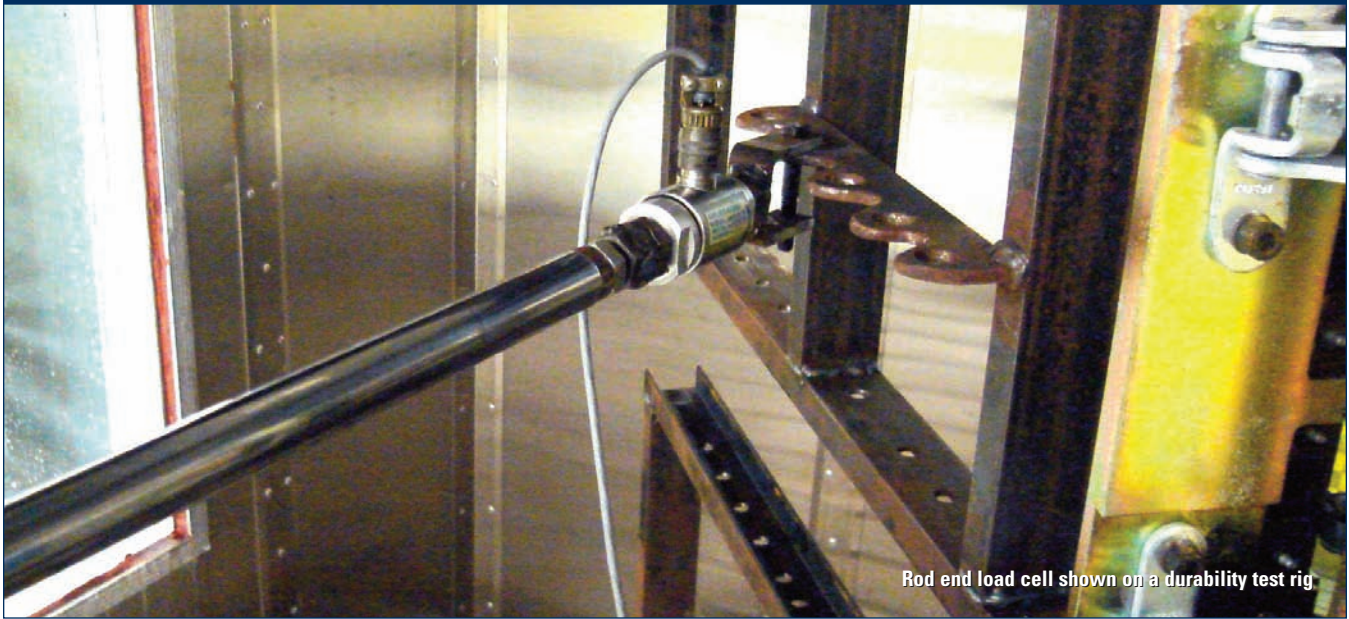
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Load Cell Handbook

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Rod end load cell shown on a durability test rig

Introduction

This handbook is intended to be a guide for test engineers, lab managers and test technicians who use load cells for test and measurement applications for dynamometer testing, hydraulics testing, and suspension and transmission testing, to name a few.

This guide will provide an overview of strain gage technology and load cell anatomy – including a description of the different types of load cells – and give instruction on how to select the right load cell for an application.

Typical Applications

- Materials Testing
- Component Life Cycle Testing
- Structural Testing
- Press Applications
- Full Vehicle Durability Testing
- Torque Arm
- Weighing
- Quality Control





Overview of Load Cell Technology

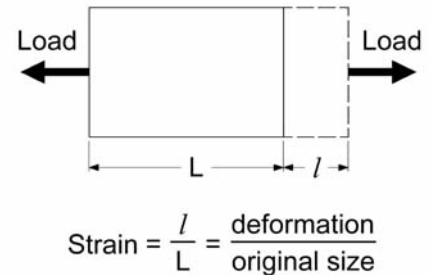


A load cell is a device that converts a force or load into a measureable output. Load cells can come in multiple styles including hydraulic, pneumatic, strain gage, piezoelectric, and capacitance, but the scope of this handbook will be strain gage load cells. Strain gage load cells are the most common and are defined as a device that converts a force or load into an equivalent electrical signal or digitized load value.

Strain gage load cells are designed for precisely measuring a static weight or quasi-dynamic load or force. The force applied is translated into a voltage by the resistance change in the strain gages, which are intimately bonded to the transducer structure. The amount of change in resistance correlates to the deformation in the transducer structure and hence the load applied (See Figure 1).

General purpose load cells include low profile, canister, rod-end, S-type, fatigue rated low profile and dual-bridge load cells. They are generally used in automotive, aerospace, industrial and process control applications.

General purpose load cells are suitable for a wide range of routine static force measurement applications, including weighing, structural testing and material testing machines. Fatigue-rated versions are designed for fatigue testing machines and applications where high cyclic loads are present. A high-quality fatigue-rated load cell should be compensated to minimize the effects of temperature and barometric pressure changes as well as applied extraneous loads. It should also be resistant to fatigue failure for about 100 million fully reversed cycles.



Strain Gage Basics

When a load is applied to an object, the object will be deformed a certain amount. The amount of deformation the object experiences is based on the size and material of the object as well as the size of the load applied. The ratio of the deformation of the object to the original size of the object is known as strain.

Strain gages are resistors that change their resistance proportional to load as they are deformed. They consist of a pattern of resistive foil mounted on a backing material (See Figure 2). Strain gages that are properly bonded to an object will deform as the object does when a load is applied. As the gage stretches, its resistance increases, and as it compresses, its resistance decreases. The amount of change in resistance indicates the magnitude of deformation.

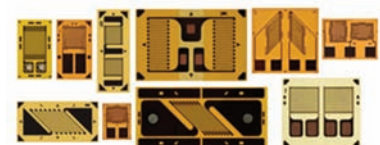


Figure 2: Strain Gages



Wheatstone Bridge

Many load cells use strain gages in a four-arm Wheatstone bridge configuration, which acts as an adding and subtracting electrical network. The Wheatstone bridge allows for compensation of temperature effects, as well as cancellation of signals caused by extraneous forces. These circuits consist of a full four-arm bridge of at least one precision strain gage per arm. A regulated 5 to 20 volt DC or AC rms excitation is required to power the bridge.

A simplified version of a strain gage load cell using the Wheatstone bridge is depicted in Figure 3. The Wheatstone bridge is shown in Figure 4. The strain gages used in the Wheatstone bridge all have the same resistance value creating a balanced bridge when no load is applied. When a load is applied to the load cell, the strain gages deform, which changes their resistance, creating a bridge that is unbalanced, causing an output voltage that is proportional to the applied load.

The load applied to the load cell in Figure 3 causes the tension gages (T1 and T2) to stretch and the compression gages (C1 and C2) to compress. An output voltage will then be sent through the signal lead wires (+S and -S) to a signal conditioner to transform the output voltage into a force value (Lb, N, kg, etc.).

Factors such as temperature, the length of wire used to complete the circuit, and gage placement have an effect on the resistance in the bridge, creating an error in the measured values. In precision load cells, these effects are compensated by adding resistance to the bridge.

Many load cells follow a wiring code established by the Western Regional Strain Gage committee as revised in May 1960. The code is illustrated in Table 1.

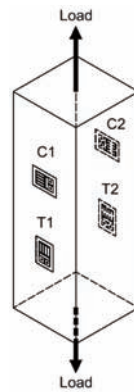


Figure 3: Model of Strain Gage Load Cell

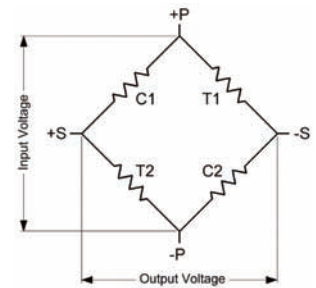


Figure 4: Wheatstone Bridge

Pin	Description	Wire Color
A	+ Excitation (+P)	Red
B	+ Signal (+S)	Green
C	- Signal (-S)	White
D	- Excitation (-P)	Black

Table 1: Western Regional Wiring Code



Overview of Load Cell Technology

Output & Sensitivity

The output of a strain gage load cell is expressed in terms of mV/V. Therefore the output of a load cell is referred to as ratiometric, where the output is directly proportional to the input. For example, a load cell with a 2 mV/V output with a 10 volt excitation applied results in an raw output of 20 mV at the defined capacity of given load cell. Most manufactures specify load cell outputs between 1.0 and 5.0 mV/V, which is dependent on the gage factor and the operating stress (psi) of the load cell structure, although 2 mV/V is most common.

The quality of the resultant load cell signal is dependent on several factors including:

1. A well regulated excitation (typically 10 volts)
2. Quality cable with two shielded twisted pairs and a drain
3. Instrumentation grade amplifier

In most cases a strain gage signal conditioner is required to provide the regulation excitation and condition/amplify the signal to a useable +/- 5 or +/- 10 volts. A wide range of configurations are available including models with a built-in scalable display.

Sensitivity in terms of mV/engineering units (such as pounds or Newtons) are not used by load cell manufacturers due to the ratiometric nature of strain gage load cells. However it's often useful to the end user to express the output of a load cell in terms of sensitivity. This can be easily calculated based on the output and capacity of the load cell.

Here are some examples:

1. A 1,000 pound capacity load cell with a 2 mV/V output and 10 volt excitation: (2 mV/V x 10)/1,000) or 0.02 mV/lb.
2. A 1,000 pound capacity load cell used with a signal conditioner scaled for a 10 volts (10,000 mV) output at 1,000 pounds: (10,000 mV/1000) or 10 mV/pound

The value of a strain gage signal conditioner becomes very clear when you consider the difference between a sensitivity of 0.02 mV/pound or 10 mV/pound. Using a signal conditioner, you can select the higher sensitivity. Consequently most load cells manufacturers offer a full range of signal conditioners in order to obtain the best measurement results.

Axis Definition

Most 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. A (+) sign indicates force in a direction which produces a (+) signal voltage and generally defines a tensile force. The primary axis of rotation or axis of radial symmetry of a load cell is the z-axis, as defined in Figure 5.

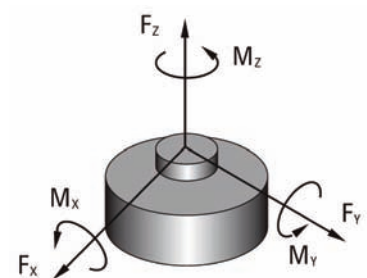


Figure 5: "Right Handed" Orthogonal Coordinate System



Load Cell Anatomy

The most critical mechanical component in any strain gage based sensor is the “spring element.” In general terms, the spring element serves as the reaction to the applied force, load, or weight and focuses it into a uniform, calculated strain path for precise measurement by the bonded strain gage. Three common structure designs used in the industry are bending beam, column, and shear.

Bending Beam

Sensor spring elements that employ the bending beam structure design are the most common. This is because the bending beam is typically a high-strain, low force structural member that offers two equal and opposite surfaces for strain gage placement. The bending beam design is typically used in lower capacity load cells (See Figure 6).

Column

The column type load cell is the earliest type of strain gage transducer (See Figure 7). Although simple in its design, the column spring element requires a number of design and application considerations. The column should be long enough with respect to its cross section so that a uniform strain path will be applied to the strain gage. When using this type of sensor, the end user must beware of second order effects as the column load cell is susceptible to the effects of off-axis loading. When using these load cells in applications where sensitivity to side-loading needs to be minimized, it is a good idea to find a model with an internal spherical design which will allow for a greater degree of off-axis loading.

Shear-Web

Shear web load cells are typically cantilever beams. This design minimizes load deflection. Under this condition, the surface strain along the top of the beam would be too low to produce an adequate electrical output from the strain gage. However, if the strain gages are placed on the sides of the beam at the neutral axis where the bending stress is zero, the state of stress on the beam side is one of pure shear, acting in the vertical and horizontal direction (See Figure 8).

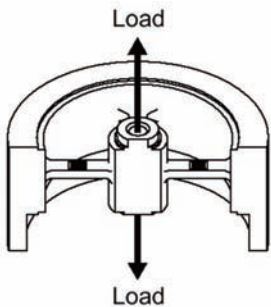


Figure 6: Bending Beam Load Cell



Figure 7: Column Load Cell

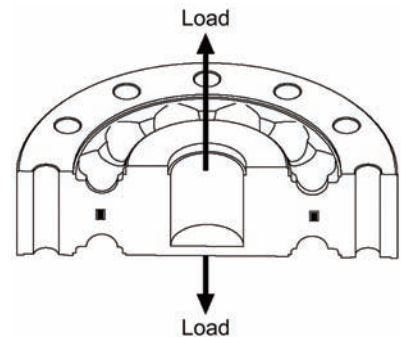


Figure 8: Shear Web Load Cell



Load Cell Classification



Most load cells are classified as general purpose, fatigue rated, or special application. Sometimes load cell suppliers will also work with you to create customized solutions for unique application needs that widely used stock products can't meet.

General Purpose

The general purpose load cell, as the name implies, is designed to be utilitarian in nature. These versatile load cells are commonly used for calibration references, manual applications, and applications that require slower cycling. Within the general purpose load cell market there are several distinct categories: precision, universal, weigh scale, to name a few. These types of load cells are often selected because they are usually the least expensive.

Fatigue Rated Load Cells

Fatigue rated load cells are designed for component durability and fatigue test machines where highly cyclical loading is present. These rugged load cells are extremely resistant to extraneous bending and side loading forces. They are used for material testing, component life cycle testing, and structural testing. Most suppliers guarantee these load cells for 100 million cycles.

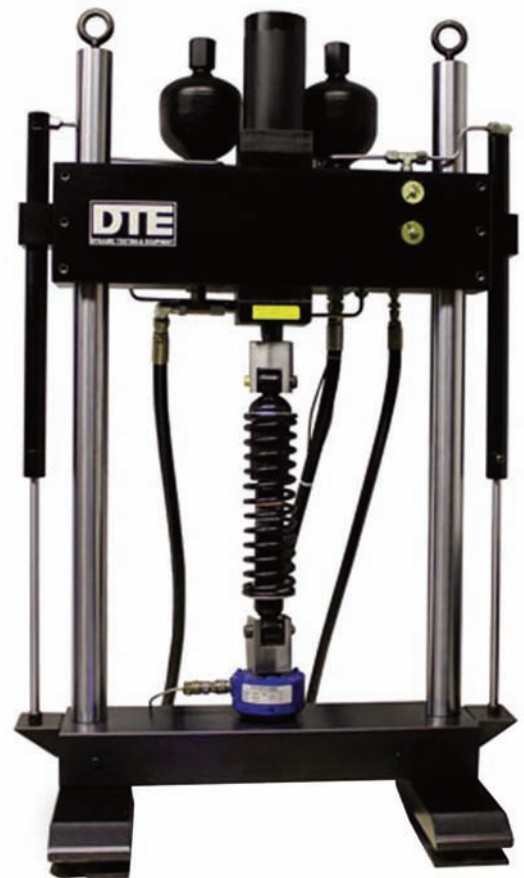
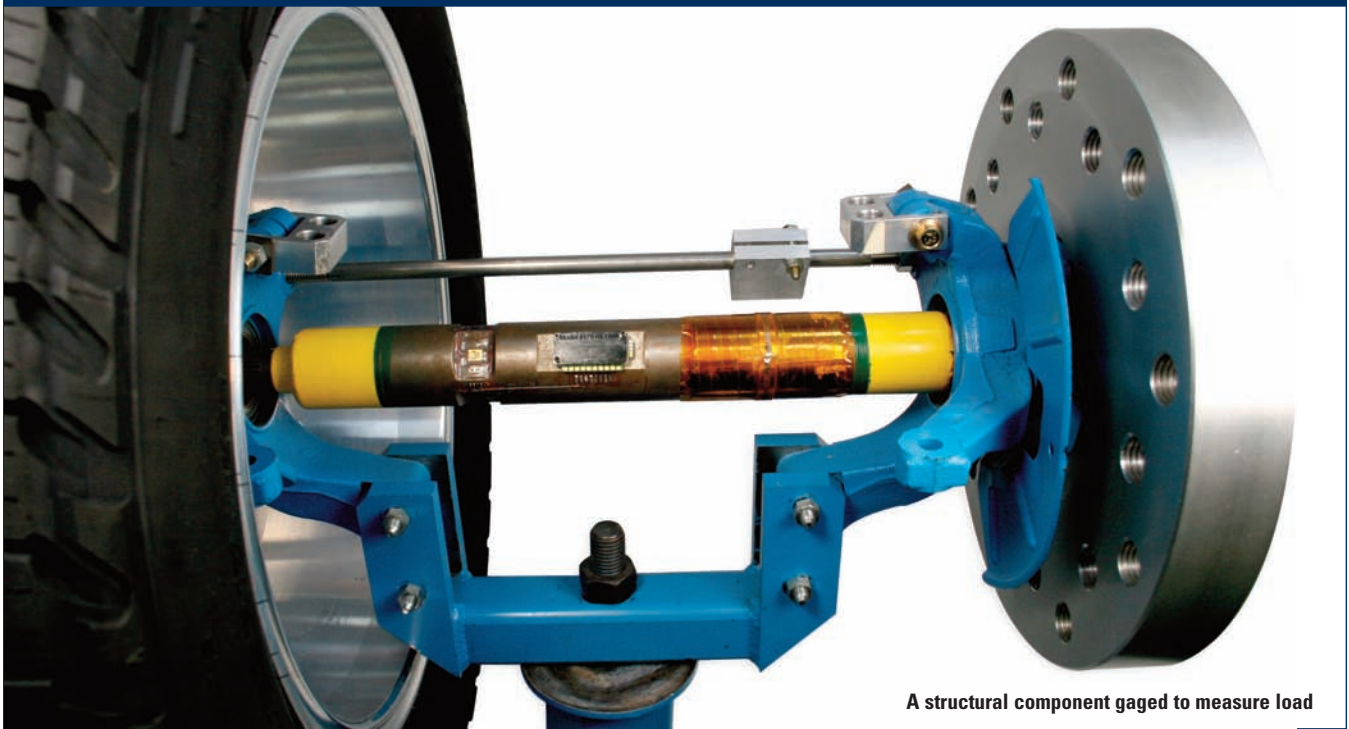


Photo courtesy of Dynamic Testing



A structural component gaged to measure load

Special Applications

Special application load cells are load cells that have been designed for a very specific force measurement task. Special application load cells can be single- or multi-axis. There are a wide range of special application load cells especially for the automotive market, such as:

- Pedal Effort
- Crash Barrier
- Bumper Impact
- Tire Test
- Hand Brake
- Skid Trailer
- Steering Column
- Road Simulator
- Horse Clamp



Pedal Effort Load Cell

Customized Solutions

General purpose load cells are quite versatile, but every so often, test engineers have unique application needs that are not met by the industry-standard models and specifications. Some companies will create custom solutions such as instrumenting customer-supplied bolts for thrust load measurements, or "transducerizing" which means taking a structural component of a system and gaging it to measure load (for example, drive shafts using telemetry for wireless data collection).





Application Guide: Choosing the Right Load Cell for the Job



There are many different types of load cells on the market which are designed for certain uses. Here is an overview of the different types and their specific applications.

Rod End Load Cells

Need to perform load tests in small areas within the vehicle? Rod end load cells are a good choice for durability and reliability testing, in-vehicle load measurements, test rigs, and in-line test and weighing applications— especially for testing in small spaces, like in-line with vehicle tie rods, and instances where sensitivity to side loading needs to be minimized.



CE **Figure 11: Rod End Load Cells**

S-Type Load Cells

S-type load cells are side-mounted strain gage-based sensors used for weighing and general force measurement applications. It is a good idea to select one with a long strain-relieved integral cable with pigtail leads that are stripped and tinned for electrical interface. These load cells are most commonly used for light structural performance testing on automotive systems such as doors, hoods and trunks, and automotive lifecycle testing on components such as hinges, latches and handles, bushings and springs, and seatbacks. These are a good choice when you need a low-cost, high performance load cell.



CE **Figure 12: S-Type Load Cells**

Canister Load Cells

Canister load cells are typically used for weighing, quality control, dynamometers, tactile forces, and static material test machines. Canister style load cells have low mass (less than one lb.) and low capacity (25 to 300 lbs). They also include a built-in mounting base and the same thread on both sides, making them easy to install. This type of load cell is used for applications such as opening and closing car doors, auto component tests, trunk doors, and switch test stands.



CE **Figure 13: Canister Load Cells**



Fatigue rated load cells measure impact forces during automotive crash studies

Low-Profile Load Cells

Low profile load cells, sometimes referred to as “pancake load cells,” include fatigue-rated and general purpose types. They are generally offered in a wide capacity range across a few different mechanical packaging/sizes. Low-profile load cells feature an advanced structural design that makes them extremely durable and accurate.

Their greatest attribute is that they are industry-standard, so you can generally use one manufacturer’s load cell interchangeably with another’s. These load cells are also known for their overall capability to handle extraneous loads due to misalignment without mechanical failures. Low profile load cells are very “forgiving” to general mistakes made during installation (such as misalignments bending loads or “moments” and shear loads).

This type of load cell also usually comes with two installation options—with a base and without a base. To perform in a linear and predictable manner, the outside diameter of the load cell must be bolted to a flat rigid surface. To ensure that they can also be properly mounted in applications where there is no flat rigid surface, they include a factory installed base that provides a convenient threaded attachment point for easy installation and use in tension and compression. For best performance, repeatability and accuracy, it’s a good idea to select one with the base included and permanently installed.

These types of load cells are used for a wide range of general force measurement applications, including weighing, dynamometer use, and static material test machines.



Dual Bridge Load Cells

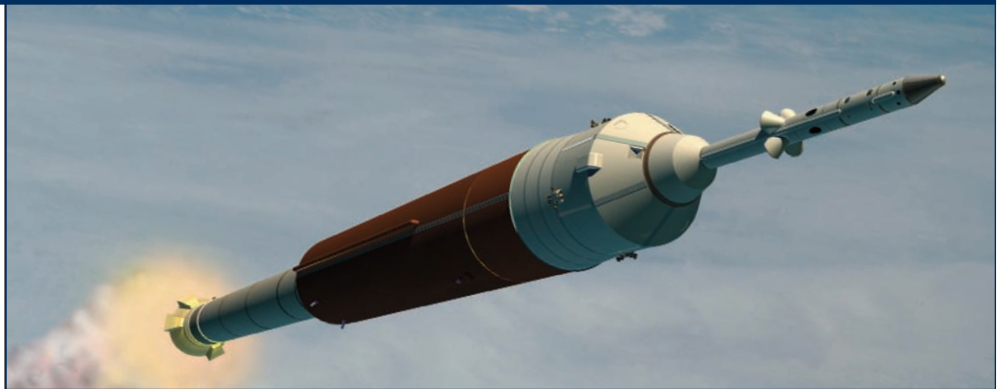
Dual bridge load cells are fatigue rated load cells that include a dual output feature that offers sensor redundancy and the ability to provide control feedback from one sensor while the other is used for data acquisition. Additional features include low deflection, high accuracy and repeatability, thermal compensation and moment compensation. Dual bridge load cells are most often used in aerospace and defense testing, where one output controls the test stand/process, and the other output for data recording.





Application Selection

When deciding which type of load cell you need, consider the following application questions to help you select the right one.



When deciding which type of load cell you need, consider the following application questions to help you select the right one.

Determine the capacity required:

- What is the maximum expected load?
- What is the minimum expected load?
- What is the typical expected load?
- What are the dynamics of the system (frequency response, voltage requirements, connector type, etc.)?
- What are the maximum extraneous loads that the load cell will be subjected to?

How will the load cell be integrated into the system:

- What are the physical constraints (height, diameter, mounting threads, etc.)?
- 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:

- What will the maximum temperature be?
- What will the minimum temperature be??
- Will there be any contaminants present (water, oil, dirt, dust, etc.)?

What accuracy is required:

- What is the non-linearity specification required?
- What is the hysteresis specification required?
- What is the repeatability specification required?
- What, if any, cross-talk specification is required (for multi-axis load cells)?
- What will the humidity be?
- Will there be any contaminants present (water, oil, dirt, dust, etc.)?

See glossary for definition of the terms above.



Dual bridge load cells in use on a life cycle test of an aircraft wing box

Error Analysis

Accuracy information for load cells is commonly reported in terms of individual errors. These errors include but are not limited to:

- Non-Linearity
- Effect of Temperature on Zero Unbalance
- Hysteresis
- Effect of Temperature on Output
- Non-Repeatability

See glossary for definition of the terms above.

Load cells are typically designed and manufactured to minimize these errors to industry standard levels. Below is a summary of the performance standards by industry.

Parameter	Typical Load Cell Performance Requirements by Market			
	Industrial	Automotive	Test & Measurement	Aerospace & Defense
Non-Linearity	0.25 % to 1%	0.1 to 1%	0.05% to 0.25%	0.04% to 0.06%
Hysteresis	0.25% to 1%	0.1 to 1%	0.05% to 0.25%	0.04% to 0.06%
Repeatability	0.1% to 0.5%	0.05% to 0.1%	0.05% to 0.02%	0.02% to 0.01%

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 is stable during the test, the temperature related errors can be ignored. If the sensor is used for increasing load measurement only, then the hysteresis error can be ignored. 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.

Often overlooked 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 extraneous loads, the errors due to them are present. The measurement engineer can design the set-up to eliminate or minimize these extraneous loads, however, if these loads are present, the errors due to them should be considered.

A typical industry-accepted means of combining individual errors is Root Sum Square, which assumes that the individual errors do not simultaneously occur.

Note: Figures 9 and 10 show exaggerated plot data to better graphically explain the load cell errors. In practice, load cell errors will appear much closer to the projected line from zero to rated output to conform to industry and specified standards. For definitions of these errors, see the Glossary of Terms section at the end of this document.

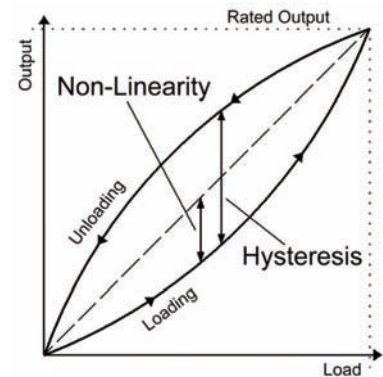


Figure 14: Non-Linearity & Hysteresis

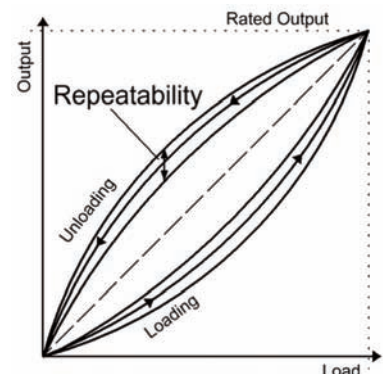


Figure 15: Repeatability



Shunt Calibration of a Strain Gage Load Cell

Shunt calibration is the known electrical unbalancing of a strain gage bridge by means of a fixed resistor that is placed, or “shunted,” across one leg of the bridge. The Wheatstone Bridge used in strain gage load cells are typically field-calibrated using the shunt calibration technique (See Figure 15).

Purpose

Shunt calibration is a method of periodically checking the gain or span of a signal conditioner, which is used in conjunction with a strain gage based transducer, without exposing the transducer to known, traceable, physical input values. If required, adjustments can then be made to the signal conditioner to insure accurate measurement results.

A strain gage bridge is “in balance” when the host mechanical structure is unloaded and unstressed. As the host structure (diaphragm, bending beam, shear beam, column, etc.) is loaded or stressed, the Wheatstone Bridge becomes unbalanced, resulting in an output signal that is proportional to the applied load.

Shunt calibration stimulates the mechanical input to a transducer by unbalancing the bridge with a fixed resistor placed across, or in parallel with, one leg of the bridge. For tension shunt calibration, the shunt resistor (R_{ST}) is shunted across the +excitation (+P) and +signal (+S) leg of the bridge. For a compression shunt calibration, the shunt resistor (R_{SC}) is shunted across the – excitation (-P) and +signal (+S) leg of the bridge.

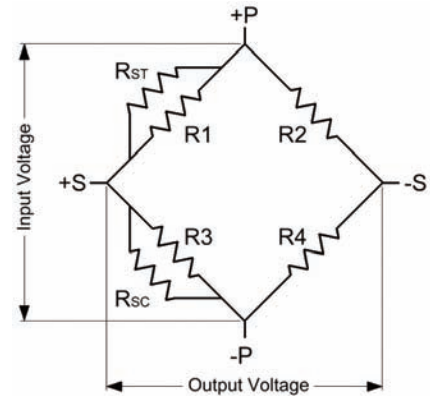


Figure 16: A Wheatstone Bridge circuit showing the location for connecting the appropriate shunt resistor for the purpose of simulating either a tension or compression input.

Method

Here are step-by-step instructions for shunt calibration of a strain gage load cell.

1. Connect the transducer to an appropriate strain gage signal conditioner and allow adequate time for the system to stabilize.
2. Apply a full-scale N.I.S.T. traceable, mechanical input (or load) to the transducer.
3. Adjust the signal conditioner’s gain or span controls, as required, to obtain a full-scale electrical output signal, and/or numeric display that represents the applied, mechanical input quantity.
4. Remove the mechanical input (or load).
5. Place a shunt calibration resistor across an appropriate leg of the Wheatstone Bridge (as discussed above).
6. Record the value of the signal conditioner’s output signal and/or numeric display. This value is the shunt calibration value, or equivalent load.
7. It is important to note that the shunt calibration value is specific for the particular shunt resistor used. This value, and the particular resistor, are now matched to the transducer and form the basis of the transferable shunt calibration.

Summary

Shunt calibration is accepted throughout the industry as means of periodic calibration of a signal conditioner and transducer between calibrations of known, applied, traceable, mechanical, input values. Consequently, most all strain gage transducer manufacturers collect and supply shunt calibration data, along with a shunt calibration resistor, as a standard feature.



Glossary of Terms

Accuracy: Stated as a limit tolerance, which defines the average deviation between the actual output versus theoretical output.

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.

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.

Ambient Conditions: The conditions (humidity, pressure, temperature, etc.) of the medium surrounding the transducer.

Ambient Temperature: The temperature of the medium surrounding of transducers.

Calibration: The comparison of transducer output against standard test loads.

Calibration Curve: A record (graph) of the comparison of transducer output against standard test loads.

Combined Error: (non-linearity and hysteresis) 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.

Compensation: The utilization of supplementary devices, materials, or processes to minimize known sources of error.

Creep: The change of transducer output occurring with time, while under load, and with all environmental conditions and other variables remaining constant.

Note: Usually measured with rated load applied and expressed as a percent of rated output over a specific period of time.

Creep Recovery: The change in no-load output occurring with time, after removal of a load, which has been applied for a specific period of time.

Cross-Talk: 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.

Deflection: The change in length along the primary axis of the load cell between no-load and rated load conditions.

Drift: A random change in output under constant load conditions.

Error: The algebraic difference between the indicated and true value of the load being measured.

Excitation, Electrical: The voltage or current applied to the input terminals of the transducer.

Fatigue Capacity: Capacity as percentage of the nominal load limit capacity, and based on 100 X 10⁶ cycles (minimum) from zero to full fatigue capacity and 50 X 10⁶ cycles (minimum) from full fatigue capacity tension to full fatigue capacity compression load.

Full Scale: The designed upper operating limit of a given transducer in engineering units (pounds, grams, kilograms, or Newtons)

Hysteresis: 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.

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.

Insulation Resistance: The DC resistance measured between the transducer circuit and the transducer structure.

Note: Normally measured at 50 Volts DC and under standard test conditions.

Natural Frequency: The frequency of free oscillations under no load conditions.

Kip: A non-SI unit of force. It equals 1000 pounds-force.

Nominal Load Limit Capacity: It is the designed normal maximum capacity of a transducer. Output sensitivity of the transducer is based on this capacity unless specified.

Non-linearity: 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.

Output: This signal (voltage, current, etc.) produced by the transducer.

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.

Output, Rated: The algebraic difference between the outputs at no-load and at rated load.

Overload Rating: The maximum load in percent of rated capacity, which can be applied without producing a permanent shift in performance characteristics beyond those specified.

Primary Axis: The axis along which the transducer is designed to be loaded; normally its geometric centerline.

Rated Capacity (Rated Load): The maximum axial load that the transducer is designed to measure within its specifications.

Repeatability: The maximum difference between transducer output readings for repeated loading under identical loading and environmental conditions.

Resolution: The smallest change in mechanical input, which produces a detectable change in the output signal.

Sensitivity: The ratio of the change in output to the change in mechanical input.

Shunt Calibration: Electrical simulation of transducer output by insertion of known shunt resistors between appropriate points within the circuitry.

Shunt-to-load Correlation: The difference in output readings obtained through electrically simulated and actual applied loads.

Standard Test Conditions: The environmental conditions under which measurements should be made, when measurements under any other conditions may result in disagreement between various observers at different times and places. These conditions are as follows:

Temp: 72 °F ± 3.6 °F (23 °C ± 2 °C)

Relative Humidity: 90% or less

Barometric Pressure: 28-32 inch Hg

Static Extraneous Load Limits: 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.

Temperature Effect on Output: The change in output due to a change in transducer temperature.

Note: Usually expressed as a percentage of load reading per degree Fahrenheit change in temperature.

Temperature Effect on Zero Balance: The change in zero balance due to a change in transducer temperature.

Note: Usually expressed as the change in zero balance in percent of rated output per degrees Fahrenheit (change in temperature).

Temperature Range, Compensated: The range of temperature over which the transducer is compensated to maintain rated output and zero balance within specified limits.

Temperature Range, Usable: The extremes of temperature within which the transducer will operate without permanent adverse change to any of its performance characteristics.

Terminal Resistance: 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.

Terminal Resistance, Excitation: 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.

Terminal Resistance, Signal: 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.

Traceability: The step-by-step transducer process by which the transducer calibration can be related to primary standards.

Zero Balance: The output signal of the transducer with rated excitation and with no-load applied, usually expressed in percent of rated output.

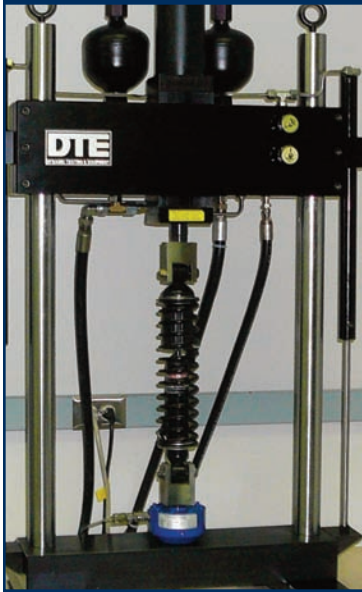
Zero Return: The difference in zero balance measured immediately before rated load application of specified duration and measured after removal of the load, and when the output has stabilized.

Zero Shift, Permanent: A permanent change in the no-load output.

Zero Stability: The degree to which the transducer maintains its zero balance with all environmental conditions and other variables remaining constant.



LOAD CELL HANDBOOK



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