7.25 Weight Sensors

B. G. LIPTÁK (2003)

Types:
A. Mechanical (lever, spring)
   A1. Laboratory
   A2. Industrial
B. Hydraulic load cells
C. Pneumatic load cells
D. Electronic load cells
   D1. Strain gauge
   D2. Piezoelectric
   D3. Piezoresistive (semiconductor)
   D4. Capacitance
   D5. Inductive
   D6. Reluctance
   D7. Magnetostrictive
   D8. Nuclear
E. Feeders (screw, belt, gravimetric, nuclear, and loss-in-weight; see Section 2.23)

Operating Temperature
Ranges:
A1. Ambient
A2. −10 to 135°F (−23 to 57°C)
B. C. 0 to 125°F (−18 to 52°C)
D. Normally from −4 to 160°F (−20 to 70°C); special units are available for −4 to 450°F (−20 to 230°C)

Ranges:
A1. From 0–3 g to 0–150 kg
A2. From 0–1 to 0–1,000,000 lbm (0–0.5 to 450,000 kg)
B. 100 to 1,000,000 lbm (45 to 450,000 kg)
C. 10 to 10,000 lbm (4.5 to 4500 kg)
D. From 0–1 to 0–12 million lbm (0–5 to 0–4.5 million kg)

Inaccuracy:
A1. Readability of a 0- to 3-g range can be as low as 0.1 µg; for a 0- to 150-kg range, the readability is 50 g.
A2. From ±0.01 to ±0.1% of full scale

Flow Sheet Symbols
B. C. From ±0.1% to ±1% of full scale
D. 0.03 to 0.25% of full scale

Costs:
A1. The cost of laboratory balances is a function of their precision. Units with 0.1% readability can be obtained for $100 to $300; with 0.01% readability, for $500 to $1000; and with 0.001% readability or better, for $1000 to $4000. Microprocessor-based balances with microgram readability can cost up to $10,000.
A2. Highly variable with application but usually in excess of $5000.
B. C. From $750 to $1500 per load cell or totalizer; $500 to $1000 per high-precision pressure gauge readout. Costs for electronic pressure transmitters range from $1000 to $2000.
D. Load washers, low-profile load cells, and compression load buttons cost from $500 to $1200; universal load cells for higher loads cost $2000 to $3500; remote display costs range from $500 for a standard indicating transducer to $2500 for an 8-channel unit. A strain gauge telemetry transmitter with FM output costs $1800. A complete batch weighing control system, depending on its complexity, will cost from $10,000 to about $25,000. A nuclear continuous weigh scale costs about $10,000.
E. Feeders (screw, belt, gravimetric, nuclear, and loss-in-weight; see Section 2.23)

Electronic Load Cells

Overload Limitations: Up to 125% of rating including shock, impact, or static loading
Nonrepeatability: Generally from 0.01 to 1%
Nonlinearity: Generally from 0.03 to 2%
Hysteresis: Generally from 0.02 to 2%
Output Signals: 2 to 3 mV per volt of excitation. Excitation voltage is usually around 10 V.

Mechanical Configurations: Canister (longitudinal tension or compression stress); cantilever (bending stress); shear

Design Materials: For high capacities, the load (spring) elements are usually steel alloys, while for low capacities, aluminum alloys are used. The strain sensing grid can be constantan, Karma, Isoelectric, or platinum tungsten. The strain gauge backings include polymides, epoxies, or reinforced epoxies. The bonding adhesive is often cyanoacrylate.

Partial List of Suppliers:
ABB Inc. (D) (www.abb.com/us/instrumentation)
Acculab (A1) (www.sensornet.com)
A & D Weighing (A1) (www.andweighing.com)
Bacharach (B) (www.bacharach-europe.com)
Cardinal Scale Mfg. (A1, A2, D) (www.cardinalscale.com)
Carson Co. (A1)
Condec (D) (www.4condec.com)
Daytronic Corp. (D) (www.daytronic.com)
W.C. Dillon & Co. (B) (www.dillon-force.com)
Fairbanks Scales (D) (www.fairbanks.com)
Flow-Tech Inc. (D) (www.flowtechonline.com)
FMC Blending (D) (www.fmcblanding.com)
Futek Advanced Sensor Tech. (D) (www.futek.com)
Global Weighing (D) (www.global-weighing.com)
Graybar Electric Co. (D) (www.graybar.com)
GSE Scale Systems (D) (www.gse-inc.com)
Hardy Instruments (A2) (www.hardyinst.com)
Hottinger Baldwin Measurements–HBM Inc. (D) (www.hbmhome.com)
Helm Instrument Co. (D) (www.helminstrument.com)
Hi-Speed Checkweigher (D) (www.highspeedcheckweigher.com)
Kistler-Morse Corp. (D) (www.kistlermorse.com)
INTRODUCTION

The more general aspects of weighing were discussed in the previous section (7.24), while the subjects of rate-of-weight measurement and gravimetric feeders were covered in Section 2.23. This section is devoted to the discussion of the detectors used in the measurement of stationary weights, whether in the laboratory or in general industry. The types of sensors discussed include the mechanical lever scales and the hydraulic, pneumatic, or electronic load cells. Naturally, because of their popularity, more space is devoted to electronic load cells than the others, and within that group, the emphasis is placed on the most popular design—the strain gauge type load cell.

The description of mechanical, hydraulic, and pneumatic designs are followed by the discussion of electronic load cells—their design variations, features, accessories, and the more recent advances that have occurred in their designs. The discussion begins with the topic of strain gauge-type load cells. The reader should be aware that strain-gauge-type sensors, circuits, and electronics have already been discussed in other sections of this volume (Sections 5.7, 7.19, and 7.21). For this reason, some of the points that were already made will not be repeated here.

LOAD CELL SELECTION

Concepts and selection procedures for weigh systems based on load cells are focused on accuracy and repeatability of measurements of relatively large loads within a variety of constraints imposed by shape and vessel sizes, structural and mechanical arrangements, materials to be weighed, and environmental conditions. Here we present some established criteria for load cell selection—design concepts used in load cell installation. For an analysis of the impact of piping arrangements, mechanical equipment, and structural deformation on total weigh system performance, refer to Section 7.24.

To obtain the best performance in designing a load cell based weighing system, consideration must be given both to the selection of the load cells (Table 7.25a) and to the choice...
of load cell installation assemblies. A correctly designed weighing system must have the following characteristics:

1. Low deflection (typically 0.005 to 0.008 in., or 0.125 to 0.2 mm): permitting process piping to be attached to the weighed vessel
2. Excellent repeatability: ±0.002% of full scale, or better, within a prescribed temperature range
3. Accuracy: Ranges from 1 to better than 0.05% of full scale

### Selection Factors

The following factors should be considered when selecting load cells.

#### Mode of Loading: Tension or Compression

This choice is determined by the type and capacity of the vessel and by structural and mechanical design criteria. It is proven by experience that tension support for very large tanks or hoppers is more difficult to design and is more costly than a

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**TABLE 7.25a**

<table>
<thead>
<tr>
<th>Type of Load Cell</th>
<th>Weight Range</th>
<th>Inaccuracy (FS)</th>
<th>Applications</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Cells</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic</td>
<td>Up to 10,000,000 lb</td>
<td>0.25%</td>
<td>Tanks, bins, and hoppers; hazardous areas</td>
<td>Takes high impacts; insensitive to temperature</td>
<td>Expensive, complex</td>
</tr>
<tr>
<td>Pneumatic</td>
<td>Wide</td>
<td>High</td>
<td>Food industry; hazardous areas</td>
<td>Intrinsically safe; contains no fluids</td>
<td>Slow response; requires clean, dry air</td>
</tr>
<tr>
<td><strong>Strain Gauge Cells</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bending beam</td>
<td>10–5,000 lb</td>
<td>0.03%</td>
<td>Tanks; platform scales</td>
<td>Low cost, simple construction</td>
<td>Strain gages are exposed, require protection</td>
</tr>
<tr>
<td>Shear beam</td>
<td>10–5,000 lb</td>
<td>0.03%</td>
<td>Tanks, platform scales, off-center loads</td>
<td>High side load rejection, better sealing and protection</td>
<td></td>
</tr>
<tr>
<td>Canister</td>
<td>to 500,000 lb</td>
<td>0.05%</td>
<td>Track, tank, track, hopper scales</td>
<td>Handles load movements</td>
<td>No horizontal load protection</td>
</tr>
<tr>
<td>Ring and pancake</td>
<td>5–500,000 lb</td>
<td></td>
<td>Tanks, bins, scales</td>
<td>All stainless steel</td>
<td>No load movement allowed</td>
</tr>
<tr>
<td>Button and washer</td>
<td>0–50,000 lb</td>
<td>1%</td>
<td>Small scales</td>
<td>Small, inexpensive</td>
<td>Loads must be centered; no load movement permitted</td>
</tr>
<tr>
<td></td>
<td>0–200 lb typ.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Other Types</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helical</td>
<td>0–40,000 lb</td>
<td>0.2%</td>
<td>Platform, forklift, wheel load, automotive seat weight</td>
<td>Handles off-axis loads, overloads, shocks</td>
<td></td>
</tr>
<tr>
<td>Fiber optic</td>
<td></td>
<td>0.1%</td>
<td>Electrical transmission cables; stud or bolt mounts</td>
<td>Immune to RFI/EMI and high temps; intrinsically safe</td>
<td></td>
</tr>
<tr>
<td>Piezoresistive</td>
<td></td>
<td>0.03%</td>
<td>Extremely sensitive; high signal output level</td>
<td>High cost; nonlinear output</td>
<td></td>
</tr>
</tbody>
</table>

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compression support. In addition, tension load cells with female threads on both ends and the need for eyes and rods require greater vertical clearances. A single load cell (Figure 7.25b) supporting a small tank in tension is stable and less expensive than a multiple compression support. A weight of maximum 20,000 lb (9000 kg) load usually limits the tension mounting applicability.

**Ambient Temperature**  The compression load cell assembly will require low friction expansion assemblies in order to accommodate differential thermal expansion or contraction between vessel and supporting structure. The tension load cell assembly does not require additional accessories for expansion compensation. The adjustment of flexure rods, which are part of the standard tension mounting assembly, will compensate for differential thermal expansion between vessel and structure.

**Lateral Restraints**  Lateral restraints on vessel movements are frequently required when a compression assembly is chosen. In a tension assembly, lateral restraints are not required for vented vessels, which store, for instance, dry, nonhazardous materials, since a hanging mass is inherently stable.

**Structure Vibrations**  Tension assemblies are more sensitive to vibration because of reduced structural stiffness and dampening capability caused by tension linkages. The compression assemblies' sensitivity to vibration is a function of the stiffness of the structure and vessel supports.

**Number of Load Cells**

The number of load cells required is determined by the plane view geometry of the supported structure—hopper, tank, or silo. The main considerations include cost and accuracy. Cost can obviously be reduced by lowering the number of load cells used. On the other hand, if a load cell is not placed under each point of support, the total load is not being measured; therefore, if the load distribution is not symmetrical between points of support, the reading will be in error. Three points fully define a plane, so the ideal number of supports for uniform load distribution is three.

Positioning can have an effect on number of cells required; for example, a vertical circular tank might require three cells (Figure 7.25c), while the same tank in a horizontal position might require four cells (Figure 7.25d). Considerations must...
Safety and Miscellaneous Sensors

also be given to the strength and rigidity of the weigh-bridge structure. Horizontal dimensions in excess of 25 ft (7.5 m) may increase the number of load cells needed. Related to the number of load cells required are two additional factors: capacity and degree of precision required.

When a load is supported from more than one point, pivots or flexures can replace some of the cells, depending on the symmetry of the load, at the expense of overall accuracy expected. Vertical vessels with supports above the center of gravity may use three cells instead of one cell and two pivots. Three cells give more accuracy but cost more. Instead of four cells, a horizontal vessel can use a flexure and two cells or a flexure and one cell. The use of a flexure reduces the staying requirements but with some loss of accuracy.

**Capacity and Type**

The minimum load cell capacity can be calculated with the following formula:

\[
C = 1.25 \times \frac{W_T + W_N}{N}
\]  

where

- \(C\) = minimum load cell capacity
- \(1.25\) = allowance factor for low tare estimates and unequal load distribution on the load cells as installed
- \(W_T\) = tare weight of the empty vessel
- \(W_N\) = net weight of projected vessel content (live load)
- \(N\) = number of load cells
- \(K\) = dynamic factor (\(K = 1.25\) for certain dynamic loads, otherwise \(K = 1\))

When calculating the tare weight of the empty vessel, one must include any additional equipment attached to the vessel, such as agitators, valves, and filters, that contributes to the weight that the empty vessel (including its accessories) will exert on the load cells.

Examples of anticipated dynamic loads are vessels with crane buckets and vessels with horizontal agitators. Assuming for these cases \(K = 1.25\), one can provide an extra capacity for sizing, resulting in a higher capacity load cell selection. A higher capacity load cell will perform better under repeated impact loads or high cycle fatigue.

**Load Cell Types** A selection must be made between hydraulic and electric load cells. Hydraulic load cells can be considered for large vessels when the required accuracy is low (within 0.25 to 1%). Hydraulic load cells are rugged and require low maintenance, and their cost is reasonable. On outdoor installations where temperature changes are drastic, heated enclosures are necessary. Electric load cells are more expensive, but are the most accurate and trouble-free. Inaccuracy is as low as 0.1% and can be even lower depending on mounting, staying, and piping factors.

**Classes of Load Cells** Manufacturers offer the following classes of load cells: general purpose, precision, high-temperature environment, corrosive environment, and rugged design.

General-purpose load cells may be used in any service (tension or compression) whenever weigh system accuracy required is not better than 1%. Precision load cells are specified in systems where accuracy is expected to be 0.1% or better. Specially designed load cells using adequate materials of construction are utilized in a high temperature environment (maximum 450°F, or 232°C). Precision and high-temperature load cells have temperature compensation accessories that make the operation unaffected by temperature variations within the compensation range (15 to 115°F, or −10 to 46°C, for general purpose and precision, and 15 to 425°F, or −10 to 218°C, for high-temperature design).

Load cells can be protected with a special coating in order to prevent deterioration due to the presence of corrosive chemicals. Rugged load cells are offered whenever mechanical shocks may affect their performance.

**LOAD CELL INSTALLATION**

Load cells measure all vertical forces acting upon the vessel. Forces other than the weight of the vessel and contents must be kept small, elastic, and repeatable so that their effect can be removed by field calibration.
The general rules for load cell and vessel arrangements are:

1. The vessel structure in the area of the load cell mounting must be rigid.
2. The supporting structure or foundation, depending upon the loading mode (tension or compression), must be rigid. If more than one vessel is to be supported on the same structure, the structure must be designed with sufficient rigidity to prevent interaction errors caused by large deflections.
3. On multiple load cell arrangements, the load cells must be positioned and should be installed so that after the vessel is fully loaded each cell will carry not more than 120% of rated capacity.
4. Optimal vessel stability requires flexibility in the vertical plane and rigidity in the horizontal plane.

Some load cell designs can tolerate more horizontal movement; these designs require less restraining of the vessel movement than others. In general, it can be said that the cantilever beam-type load cell requires less restraining. The cantilever load cell is illustrated in Figure 7.25e. It is connected to the weighed vessel through the retainer yoke, which encircles the sensing beam of the cantilever load cell. Therefore, when this type of load cell is used, the weigh tank is securely held in place and often does not require additional restraining.

If the weigh tank is expected to undergo thermal expansion, bearings can be provided with the retainer yoke to accommodate the movements caused by thermal expansion. Naturally, in case of outdoor installation of tall vessels where heavy winds can create extreme forces, restraining is still necessary.

The canister type of load cell is illustrated in Figure 7.25f. When this type of load cell is used, the weigh tank must always be stabilized (restrained). Most of the discussion that follows assumes the use of canister-type load cells.

**Load Cell Adapter**

As already noted, many load cell based weighing installations involve large differential expansions that can impose severe horizontal forces on the installed load cells. Also, in vehicle scales, large horizontal forces can be applied owing to deceleration and acceleration forces associated with bringing the vehicle on and off the scale. The load cell adapter described here virtually eliminates such forces.

Primarily a mechanical arrangement, the active weighing platform is suspended from the top of the load cell by three suspension links (Figure 7.25g), and an upper plate and adapter ring contact the load cell at the desired loading point. The upper plate carries the three links by link pins projecting radially from the upper plate. Hanging on the opposite end of the links is the lower plate that includes three additional link pins for engaging the lower end of the links.

The lower plate is connected to the active weighing platform, thereby transmitting the weight through the links and upper plate to the top of the load cell. The load cell is supported by a base plate, that rests on the foundation or ground structure. The base plate also serves to absorb heavy side loads when the horizontal deflection of the weigh-bridge exceeds the clearances provided between the base plate and the cutout portion of the lower plate. The height of the adapter assembly can be adjusted by a center screw, enabling the equal distribution of total load among the several load cells in a given installation.

The structure provides a highly flexible load cell adapter assembly, which transmits virtually no side loads to the load cell caused by differential expansion of the weighing structure relative to the ground structure. The side loads that are transmitted to the load cell are from weigh-bridge deflections, imposing angular loads on the load cell. These are minimized by appropriate structural design of the weigh-bridge.
Another load cell adapter used in the past in weighing systems was the rocker assembly (Figure 7.25h). An adapter is added to the bottom of the load cell, which in effect provides a convex loading surface on both the bottom and top of the unit. The load cell and adapter are located in place by a stabilizer plate. Load is introduced to the load cell through the upper bearing block and transmitted through the load cell and the lower bearing block to the mounting plate. The stabilizer plate allows partial rotation of the load cell, while at the same time restricting excessive lateral motion.

Differential expansion between the structure being weighed and the foundation causes slight rotation of the load cell, reducing the magnitude of the horizontal forces, which would have been present in the absence of the rocker assembly. The load cell is thus protected from the adverse effects of large lateral forces caused by differential expansion in multiple cell weighing systems. While found in existing installations, the spring-loaded stabilizing plate has not been a successful solution and is seldom used on new installations.

### Vessel Expansion

Temperature variations can cause the vessel or the supporting structure to contract or expand. Under these circumstances, load cells are subjected to horizontal loads resulting in weighing errors. Whenever the mode of loading is compression, one can minimize the expansion/contraction effect by adapting the following solutions.
**I-Beam Flexure**  
I-Beam flexures are short lengths of standard I-Beams used to provide flexible support for weigh vessels. I-Beam flexures bend through very small angles about their web and allow slight motion perpendicular to the web. The flexures mounted as supports can accommodate lateral movement up to 0.010 in. (0.25 mm). I-Beam flexures are utilized in weigh systems where load cells sense only a portion of the tank weight (Figure 7.25d). This arrangement is commonly used for weighing liquids where an accuracy of 0.5% or less is acceptable.

**Expansion Assemblies**  
These assemblies are, in principle, sliding bearing units that have a low coefficient of friction and can move laterally within ±3/8 in. (9.5 mm). Figure 7.25i illustrates a self-aligning strut bearing installation that is well suited for minimizing the effect of vessel movement due to thermal expansion.

Load cells used outdoors in areas subjected to large temperature variation should be provided with expansion assemblies. In cases where the mode of loading is tension, flexure rods are used (Figure 7.25b). Flexure rods link the load cell with the structure in a tension weighing arrangement; the flexure rod had tensile strength of approximately 90,000 PSI (621 MPa) and can accommodate deflection of ±3/32 in. (2.3 mm).

**MECHANICAL LEVER SCALES**

All mechanical lever scales employ lever systems that balance the weight of the unknown (gravity pull) against a known (calibrated) lever and mass: it is, in fact, a balancing of one moment against another. It is customary to adjust the lever system so that the pull from the unknown will fall within a convenient range—usually 25 to 50 lb (11 to 23 kg).

The unknown mass includes the mass of the bin, hopper, or platform holding the material to be weighed. A tare device cancels out these weights by balancing them. In Figure 7.25j, the hopper, hopper supports, gathering levers, hanger rods, and the pull rod leading to the counterbalancing means, or balance device, are shown for a typical industrial scale. In the same figure, two widely used balancing devices—the tare beam and the pendulum—are also shown.

**Balancing Devices**

The most often used mechanical scales transmit the load by levers. For the different moving connections, such as the fulcrum, knife-edge bearings were traditionally used. More recently these have been replaced by V-grooves to receive the knife-edge or by ball bearings or plate-fulcrum elements. The mechanical balance can be established by moving poises on a weigh-beam, by helical springs, or by the rotation of pendulums. In the latter designs, oil-filled cylindrical dashpots are included to dampen the oscillation.

The tear beam (top left in Figure 7.25j) is usually an array of three smooth bars, each marked off linearly, and each carrying a poise. One beam is for balancing out tare weight;
it may not be calibrated. Another is for balancing out hundreds (or perhaps thousands) of pounds; it carries a rather heavy poise. The third is calibrated to balance out tens and units, and its poise is one-tenth the weight of the hundreds poise. The total moment exerted by the beam is the sum of the three. Balance is indicated by the position of the free end of the beam, usually guided within a trig loop.

The pendulum (often a double pendulum for greater stability and accuracy) employs a heavy mass swinging around a horizontal pivot (top right of Figure 7.25j); the moment is proportional to the displacement of the mass in a horizontal direction. This displacement is indicated on a circular scale. Linear calibration is provided by the use of a contoured cam and a draw-band. Tare corrections are made with a tare beam.

**Scale Ranges**

A few of the most widely used types of industrial scales, and their typical ranges are listed in Table 7.25k.

**Applications**

Mechanical lever scales are used in virtually every phase of industry, in development and in scales. The greatest scope for their application is probably in the weighing of stationery objects or quantities of material. Such scales may have almost any capacity, and can accommodate loads of almost any material. Overhead track scales, motor truck scales, and railroad track scales are all forms of mechanical lever scales.

Great many moving-body scales are also used. Vehicles in motion (trucks, railroad cars, etc.) can be weighed on mechanical lever scales if their velocity is low—usually less than 5 mi/h (8 km/h). Such scales usually employ pendulum counterbalances, indicating on a dial for easy reading.

**Gravimetric Feeders**

Granular materials are conveniently weighed on conveyor-belt scales. A short section of conveyor belt is built into the scale mechanism, with tare adjustment to balance the scale with the belt empty; the balancing device then indicates the weight of the material on the belt.

An extension of this is the integrating weighing device. The belt is driven at a known speed; the total amount of material delivered is readily computed from the duration of the operation and the average weight of material on the belt. Accuracy is improved if the amount of material on the belt is kept uniform and constant.

Granular material can be conveniently supplied at a known rate by a conveyor-belt scale. The feed rate to the belt is controlled by the balance device; the load on the belt is thus kept constant (Figure 7.25i). Under such conditions, the feed rate can be manipulated by adjusting the speed of the belt.

**Batch Additives**

Many industrial processes require the weighing of batches of material individually; others require the weighing of a series of materials for later mixing or other treatment. Batches of constant size are readily weighed into a hopper, using beam scales, with the position of the beam indicating when the feed should be stopped.

A series of quantities of materials can be weighed into the same hopper; this is most readily done with a dial-type scale (although a series of balance beams, dropped into position in succession, can also be used). The dial pointer positions for each added material are made to actuate gates to stop the flow of each material when the required weight is reached. Pointer positions are detected by various means: photoelectric pickups, reed switches, etc. Similar devices are used to sense balance-beam position.

**Output Signals**

While many scales provide only a visual indication of balance, many electrical output devices are available. The simplest of these are cutoff devices, which indicate only when a desired weight (or each one of a series of weights) has been reached. There are also transducers that are attached to dial-scale pointers; these provide a continuous electrical output that can be fed into computer controls to perform sophisticated functions.

**Advantages and Limitations**

Mechanical lever scales are notable for long-time accuracy, with proper maintenance; they are also quite resistant to most environmental conditions. They are available in an extremely

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**TABLE 7.25k**

*Types of Mechanical Scales Used in Industry and Their Typical Ranges*

<table>
<thead>
<tr>
<th>Type</th>
<th>Typical Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Even-arm scale</td>
<td>5/2.26</td>
</tr>
<tr>
<td>Bench dial scale</td>
<td>200/90</td>
</tr>
<tr>
<td>Platform scale</td>
<td>1500/680</td>
</tr>
<tr>
<td>Floor scale</td>
<td>6000/2720</td>
</tr>
<tr>
<td>Overhead scale</td>
<td>12,000/5443</td>
</tr>
<tr>
<td>Suspended hopper scale</td>
<td>25,000/11,345</td>
</tr>
<tr>
<td>Truck scale</td>
<td>100,000/45,400</td>
</tr>
<tr>
<td>Railroad track scale</td>
<td>400,000/181,800</td>
</tr>
</tbody>
</table>

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wide range of capacities and forms; they are available in sizes ranging from quite small to a railroad-track scale more than 100 ft (30 m) long. They can readily be made a working part of other industrial devices; in fact, most industrial scales are so used.

Their principal limitation is in speed of response. The mass and inertia of the lever system does not permit weighing speeds as great as strain-gauge load cells, which can be used to weigh vehicles moving at high speeds. The normal output of a mechanical lever scale is a visual signal, not readily coupled into other systems, but may be handled quite easily.

HYDRAULIC LOAD CELLS

All hydraulic load cells function on the principle of a force counterbalance. Weight imposed upon the load cell causes a change in internal fluid pressure. A wide variety of pressure detecting devices is employed to translate pressure into an analog signal proportional to weight. The most popular readout device is a precision bourdon tube.

For practical application, hydraulic load cells must function without leakage, they must be relatively free of internal friction, and, most desirably, they must be linear and precise in operation.

One approach to the above criteria has been through the use of a close fitting piston and cylinder, using an ordinary O-ring as a means of preventing leakage past the piston. While such devices will function rather satisfactorily under some conditions, one must guard against frictional losses due to the rubbing of the O-ring.

The Rolling Diaphragm Design

With the introduction of the so-called rolling diaphragm, a new and very successful design of hydraulic load cell appeared. This is illustrated in Figure 7.25m. Here we note that the hydraulic fluid is confined within the diaphragm chamber by means of the clamped seal between the cylinder wall and base plate. The piston or load-bearing member is guided within the cylinder by two sets of ball guide rings. Thus, the piston is substantially limited to one degree of freedom (i.e., parallel to its major axis). The effective acting area of the piston equals the area of a circle whose diameter is the mean diameter of the diaphragm convolution. It has been found that this area is very constant over a wide range of piston displacements. Thus, the requirement of linearity and precise performance is satisfied. One limiting factor on this design is the ability of the elastomer diaphragm to withstand pressure. Materials available limit the maximum internal pressure to 800 to 1000 PSIG (5.5 to 6.9 MPa). One can increase the size (area) of the load cell to overcome this pressure constraint, but the diaphragm molding techniques tend to limit size.

Performance  Performance of the rolling diaphragm type of hydraulic load cell is acceptable for most process weighing applications. One may except measurement inaccuracies of ±0.25% of full scale or better on properly installed systems.

An outstanding feature of the rolling diaphragm type hydraulic load cell is its relative insensitivity to the amount of hydraulic filling. Thus, in making connections to gauges or other readout equipment, high-pressure hoses rather than rigid tubing may be permitted where desirable.

It is also easy to visualize that because of the relative insensitivity to filling, changes in hydraulic fluid volume due to ambient temperature variations have little effect on load cell performance. The system tends to be quite stable under varying temperature conditions provided that other factors, such as diaphragm stiffness variations, do not affect its performance.

All Metal Design

A more complex design, eliminating the flexible (elastomeric) diaphragm, is shown in Figure 7.25n. This design
is characterized by all metal construction, using a very limited quantity of hydraulic fluid. One outstanding feature of this design is its ability to accept extremely heavy unit loads. Successful hydraulic load cells with individual capacities of 10,000,000 lbm (4,500,000 kg) have been constructed.

By eliminating all bearings, pivots, and knife-edges, hydraulic load cells offer high sustained accuracy. Displacement under capacity load, although dependent on connected auxiliary instrumentation, can usually be limited to 0.005 to 0.010 in. (0.125 to 0.25 mm). The natural frequency of hydraulic load cells is high, and on dynamic load applications, resonance is rarely, if ever, encountered. The viscous damping characteristics of the hydraulic medium tend to yield stable weight signals even under dynamic disturbances.

Hydraulic load cells are self-contained and require no outside power for operation. They are inherently explosion proof and are available for both tension and compression force measurement. The hydraulic load cells illustrated in Figures 7.25m and 7.25n are applicable to tank, bin, and hopper weighing. In both types, the supported load is borne by a top member, or head plate, which in turn rests upon a ball or rolling member.

The rolling member is supported by the load sensitive piston or column. Any tendency of the load head to move in a horizontal plane, as under the influence of an expanding or contracting vessel, is accommodated by a corresponding rolling action of the ball. The load cell is protected from heavy side forces that would tend to interfere with its free vertical displacement under varying load conditions.

**Hydraulic Totalizers**

In using hydraulic load cells for process weighing applications, a special problem arises when the vessel is supported on more than one load cell. In order to obtain the total weight of the supported body, the output of the support points must be added. If the load cells are simply interconnected, and an average pressure is obtained, the danger of grounding of one point may occur, especially under conditions of nonuniform support loading.

This problem is solved through the use of a hydraulic totalizer, as shown in Figure 7.25o. Here, the output of each load cell is conducted to individual modules, which are, in effect, small pistons and cylinders. The output forces of the piston/cylinder combinations are collected on an output module, usually of larger acting area than the input modules. Provided this can be accomplished without serious internal losses, one pressure signal proportional to the several inputs may be developed.

Units totalizing two, three, and four inputs have been constructed with totalizing inaccuracy of \( \pm 0.1\% \) of full scale. However, due to temperature sensitivity and other nonlinear effects, hydraulic totalizing inaccuracy in the order of \( \pm 0.25 \) to \( \pm 0.50\% \) of full scale is more commonly encountered.

**Electronic Totalizers**

Hydraulic load cells used in multiples may also be totalized by transducing the hydraulic pressure output into proportional DC voltage or current. Commercial transducers of high quality are available for this purpose. This method has the added capability of very long transmission without loss of accuracy.

**Other Features**

Hydraulic load cells are particularly well adapted for high impact loading applications and will withstand high overloads (300 to 400% in some instances), without loss of accuracy or zero shift.

Well-designed hydraulic load cells do include some means of temperature compensation for both span and zero effect. Nevertheless, most manufacturers specify standard operating limits of 0 to 120°F (−18 to 49°C) as a basis for the performance guarantees. Operation outside these normal limits will necessitate the reference to temperature correction charts and graphs available from all suppliers.

Hydraulic load cells have found other applications in the force measurement and weighing field. The high natural frequency, low deflection, and fast response rate make this device well adaptable to web tension control, dynamometer torque measurement, jet engine and rocket thrust measurement, and other similar highly dynamic installations.

**PNEUMATIC LOAD CELLS**

Pneumatic load cells have been successfully applied in process weighing. The units that are still available are all force-balance designs and function with high accuracy. Most pneumatic weighing systems are offered with tare balancing chambers, which enhance their overall performance.

The pneumatic output signal from the load cell may be read locally or transmitted by metal or plastic tubing to a remote point. The local readout of weight is usually by precision bourdon tube gauges, while for remote readouts, outputs can be transduced into electronic or digital forms.
Pneumatic weighing systems have several advantages. They are inherently explosion-proof; are quite insensitive to temperature variation; and in the event of rupture or leakage, they contain no contaminating fluid medium (e.g., hydraulic fluid). This feature is of particular interest to the food and drug industry.

For successful operation, pneumatic load cells and associated weighing equipment must have a carefully regulated source of clean, dry air. Although systems have been operated for short periods on inert gases such as dry nitrogen, such operation would be too expensive and impractical for process applications. Therefore, when installing a pneumatic weighing system, in addition to the system components themselves, attention must be directed to the air supply for the system. A typical requirement is 10 SCFM (283 lpm) of dry air (−40°F [−40°C] dew point) per load cell.

Figure 7.25p illustrates the cross section of a pneumatic load cell. The natural frequency of pneumatic load cells is quite low, but under certain conditions of dynamic loading, resonance may occur. This problem has been largely overcome by incorporating stabilizing or dampener chambers (Figure 7.25p).

Pneumatic weighing systems have relatively slow rates of response when the load changes incrementally. Their deflection is also low, because of their force-balance principle of operation, usually from 0.003 to 0.005 in. (0.075 to 0.125 mm).

**ELECTRONIC LOAD CELLS**

A variety of electronic load cells will be discussed here, including their design variations, features, accessories, and more recent advances. The more advanced, microprocessor based designs have been programmed to automatically recognize and correct errors caused by external influences, such as wind or loads moving on the scale base while weighing is in progress.

The discussion of electronic load cells starts with the strain-gauge type sensors. These detectors, their circuits, and electronics have already been discussed in Sections 5.7, 7.19, and 7.21, so the reader is also referred to those sections.

**STRAIN-GAUGE-TYPE LOAD CELLS**

One of the first uses of the bonded resistance wire strain gauge following its discovery in the early 1940s was in the development of an accurate and reliable load cell or force transducer. The strain gauge and its applications have been one of the most intensely researched fields in recent technological history. As a result of this work, there is a wide variety of accurate, stable, and reliable strain gauge load cells available for nearly all applications.

Strain gauge load cells represent the most practical means of weighing. One of the largest uses is in retailing, but other uses include postal and shipping scales, crane scales, laboratory scales, onboard weighing for trucks, and agricultural and petrochemical applications. Strain gauge applications include thrust measurement on rocket and jet engine test stands, launching pads, and also wind tunnels and other branches of aeronautical research.

**Operating Principle**

If a wire is bonded to a spring element in such a manner that its cross section varies as the spring element is strained, it is possible to establish a relationship between the electrical resistance of the wire and the force causing the deformation of the spring element. Strain gauge load cells are designed to permit controlled elastic deformation of the spring element.

In Figure 7.25q, a column is loaded in the direction of the Z-axis. Bonded to the four sides of the column are grids...
of fine wire, a, b, c, and d. As load increases, gauges a and c tend to decrease in length, and their resistance decreases. Gauges b and d, mounted perpendicular to Z, are placed in tension by the column tending to decrease in cross section (Poisson effect), and their resistance will increase.

The four gauges are connected into a Wheatstone bridge circuit as shown in Figure 7.25r. By having gauges b and d strain opposite to a and c, the bridge unbalance due to load variations is amplified and output voltage is greater than if b and d were strained in the same manner as a and c.

In the 1950s, metallic foil bonded strain gauges were introduced and quickly supplanted wire gauges in most forms of strain gauge load cells. Using foil instead of wire improved heat dissipation, reduced creep effects, and allowed much greater design freedom in adapting gauge shapes and sizes to complex transducer geometry. For a discussion of the more recent diffused semiconductor and thin-film designs refer to Sections 5.7 and 7.21.

**Design Variations**

The most critical mechanical component in any load cell is the spring element. Broadly stated, the function of the spring element is to serve as the reaction for the applied load, and, in doing so, to focus the effect of the load into an isolated, preferably uniform, strain field where strain gauges can be placed for load measurement. Load cell spring elements can be divided into three types: bending, shear, and direct stress. Each will be described below.

**Bending or Cantilever Elements** The simplest beam configuration for a bending transducer is the basic cantilever beam (Figure 7.25s). In configuration A, pairs of longitudinally aligned strain gauges are mounted on the upper and lower surface, near the root of the beam. For certain types of applications, the characteristics of the straight cantilever beam can be improved upon by designs that induce multiple bending in the beam element. A rather simple and popular way of accomplishing this in commercial load cells is shown in configuration B, often referred to as the binocular design.

Another type of bending spring element, which ranks with the beam designs in terms of the number and variety of its implementations, is the ring. The ring design is shown in configuration C in Figure 7.25s.

Figure 7.25s shows some of these elements incorporated into canister-type (A, B, and D) or cantilever-type (C) load cell installations. As was explained in connection with Equations 7.24(1) and 7.24(2), this type of load cell is insensitive to changes in the location of the point of loading. Therefore, it can tolerate some amounts of tank movement due to thermal expansion or other causes. The cantilever beam design is also insensitive to torsional loads. This insensitivity can permit the use of simplified installations and less staying or restraining of the weigh tanks.

**Beam-Type Load Cells** The beam-type design consists of a slotted bending beam construction (Figure 7.25u). Strain gauges at the locations shown are arranged in a Wheatstone bridge configuration, so that the output of the sensing element is independent of the position of the applied load. Electrical compensation of the bridge circuitry can reduce the load position sensitivity to virtually zero. As will be observed, this is a very important feature.
Protection from environment effects is by a simple bellows arrangement, making the conventional diaphragm and cylindrical casing unnecessary. Strain gauge location and beam design make the installation insensitive to variations in the location of the loading point or to end loading and torsional loads. This simplified load sensing configuration provides inherent linearity as well as very low creep and very high repeatability. Typical performance features are summarized in Table 7.25v.

**Shear Elements** The operating principle of the shear-web spring element is illustrated in Figure 7.25w. At section P–P of the beam, a recess has been machined in each side, leaving a relatively thin web in the center. Pairs of strain gauges, with their grid lines oriented along the principal axes, are installed on both sides of the web. Shear-web spring elements are not limited, of course, to cantilever beam configurations; a variety of other designs can also be found in commercial load cells.

**Direct Stress or Column-Type Elements** The history of the column load cell dates back to the earliest strain gauge transducers. The column spring element consists of one or more cylindrical members of the general form shown in Figure 7.25q. The spring element is intended for axial loading. It typically has a minimum of four strain gauges, two in the longitudinal direction and two oriented transversely to sense the Poisson strain. Column spring elements take on a wide variety of forms in designers’ attempts to optimize the load cell in terms of both production and performance considerations. The column cross-

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**TABLE 7.25v**

*Performance of Beam-Type Strain Gauge Transducer*

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated capacity range</td>
<td>10 to 5000 lbs (4.5 to 2270 kg)</td>
</tr>
<tr>
<td>Output</td>
<td>2 mV/v</td>
</tr>
<tr>
<td>Terminal linearity</td>
<td>±0.03%</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>0.015%</td>
</tr>
<tr>
<td>Creep (30 min)</td>
<td>0.02%</td>
</tr>
<tr>
<td>Temperature effect on zero</td>
<td>0.15%/100°F (38°C)</td>
</tr>
<tr>
<td>Temperature effect on output</td>
<td>0.08%/100°F (38°C)</td>
</tr>
</tbody>
</table>

---

**FIG. 7.25t**

Canister (A, B, D) and cantilever (C) load cells with strain gauge elements that detect bending.

**FIG. 7.25u**

*Beam-type strain gauge transducer.*

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section may be square, for example, instead of circular, or it may be circular with flats machined on four sides to facilitate strain gauge installation (Figure 7.25x).

**Transducer Design**

Selection of the transducer spring material deserves careful attention. Linear-elastic load response, with minimal hysteresis, is one of the most desirable mechanical properties for a spring material. Among thermal properties, thermal conductivity is important. From a manufacturing perspective, it is important that the transducer material be easily machined and must harden without distortion.

The modulus of elasticity of the material is important in determining the dimensions of the spring element with respect to load rating. While steel alloys make excellent materials for high-capacity spring elements, they are often unsatisfactory for low-capacity units. In the latter case, to achieve suitable strain levels in reasonably thick and easy-to-machine sections, it is generally necessary to use low-modulus materials such as aluminum alloys.

Practical transducer design considerations dictate that the strain gauge be mounted in the area of highest strain. For most load-cell designs, a good general rule of thumb is that the strain under the gauge grid should not vary by more than 10 to 15% from the absolute maximum. Usually gauge lengths are in the range from 0.060 to 0.125 in. (1.5 to 3.2 mm).

**Strain Gauge Backings and Bonding**

Three broad types of strain gauge backings are commonly used in transducers. These are: polymides, epoxies, and reinforced epoxies. For the strain-sensing grids, four alloy types are commonly used: constantan, Karma, Isoelastic, and platinum-tungsten. Since not all backing alloy combinations are mutually compatible, the strain gauge catalog must be consulted for actual selection.

No single manufacturing step in transducer production has more influence on the performance and longevity of a transducer than does strain gauge bonding. Paramount to this process is the selection of the appropriate adhesive. The epoxies form the largest class of adhesives used for strain gauge bonding. Cyanoacrylate adhesive is used in simple load cells where high accuracy is not required.

**Strain Gauge Circuits**

As illustrated in Figure 7.25y, modern strain gauge transducers commonly employ four strain gauge grids electrically connected to form a Wheatstone bridge measuring circuit. All strain
gauge load cells are compensated for the effects of temperature on zero shift and span. This is accomplished by making the strain wires out of temperature insensitive alloys and introducing suitable compensating resistors into the bridge network.

A typical strain gauge circuit is shown diagrammatically in Figure 7.25y. The output signal of a strain gauge is relatively small and is a function of the excitation. A common value is 2 to 3 mV per volt of excitation. The excitation voltage (AC or DC) is usually in the range of 5 to 20 V, with values in the order of 12 V recommended for average installations.

**Performance of Strain Gauge Load Cells**

As a result of increasing experience and a widening background of empirical knowledge, it is practical to consider the use of strain gauge load cells on installations requiring inaccuracies from ±0.03 to ±0.25% of full scale.

Temperature compensation systems for span and zero shift are now an intrinsic part of all high quality strain gauge load cells. Nevertheless, for operation outside normal temperature limits, generally –4 to 160°F (–20 to 70°C), the use of correction factors is needed. One might also provide means of controlling temperatures around the load cells by auxiliary means.

Strain gauge load cells should be protected from angular or nonaxial loads. Any force other than normal or axial will tend to cause bending of the support column or columns. Inasmuch as a strain gauge cannot discriminate between bending and axial loads, errors in output can result. Where strain gauge load cells are installed under tanks, bins, or hoppers that are subject to excessive bending, expansion, or contraction, special mounting equipment is available to help isolate the load cell from undesirable external side forces (Figures 7.25f, 7.25g, 7.25h, and 7.25i). In extreme cases, specially designed mounting pedestals may be required.

Strain gauge load cells are designed for operation within specific capacity ratings. Excessive overloads may result in loss of accuracy or failure. In general, the load cells should not be subjected to more than 125% of their rated capacity. This includes impact or shock loading, as well as static loading.

**OTHER LOAD CELL DESIGNS**

For the sake of completeness, a large variety of load cell designs are described in the following paragraphs. The capacitance-type load cells are not covered here, because their principle of operation has already been described in connection with Figure 5.7i. Similarly, the piezoelectric dynamometer load cells are not discussed here either, as they have already been discussed in Figure 7.21b. Some of the load cell designs that are discussed in the following paragraphs are only addressed to make the coverage of the topic complete (inductive, reluctance, magnetostrictive), but they are not widely used.

**Semiconductor Strain Gauge**

The scientists at Bell Laboratories discovered the piezoresistive characteristics of germanium and silicon semiconductor materials in the mid-1950s. It was discovered that the terminal resistance of these devices is highly sensitive to applied stress or strain. In fact, their gauge factors (unit change in resistance divided by unit strain) are more than fifty times those of their metallic wire or foil strain gauge counterparts.

While possessing very high strain sensitivity relative to that of metallic strain gauges, they also exhibit substantial nonlinearity, and temperature effects on strain sensitivity and terminal resistance are also relatively high. The latter characteristics have somewhat limited their application. Nevertheless, semiconductor strain gauges are used in force measuring devices in which high output signal level and low system cost are the primary objectives.

Semiconductor strain gauges in load cell configurations provide units with rated output capabilities of 1.0 V at 15 V bridge excitation. As a result of the high signal level, semiconductor units are used in simple weighing systems with simple regulated power supplies and direct meter readouts. Sometimes an amplifier is interposed between the transducer and the meter display.

Typical performance characteristics of semiconductor load cells are listed in Table 7.25z along with the load cells’ metallic strain gauge counterparts.

The moderately high cost of semiconductor load cells and the dramatic cost reductions in linear integrated circuitry have limited the use of the semiconductor load cell in low cost weighing systems. In other words, the cost of linear amplification required to raise metallic strain gauge load cell signals to the levels offered by their semiconductor counterparts is now less than the additional cost for semiconductor load cells.

**Nuclear Radiation Sensors**

This form of weight sensing is generally applied to in-motion weighing of bulk materials. It utilizes a radioactive source of gamma rays that are directed through a certain section of the moving material. The material absorbs some of the gamma
rays and allows others to pass through. The amount of radiation transmitted through the bulk material depends on the amount of material on the conveyor.

A radiation sensor converts the transmitted radiation to an electronic signal, which bears a known relationship to the amount of material on the weighing section of the conveyor (Figure 7.25aa).

The nuclear radiation form of weight sensing is applicable when the weight sensor should not contact the material or the conveying devices. Certain shortcomings of conventional belt scales can be avoided with this technique.

**Inductive Sensing**

Inductive weight sensors use the change in inductance of a solenoid coil with changing position of an iron core. Two forms of the inductive sensing principle are illustrated in Figure 7.25bb. If iron core in configuration #1 moves to the right, the inductance of coil B increases and the inductance of coil A is reduced. Arranging the two coils in a Wheatstone bridge with resistors completing the bridge network provides a means for developing a voltage signal proportional to the core position.

Configuration #2 utilizes three solenoid coils. Coils C and D are wound in opposite directions and surround an iron core, whereas coil E is placed between the two coils and is excited by an external AC voltage source. When the iron core is centrally located, voltages induced into the secondary coils (C and D) are equal and opposite, and no voltage appears across the output terminals (F and G). If the iron core is moved to the right, the voltage coupled into coil D is greater than that coupled into coil C, and a voltage is developed at the output terminals.

If the core were moved in the opposite direction by the same amount, a similar voltage of opposite phase would be developed. Other embodiments of inductive sensors are in current use. Those discussed here are for illustrative purposes only.

Inductive sensors furnish relatively high output signal levels and efficient null stability. Since their inertial masses are greater than strain gauge sensors, they are more subject to vibration.

**Variable Reluctance Sensing**

This design is similar to the inductive sensing method. The difference is that here the inductance of one or more coils is changed by altering the reluctance of a very small air gap. This technique is illustrated in Figure 7.25cc. Solenoid coils A and B are mounted on a structure of ferromagnetic material, and a U-shaped armature completes the magnetic circuit through air gaps 1, 2, and 3. Motion of the coil assembly to the right decreases air gap 2 while air gap 1 is increased. Air gap 3 remains constant during the translation of the coil assembly.

As a result of horizontal translation, the inductance of coil B increases while that of coil A drops. Incorporating the two coils in a Wheatstone bridge similar to that utilized in

---

**FIG. 7.25aa**

*Nuclear belt scale. (Courtesy of Thermo MeasureTech/Kay-Ray.)*

**FIG. 7.25bb**

*Inductive sensing techniques.*

**FIG. 7.25cc**

*Variable reluctance sensing technique.*
the inductive sensing principle permits development of a voltage proportional to the translation of the coil assembly.

The variable reluctance sensing principle also offers a relatively high output voltage and efficient null stability with the higher vibration sensitivity due to the relatively high inertial masses of the mechanical structure.

**Inductive and Reluctance Load Cells**

Inductive and reluctance load cells incorporate the two basic sensing principles in the same way (i.e., the motion of a ferromagnetic core [inductive] or a coil assembly [reluctance] is converted to a voltage signal directly proportional to the displacement).

Various force sensing elements convert the applied force (weight) to a displacement to which the sensing element is coupled (Figure 7.25dd).

These transducers furnish relatively high output signal levels and moderate to high accuracy. They also cover a broad range of measuring capacities (Table 7.25ee).

**Magnetostrictive Sensing**

Based on the Villari effect, this technique utilizes the change in permeability of ferromagnetic materials with applied stress. A stack of laminations forms a load-bearing column (Figure 7.25ff), and primary and secondary transformer windings are wound on the column through holes oriented as shown. Coil A is excited with an AC voltage and coil B provides the signal voltage. In the unstressed condition, the permeability of the material is uniform throughout the structure. Since the coils are oriented at 90 degrees with respect to each other, little or no coupling exists between coil A and coil B. Hence, no output signal is developed.

When the column is loaded, the induced stresses cause the permeability of the column to be nonuniform, resulting in corresponding distortions in the flux pattern within the magnetic material. Magnetic coupling now exists between the two coils and a voltage is induced in the signal coil, providing an output signal proportional to the applied load.

The magnetostrictive principle produces relatively high output signal levels and offers extreme ruggedness in load cells incorporating this sensing principle.

**Magnetostrictive Load Cells**

Magnetostrictive sensing load cells (pressductors) are finding use in industrial applications in which large output signals and ruggedness are desirable. Several typical configurations are shown in Figures 7.25gg and 7.25hh.

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**TABLE 7.25ee**

Performance Characteristics for Inductive or Reluctance Load Cells

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity range</td>
<td>0.01 to 100,000 lbs (0.0045 to 45,000 kg)</td>
</tr>
<tr>
<td>Rated output range</td>
<td>5 to 200 mV/V</td>
</tr>
<tr>
<td>Linearity range</td>
<td>0.1 to 0.5%</td>
</tr>
<tr>
<td>Repeatability</td>
<td>0.05%</td>
</tr>
<tr>
<td>Temperature effect on zero</td>
<td>1%/100°F (38°C)</td>
</tr>
<tr>
<td>Temperature effect on output</td>
<td>1%/100°F (38°C)</td>
</tr>
</tbody>
</table>
Safety and Miscellaneous Sensors

The first configuration is for applications in which there are no bearing surfaces on the devices being weighed; in the presence of lateral loads, the pressductor is very sensitive unless adequately protected. The vertical load (Figure 7.25gg) is transmitted through the flexures (1 and 2) to the sensing element (3). The same flexures also transmit lateral forces to ground in a way so that the pressductor sensing unit is subjected to only a small portion of the adverse lateral loads.

The second embodiment (Figure 7.25hh), designed for weighing during coiling operations, uses a similar construction with an additional overhanging member (4) that supports the coiler shaft, and continuous weighing during coiling operations is provided. All units are adequately protected with watertight covers to accommodate applications in industrial environments.

New pressductor designs provide weighing inaccuracies of 0.1% of rated capacity. Output signal levels range from 1 to 20 VDC, with source impedance ranging from 0.5 to 25 Ω. Overload ratings as high as fifteen times the rated load are supplied. Although usable for weighing, the pressductor has greater applicability in the steel industry for the measurement of roll-forces in rolling mills and strip-tension in strip mills.

**Linearization of Load Cells**

Column-type strain gauge load cells in capacities above 10,000 lb (4500 kg) heretofore have suffered from a characteristic nonlinearity of about 0.15% of rated capacity. The inherent nonlinearity of these devices results from electrical bridge nonlinearity caused by the fact that all strain gauges are not subjected to equal strain. Additional nonlinearity also results from the column area change with increasing load. The characteristic column-type load cell nonlinearity is parabolic and lends itself to almost perfect compensation by utilizing a semiconductor strain gauge compensating element.

Figure 7.25ii shows a semiconductor strain gauge incorporated in series with the excitation terminals of the load cell bridge circuitry. From the curve of output voltage vs. applied load, an uncompensated column-type load cell exhibits a drooping concave downward characteristic when loaded in compression. The linearizing strain gauge senses column strain induced by the applied compressive load and, due to its piezoresistive characteristics, its terminal resistance decreases with increasing load. The decreasing resistance with load causes the net excitation voltage applied to the bridge circuitry to increase with increasing load (dotted line), which compensates for the drooping characteristic of the uncompensated load cell and results in improved linearity (interrupted line). Adjusting the terminal resistance of the linearizing strain gauge almost exactly compensates for the inherent parabolic drooping characteristic, and terminal linearity of better than 0.02% of rated load can be provided.

Linearity of this magnitude not only eliminates external linearization within the instrumentation, but also reduces errors in multiple load cell weighing systems in which unequal distribution of total load between the individual load cells may be substantial. Unequal loading on nonlinear load cells can cause serious system errors, even in systems in which load cell nonlinearity compensation is included in the display instrumentation.

**Load Cell Housings and Safety**

The standards governing the sealing of load cells are usually based on sealing against water only; they are not useful in connection with chemical protection. The typical water-sealing test is performed by submerging the load cell for
0.5 \text{ h in 3 ft (1 m)} \text{ of water. The hydrostatic head of the water is usually less than the water pressure that can occur during wash-down procedures.}

Load cells for explosive atmospheres are specially designed and tested. For Europe, the regulations are dictated by the European Committee for Electro-technical Standardization (CENELEC). (For electrical safety practices in the United States, see Section 7.2.) The best protection can be achieved by using a flameproof enclosure. This protection is called \text{d} and is marked as \text{EEx-d}. With this type of protection, the load cells can be directly connected to the instrument in the safe area.

Another solution is to place Zener barriers between the instrument and the load cells. This is called intrinsic safety \text{i} and is marked as \text{EEx-i}. However, it should be noted that the load cells and the indicator are temperature-compensated devices and the Zener barriers have a serious temperature effect. The instrument must be compensated for temperature errors.

The classification system used to identify situations where the presence of electrical equipment could create an explosion hazard is differently determined in various countries. In the United States, Factory Mutual is the recognized leader in certifying equipment for hazardous environments. A hazard can be caused by the equipment’s generating enough heat to reach the ignition temperature of ambient gases (or dusts) or by generating an arc due to shorting or to opening an electrical connection.

**Intrinsic Safety**

Ultra-low power displays are marketed by some weighing system manufacturers like Fairbanks Scales. This instrument is intrinsically safe for every class, division, and group of the classification discussed above. It has fiber-optic digital outputs, 1 to 4 set points, and 4 to 20 mA analog output for weighing and for process control applications. It needs no explosion-proof enclosures, and its 1.25 in. (30 mm) large liquid crystal displays are easy to read. Both the platform and the indicator can be placed in the same hazardous area. The battery, which powers the unit, lasts up to 6 months before recharging is required.

**SPECIAL APPLICATION**

**High Temperature Load Cells**

As load cell weighing was applied to the metal processing industry, the need for devices to withstand high environmental temperatures became pressing. In recent years, organic and inorganic bonded strain gauge backing and installation materials have become available and can withstand higher temperatures than conventional units. Bonded strain gauges with organic backings are now available for continuous operation at temperatures as high as 500°F (260°C).

On special applications, high temperature strain sensing wire alloys have been installed with inorganic bonding materials, such as ceramic cements and flame spray techniques, where molten aluminum oxide is sprayed on the sensing element and on the strain sensing grid to hold the latter firmly in place. These installations allow short-term operation at temperatures of 1000°F (538°C), but with some degradation in performance.

**Weighing of Tank Legs**

In some installations, load cells cannot be used at all. This can be because the structures are already fabricated and erected, and their support by load cells would require extensive field modification.

One solution to the weighing of these structures is installing strain gauges directly on the supporting legs. In such installations, the legs become the sensing elements to which the strain gauges are applied in full bridge configurations.

In a typical installation (Figure 7.25jj), a pair of gauges is applied longitudinally, sensing the compressive stresses in the tank legs. Another pair is applied in the transverse direction, sensing the tensile strains due to the Poisson effect. The four gauges are connected in a Wheatstone bridge arrangement and leads are brought out from each leg to a summing box and from there to the readout instrumentation. The installation is thoroughly protected with waterproofing materials.

Usually, the strains established in the supporting legs are very low and it is difficult to achieve perfect waterproofing permanently. As a result, the accuracy of such a weighing system tends to be relatively poor—3 to 5% of rated capacity.

**DEVELOPING NEW SENSORS**

In the area of new sensor developments, fiber optic load cells are gaining attention because of their immunity to electromagnetic and radio frequency interference (EMI/RFI), suitability...
for use at elevated temperatures, and intrinsically safe nature. Work continues on the development of optical load sensors. Two techniques are showing particular promise: measuring the micro-bending loss effect of single-mode optical fiber and measuring forces using the Fiber Bragg Grating effect. Optical sensors based on both technologies are undergoing field trials in Hokkaido, Japan, where they are being used to measure snow loads on electrical transmission lines.

A few fiber optic load sensors are commercially available. One fiber optic strain gage can be installed by drilling a 0.5 mm diameter hole into a stud or bolt, and then inserting the strain gage into it. Such a sensor is completely insensitive to off-axis and torsion loads.

The development of micro-machined silicon load cells is also underway. At the Universiteit Twente in The Netherlands, work is progressing on a packaged monolithic load cell using micro-machining techniques, and it is possible that silicon load cells will dominate the weighing industry in the future.

**New Load Cells**

Load cell technology is advanced by improved accuracy, reduced sensitivity to interferences, increasing life through better sealing, better calibration, reduced costs through high volume production and calibration, and the use of built-in microprocessors. An illustration of a newer load cell is given in Figure 7.25kk. This bending ring load cell is only 3 in. in diameter and 1 in. tall (75 × 26 mm) for a load of 1.3 tons and 3.75 × 1.4 in. (95 × 35 mm) for a 13-ton load application.

Load cells of this type with foil strain gauges are produced for retail shop scales having a resolution up to 6000 graduations over their ranges. The foil gauges can be used down to 5 lbm (2 kg) and with bridge resistance values over 2 kΩ. With smaller loads, a force shunt occurs which increases the errors due to creep.

**Thin-Film Strain Gauges**

Load cells using thin-film strain gauges are available with nominal loads from 1 to 10 lbm (0.5 to 5 kg) and with a bridge resistance of 4 kΩ. These provide the measuring stability of load cells without hermetic metallic encapsulation of the strain gauge. Stability is tested for a period of 50 days with daily temperature cycles ranging from 77 to 131°F (25 to 55°C) under saturated conditions, which cause occasional condensation. The sensitivity of such a load cell having 5000 graduations may vary by up to 0.02%, and its zero signal may vary by up to 10% (Figure 7.25ll).

In the new thin-film load cell, CrSi thin-film technology is used. Stability and moisture resistance are provided by a patented insulation layer between the spring body and the strain gauge elements that consists of a fourfold sandwich of SiO₂ and Si₃N₄. SiO₂ supplies the necessary insulation against electronic current flows. Si₃N₄ prevents ion migration into the strain gauges that could otherwise happen due to the electric field generated by the bridge excitation (Figure 7.25mm).

Another problem in thin-film technology is the material of the spring element in the load cell. This is because the thin film has no creep at all, and the strain gauge cannot compensate for the creep of the spring material. For this reason, the spring material is the rather expensive FeNi alloy. Due to the cost of FeNi, the spring is rather small (3 mm thick).

Thin-film load cells have low power consumption, small size, and meet the following calibration requirements:

<table>
<thead>
<tr>
<th>Weight Range</th>
<th>Graduations (Divisions)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4 to 10 lbm</td>
<td>3000</td>
</tr>
<tr>
<td>2 to 4 lbm</td>
<td>2000</td>
</tr>
<tr>
<td>1 to 2 lbm</td>
<td>1500</td>
</tr>
</tbody>
</table>

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Hydraulically Damped Load Cells  Another new load-cell combines a mechanical damping system with adjustable mechanical tare compensation. The single-point load cells are provided with a damping plate immersed in high-viscosity silicone oil and provide a stabilized signal within 150 ms (Figure 7.25m). On applications involving bins or conveyors, preloads of up to 20 lbm (10 kg) can be tared out with the help of a built-in adjustable spring. Thus smaller-range load cells with higher output signals can be used for the same application.

The hydraulically damped load cells are available with 6 to 10 lbm (3 to 5 kg) ranges with a combined error of less than 0.02% full scale. They are particularly advantageous in multi-head, computerized packaging scales. Overload protection is effective up to 1000%.

Microprocessors and Networks

There are many load cell designs that are provided with built-in microprocessors. Some are able to withstand the adverse weather conditions in outdoor sites. Others contain a microprocessor that has been programmed to automatically recognize and correct errors caused by external influences or by the movement of the loads on the scale base while weighing is in progress. The capacity of some of these intelligent weight bridges can be in progress. 500 tons.

Interfacing with Programmable Logic Controllers  Advanced weighing modules can exchange weighing information on a digital bus or network, using 32 read and write registers, or work as a stand alone device (Modbus Plus, Modbus TCP/IP, Interbus, I/O bus supported).

They can interface with up to 8 load cells to give one weighing measure. Such modules have 4 inputs (tare, reset tare, zero, print) and two high speed outputs (1 ms resolution). Such advanced weighing modules bring the data to the programmable logic controllers. Therefore, it becomes global in the sense that the user has access to the weighing system from all the different devices on the plant’s network.

The Role of the Personal Computers  The output signals of the load cells must be compatible with computerized data processing systems and/or with personal computers (PCs). The software tasks include in-motion and multi-head scale weighing and the intergration of these systems into plant-wide bus systems.

An example of newer digital load cell electronics is the signal by Hottinger Baldwin Messtechnik. In this unit the electronic circuit is on a small board and it forms a link between the strain gauges and the serial RS-232 interface of a PC. It supplies the bridge with DC power and digitizes the output over the full measurement range. Gate-array technology is applied in the analog-to-digital (A/D) converter, utilizing a method of conversion that offers a resolution of 16 bits, coupled with a speed of 150 measurements per second.

Following the A/D conversion, the signal conditioning is implemented by a mask-programmed microprocessor that carries out the zero-point balancing and auto-calibration, scales the transducer signal, filters, forms mean values, and tares the system. The digital filter can provide suppression of noise or unwanted parts of the signal. Various filter cutoff frequencies are selectable. When averaging consecutive measurements, the measurement rate can be changed in steps.

There is also a trend to use PCs as weighing system components, because of their low cost and flexibility. One consideration in the use of PC is the operator accessibility of software functions and data security against manipulations.

Verified Weighing with PCs  Figure 7.25oo illustrates a method of verified weighing through the use of personal computers. In this system, the hardware and software for the handling of the verified data are collected in an external PC card that communicates through an optional slot with the PC. This is called the security unit (SU)—a data channel that transfers measurement and print data among the PC, printer, and verified receiver.

The video displays the verified data (with the highest priority) as a window into the existing picture on the PC monitor. As is shown on the block diagram, the output of the enhanced graphics adapter video card is directly connected to the video input of the SU. Therefore, a window for the display of weight data is generated into the normal display without an access possibility of the PC.

Networks and Buses  As one integrates weighing systems into plant-wide process control systems, it becomes an important requirement to easily connect single sensors and actuators into networks. Bus systems for high-capacity data transmission have been primarily developed for computer communication, and the demand for networking of passive field instruments started only recently. For a listing of the various fieldbus protocols and their attributes, refer to Table 7.24d in the previous section.

In Europe, the process field bus Profibus has been around for a while, and Sensorbus has also gained some ground. IISbus has been offered to the international standardization bodies based on a rugged and environmentally resistant connection method—the inductive coupling. Its ability to combine high data rates and power transfer to field devices operating...
in hazardous areas makes ISIlbus a useful contribution to the field bus concept.\(^4\)

**CALIBRATION AND TESTING**

Calibration and testing of large weigh-bridges is usually done by deadweights, and it is an expensive, time-consuming, and sometimes even dangerous process. To calibrate a 60 or 100-ton road weigh-bridge or 200-ton railway weigh-bridge, considerable amounts of standard weights must be transported to the location and placed on the bridge.

The idea of the application of master load cells instead of standard weights is not new, but until recently, their stability and accuracy were not satisfactory. The accuracy of the master cell must be at least 3 times better than that of the weighing cell. The master load cell approach\(^5\) offers 10 times higher resolution even when calibrating a 6-load-cell weigh-bridge with 3000 divisions.

In terms of the number of steps, this corresponds to \(10 \times 3000 \times 6 = 180,000\) steps. In the system illustrated in Figure 7.25oo, the force is generated by a DC servomotor instead of by hydraulic systems, which have been found to be unstable.

The procedure for calibration can involve incremental loading, where at each step in load the two output signals (weigh-bridge and master load cell) are compared, or it can be continuous. If continuous calibration is used, both sensors are triggered at certain load levels and the instantaneous readings are compared. Figure 7.25qq shows the results of the calibration of a 60-ton 6-load-cell weigh-bridge using deadweights and also using the test rig.

**Aircraft Weighing** The weighing of aircraft is a specialized application and serves the function of loading controls, deicing, etc.\(^9\) The weighing is done either by jacking and leveling the aircraft at three points or by using mobile weighing platforms. Still air environment is essential (even the blower heaters must be turned off) and an enclosed hangar is necessary.

The center of gravity of the airplane is obtained from weighing and is used to evenly distribute the passenger/cargo/fuel loads in the aircraft to ensure that the balance is within specified limits.

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\(^{7}\) FIG. 7.25oo  
Verified weighing with personal computer.

\(^{8}\) FIG. 7.25pp  
Weigh-bridge calibration using master load cells for reference.

\(^{9}\) FIG. 7.25qq  
The relative performance of a weigh-bridge when calibrated against deadweights and when calibrated against master load cells.
limits. For this purpose, the GEC Brainweigh microcomputer can be used, as it memorizes the geometry of most popular aircraft types and thereby provides quick and reliable measurements.10

**Packaging Industry** The packaging industry uses some of the most sophisticated scales. Net weighing scale technology has progressed substantially in recent years.

A new concept is the combination weighing system, which offers high packaging speeds. The system consists of a series of weighing heads with computer control. The Yamato Dataweigh design11 with 16 heads is able to produce 160 packs per minute with weighing precision of 2000 graduations per scale range.

The command console with a 16 bit microprocessor provides all necessary controls and monitors the operation. System connection is via optical fiber cables which guarantees noise-free operation. Information or commands are entered by touching the appropriately labeled rectangles on the light emitting diode touch screen. Menu-driven software makes it easy to call up operational, monitoring, or diagnostic displays.

In-line check-weighers can provide more than weight control. As the packages travel across the weigh cell platform, they are transported on flying belts, chains, or ultra light ribbons. These systems can attain product speeds of 400 to 500 units per minute. In addition to rejecting out-of-spec packages, their most important feature is the feedback, which controls the filling machine for automatic optimal adjustment of fill. The modern check-weighers inform line operators of almost everything they want to know about the product and its statistical weight, record, and trend.

The face plate of modern Yamato check-weigher is shown in Figure 7.25rr. Four reject modes and programmed, including the T1-T2-Qn modes in full compliance with International Electrotechnical Commission (IEC) legislation. The built-in bar graph indicator provides instant information on product weight deviation from the target. The stated accuracy is maintained up to a rate of 300 packs per minute.12

**References**

2. Siemens, “Siwarex R Bending Ring Load Cells,” catalog no. 05.91.
15. “Momentum-Based Weighing I/O Module of Modicon,” refer to www.Modicon.com or contact gilles.heinrich@modicon.com.
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