Load Cells

Introduction and Applications

White paper

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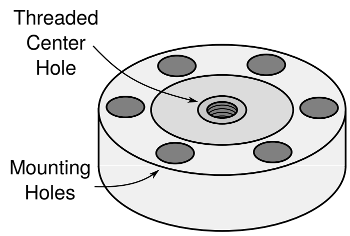

Figure 1: Pancake Load Cell

1 Introduction

Many disciplines require the measurement of the force being applied against a physical object. One tool commonly applied to such measurement is the *load cell*.

A load cell usually is in the form of a properly shaped and sized piece of material, often a form of metal, to which the force is applied. The distortions to this material caused by the force may be measured by attached strain gauges, piezoelectric elements, or other methods. The material's shape and elasticity determine the output response, which may be balanced or adjusted to counteract effects such as temperature or lead run. This signal is then amplified for further processing. [22, secs. 3.4, 4.1-4.2]

Factors affecting the selection and application of load cells include relative size and cost, direction of force, range of measurement, vibration or signal noise, frequency of oscillation, temperature changes, fatigue, and the use in underwater, explosive, or other special environments.

2 Common load cells

2.1 Shapes and applications

See figs. 1 to 6 for examples of load cell shapes.

Load cells are used in many applications [22, sec. 5], including:

Product development: Testing materials and components, measuring thrust/torque output of engines and transmissions.

Manufacturing applications: Laying cable and pipe, pressing sheet metal, controlling cutting or drilling tools.

Safety operations: Monitoring attachment and suspension forces.

Process weighing: Mixing, loading, packing, and filling.

2.2 Shape-specific applications

Pancake

See fig. 1.

Mounting:

- Center female thread, thru holes on the outer ring for mounting, also allowing for the use in tension.
- Some models have an optional load button.
- Some models have a clearance hole instead of a thread.

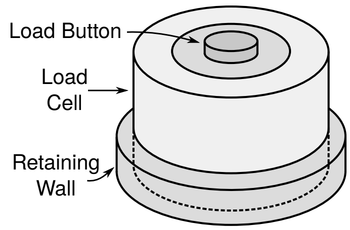

Figure 2: Button Load Cell

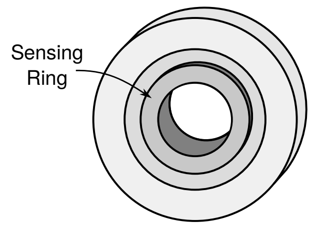

Figure 3: Thru-Hole/Ring Load Cell

Applications:

- Insertion/withdrawal forces, friction forces, weights (e.g. silos, skips), tensile forces (tension in cables, chains, etc. with load centering plate), materials testing. [13]
- Measurement of bar, rods and framework forces, press-fit processes, balance and test scales. [10]
- Airframe test fixtures. [25]

Load Button

See fig. 2.

Mounting:

- Must be retained by a wall, and the surrounding assemblies.
- Some are available with a mounting system on the base.

Applications:

- Fully-automated production centers, measuring and controlling equipment, precision mechanics, tool manufacturing, equipment construction. [2]
- Device manufacture, manufacture of fixtures and special machines, geological applications. [11]
- Reference sensor for adjustment and control of force-measurement facilities in production and in laboratories, material testing, spring-frame force measurements, press-in operating, weighing technology. [12]

Thru-hole/Ring

See fig. 3.

Measures axial shaft pressure.

Mounting:

Mounted inline along a shaft.

Applications:

- For press-in force control [20]
- Bolt-force measurements, material-testing applications, civil-engineering projects, rolling and reduction mill applications, suspension weighing. [24]

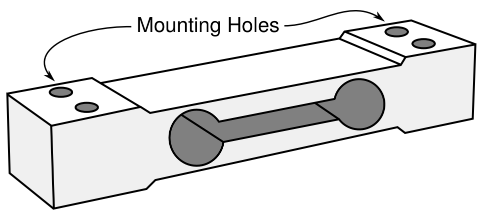

Figure 4: Load Beam Cell

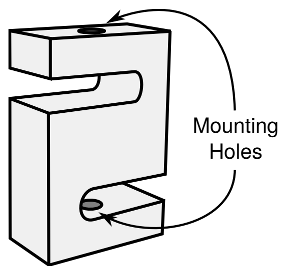

Figure 5: S-Type Load Cell

- Bolts, screws, plate and cover fasteners, bearing-contact forces, spot-welding machines, cutting tools. [5]

Load Beam

See fig. 4.

Bending-beam, cantilever, single-point shapes.

Applications:

- Single-point scales or batching/dosing machines. [18]
  Switches (limit-, micro- and toggle-switches), buttons, contact-coupling and contact-decoupling forces, friction forces, spring characteristics, tension of wire and spring windings. [8]
- Dosing systems, load-deflection curve, tension-force measurement for wire or thread winders, cable force, withdrawal force. [9]
- General research instrument. [17]

S-type

See fig. 5.

Applications:

- Bidirectional forces with a threaded load connection on each end. [19]
- Suspended-hopper weighing. [21]
- When applied as an inline load link or base mounted, some models offer good side-load rejection. [27]

Rod

See fig. 6.

Threaded connectors for inline rods on each side. Measures axial forces.

Mounting:

The force must only be applied centrally, along the center line, and only through the threads. Other fitted parts must not touch the sensor housing. It is recommended that adhesive is applied to the threads. Bending, flexing or torsion forces will cause errors in the measurements and can damage the sensor. [14]

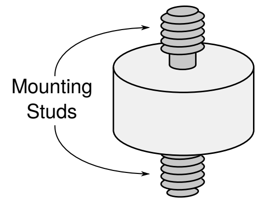

Figure 6: Rod-Type Load Cell

Applications:

- Determining forces in Bowden cable, testing the durability of soldered and welded joints, measuring interactive forces of plug connections, monitoring forces when winding cables onto cable reels. [3]
- Robot applications, special-purpose machinery manufacture, tool manufacturing, handling gear. [4]
- Forces in component joining, press-fitting, bending forces during material deformation, cutting forces when severing material, forces during stamping processes, punching forces for blanks, break-out forces used in destructive testing. [6]
- Vehicle and container scales, test machines, measurement of cable forces and cranes, avalanche research, oil production. [7]
- Airframe test fixtures, material-testing machines. [23]

2.3 Output options

Several choices of output are available, depending on the load cell selected:

mV/V: The output from a typical strain gauge. Requires the use of an instrument amplifier.

Voltage: Built-in amplifier, may require a constant-current power supply.

Charge: The output from a piezoelectric element. Requires the use of a charge amplifier.

RS-485: Built-in A/D converter, digital output, may be chained in a network with other sensors.

2.4 Optional features

Various manufacturers' load cells may provide additional options such as:

- Threaded/non-threaded holes.
- Mounting plates.
- Load button conversions.
- High-precision.
- Fatigue rating.
- Waterproof rating.
- Rating for use in explosive or other special environments.

3 Load-cell measurement technology

3.1 Strain-gauge load cells

The most common measurement technology for load cells is the *foil strain gauge*. This cost-effective sensor packs a long resistance element into a small physical space in a manner which maximizes its sensitivity to changes in length due to the

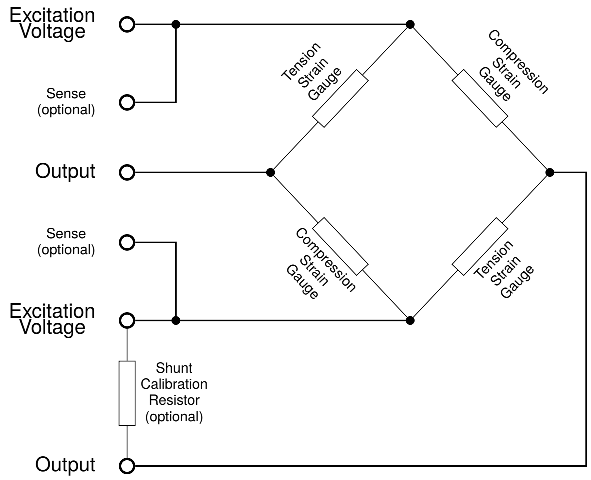

Figure 7: Basic arrangement of four strain gauges in a load cell

strain of the underlying material. The use of four of these sensors connected together in an electrical bridge, as shown in fig. 7, allows for the measurement of tension and compression, and can compensate for the dimensional changes induced by temperature variations. [22, sec. 4.2.3, fig. 6]

3.2 Piezoelectric load cells

A *piezoelectric* sensor is made of a crystal which forms an electrical charge on its surface when it is under compression. An external *charge amplifier* is required to convert this charge to a usable signal. [22, sec. 4.3]

Piezoelectric load cells are very stiff, and able to measure fast transients. When preloaded, these sensors may be used to detect both tension and compression. Charge leakage causes signal drift, making piezoelectric sensors less-than-ideal for long-term static measurements.

Load cells may be designed with piezoelectric elements stacked and oriented in such as way that they can simultaneously measure forces in all three dimensions at once, yielding three signals, one for each of the $\vec{X}$, $\vec{Y}$, and $\vec{Z}$ directions.

3.3 Pressure load cells

Hydraulic: A hydraulic load cell uses a fluid-filled chamber with a load piston to which the load is applied, which changes the pressure on the hydraulic fluid. A small pressure-output opening is provided, which sends a pressure proportional to the load to a pressure transducer, which may be at the other end of a hose. [22, sec. 4.4.1]

Being without an electrical current, the hydraulic load cell may be appropriate for use in explosive environments. See the manufacturer for details.

Pneumatic: The pneumatic load cell forces air pressure against the load plate until the load rises enough to vent pressure out of special holes. At this point, the pressure is directly proportional to the load, and may be measured and scaled appropriately. [22, sec. 4.4.2]

3.4 Other load cells

Elastic: These load cells directly measure the change in physical size of an elastic element under load. Examples are the loading column, proving ring, linear-variable differential transducer, capacitive, optical, and interference-optical load cell. [22, sec. 4.5.1]

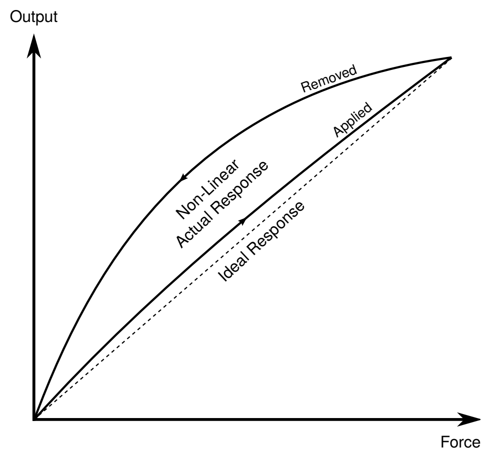

Figure 8: Non-linearity and hysteresis in a force-measurement system

Vibrating elements: These load cells convert force into a change in frequency. Examples are the tuning fork, vibrating wire, and surface-wave resonator load cell. [22, sec. 4.5.2]

Magneto-elastic: The magneto-elastic load cell senses force by inducing and sensing changes in a magnetic field through a steel elastic element. This load cell is useful in physically and electrically noisy environments. [22, sec. 4.5.3]

Dynamic balance: These load cells measure force by balancing against a known counterforce.

Gyroscopic: A gyroscopic load cell has a gyroscope mounted in a multi-axis rotating frame. Force is converted to rotation of the outer gimbal, whose rotation rate is proportional to the force. This load cell is fast-responding and free of hysteresis and drift. [22, sec. 4.5.4]

Force-balance: The force-balance load cell uses an electromagnet to resist the applied force, and senses the resulting movement. The current required to keep the load steady is proportional to the applied force. This load cell is stable and accurate, with good dynamic performance. [22, sec. 4.5.4]

Plastic deformation: This is a one-time recording of an applied force. The permanent deformation of the element is proportional to the applied force, and may be compared to that caused by a calibrated force. [22, sec. 4.5.5]

4 Output characteristics

An ideal load cell would generate an output exactly proportional to the force being applied, irregardless of conditions such as temperature and dynamic changes in the force. Real-world devices deviate from this ideal in several ways.

4.1 Linearity and Hysteresis

Figure 8 shows some (exaggerated) differences between an ideal output curve (the dotted line) and a real-world output, both as force is being applied, and as it is being removed. [22, sec. 3.5, fig. 1]

Non-linearity: The deviation of the real-world output from the ideal (dotted line) output shown in fig. 8. Even though the endpoints may be the same, the real-world output curve bends slightly away from the straight-line ideal.

Hysteresis: The difference in the output depending on whether force is being applied or removed.

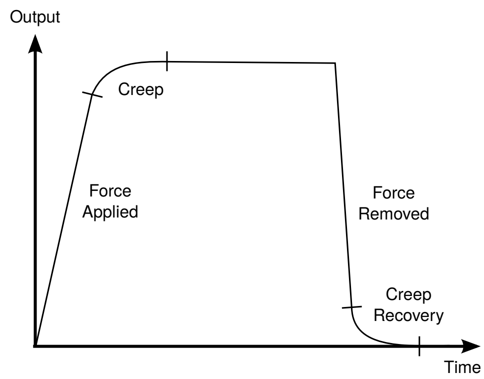

Figure 9: Creep curve of a typical force transducer

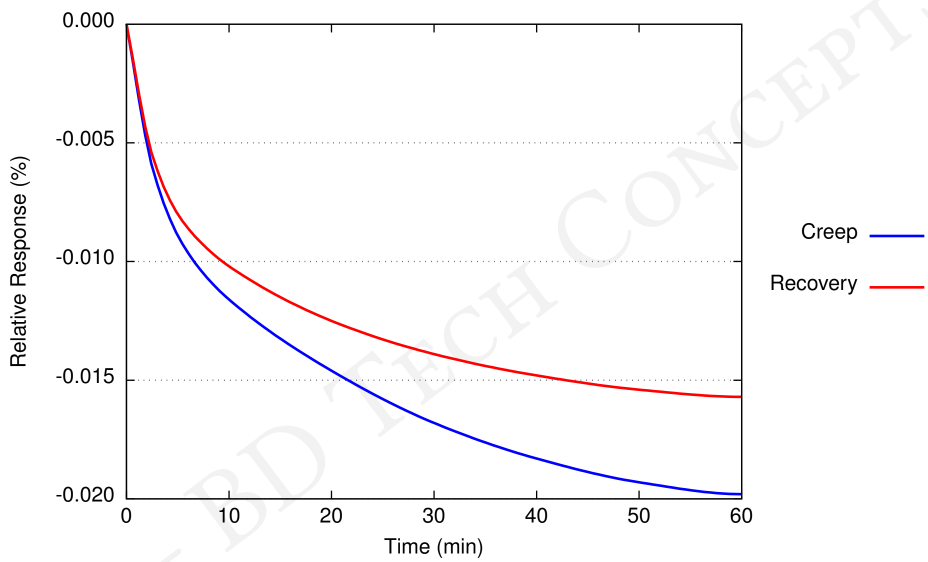

Figure 10: Example creep/response curve of a shear-beam load cell

4.2 Creep and creep recovery

Creep: Load-cell creep, as shown in fig. 9, is the final settling of the load cell after force is applied.

Creep recovery: The similar final settling once force is removed.

The load cell outputs most of its response quickly, but may slowly settle a bit as the force is held for a long amount of time. [1] [22, fig. 2]

Bartel and Yaniv [1] have done testing for load cell linearity, hysteresis, repeatability, temperature effects, and creep.

An example creep/recovery curve [1, fig. 3] for a shear-beam load cell is shown in fig. 10.

4.3 Other factors influencing the response curve

The output of a load cell can be further influenced by the following factors: [22, sec. 3.5]

Natural frequency: The application of dynamic force at a frequency close to the natural frequency of the load cell and its mounting mechanism.

Frequency response: The highest usable frequency which may be measured.

Temperature: Influencing both the zero point and the sensitivity of the output.

Loading conditions: A change in the position and distribution of the force upon the load cell.

Repeatability: Agreement of outputs for repeated applications of the same force under the same conditions.

Reproducibility: Agreement of outputs for repeated applications of the same force under changed conditions.

5 Selection and design

Numerous items affect the design of force-measurement systems and the selection of load cells. These include operating capacity, number of transducers, uni-directional or bi-directional transducers, dynamic forces, multi-component force measurement, instrumentation and data collection, safety, environment, installation space, mounting, warm up, and occasional recalibration. [22, section 6] Contact the supplier for advice on selecting load cells.

Ghanvat [15] discusses the use of finite-element analysis to minimize the designed weight of a load cell while meeting the desired objectives for force measurement.

6 Calibration

Initial and recurring calibrations are required to ensure the required degree of limitations in uncertainty. [22, section 7]

A *traceable* measurement is related by a chain of calibrations to a national or international *standard*. Force calibrations require the use of a *force-standard machine*. A *primary* force-standard machine is verified through direct physical principles, while a *secondary* standard machine is compared to a primary machine by use of a *force-transfer standard* — a calibrated force transducer. Documentary standards exist to provide traceability.

The best calibration is performed by permanently installing the force transducer to be tested and occasionally applying a transfer standard to the transducer, measuring and verifying the result. When in-machine calibration is impossible and it is required to remove the transducer for calibration, some potential installation-related influences are not taken into account. When it is not possible to apply a calibrated force to the transducer, in-machine or via removal, shunt-calibration testing may be performed to at least partially ensure correct operation.

7 Error sources

A number of possible error sources exist for force-measurement systems.

An example of error-source analysis for a load cell is given by Suzanne Castrup and Dr. Howard T. Castrup, et al. [26, sec. 4.5.3, p. 41].

Equation (1) shows the basic transfer function of a load cell. [26, eq. 4-4]

$$LC_{out} = W \cdot S \cdot V_{Ex} \tag{1}$$

where

$$W = \text{Applied load or weight}$$
$$S = \text{Load cell sensitivity}$$
$$V_{Ex} = \text{Excitation voltage}$$

Equation (2) takes error sources into account. [26, eqs. 4-5 to 4-7]

$$LC_{out} = [(W_s + TE_{out} \cdot TR_{°F}) \cdot S + NL + Hys + NS + ZO + TE_{zero} \cdot TR_{°F}] \cdot V_{Ex} \tag{2}$$

where

$$W_s = W_n + W_e \tag{3}$$

$$V_{Ex} = V_n + V_e \tag{4}$$

and

$$\begin{aligned}
W_n &= \text{Nominal or stated value of weight standard} \\
W_e &= \text{Bias of weight standard} \\
V_n &= \text{Nominal excitation voltage} \\
V_e &= \text{Excitation voltage error} \\
TE_{out} &= \text{Temperature effect on output} \\
TR_{°F} &= \text{Temperature range in °F} \\
NL &= \text{Nonlinearity} \\
Hys &= \text{Hysteresis} \\
NS &= \text{Noise and ripple} \\
ZO &= \text{Zero offset} \\
TE_{zero} &= \text{Temperature effect on zero}
\end{aligned}$$

Estimating the uncertainties in a measurement system composed of serial chain of modules, including the use of a load cell [26, sec 7.5.1], takes into account:

- Calibration Weight
- Excitation Voltage
- Nonlinearity
- Hysteresis
- Noise
- Zero Balance
- Temperature Effect on Output
- Temperature Effect on Zero

In one case, force-gauge digital resolution was the most significant source of uncertainty in the calibration of a force gauge. [26, fig. F-1].

8 Improved performance in a noisy environment

The signal-to-noise ratio of a force-measurement system may be improved through the use of an adaptive algorithm. [16]

In the cited case, use of a recursive least-squares (RLS) lattice algorithm yielded a S/N improvement of 27 dB, using low-cost components and taking advantage of the processing power of today's inexpensive microelectronics.

9 Prediction of the failure of a load cell

Given historical data for a force-measurement system's zero and sensitivity, *grey theory* may be used to predict near-future values, and perhaps call for preventative action before system calibration goes outside of its acceptable range. [28, p. 1937]

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