WEIGHING

The term "weighing" usually implies a measurement of mass. The mass of a body is a measure of the amount of substance it contains. A direct measurement of mass is not simple, but we are accustomed to sensing the mass of a body in terms of its weight, that is, how "heavy" it is. The weight of a body is dependent on its mass and also on the strength of the gravitational field in which it is located. Comparison of the weight of one body with the weight of another in the same gravitational field is a relatively simple task, and because much of our experience occurs within a common gravitational field, that of the earth, we can use the process of comparison of weights as a means of measuring mass. But in doing so we must be careful not to confuse mass and weight, remembering that they are essentially different quantities.

There are ways of measuring mass that do not rely on the presence of a gravitational field. One can for example measure the *inertial mass* of a body by measuring a change in momentum. But these methods are only appropriate in special circumstances and will not be described here.

As we shall see below, the measurement of weight is essentially the measurement of a force—specifically, the force exerted by a body in a gravitational field on its support. The second part of this article concentrates on the measurement of force, with particular reference to force measurements for the purpose of weighing.

MASS AND WEIGHT

We should first establish the meaning of the terms mass and weight. Mass is a measure of the amount of substance in an item. Everything has mass, and the mass of a body is independent of its other properties. Unfortunately, human beings cannot detect mass. However we are sensitive to the force that results from a body's mass. This force is revealed in two ways, either by the inertia of the body (inertia is the tendency of a body to resist a change in motion), or by the attraction between bodies. The attraction between bodies provides the most common means of measuring mass, through weighing.

All bodies are attracted to one another. The strength of the gravitational attraction between two bodies results in an acceleration of each towards the center of mass of the other. In the case of a body whose mass we wish to measure in the earth's gravitational field, the acceleration of the earth toward the body will not be apparent (and will be very small), so we need only consider the acceleration of the body toward the center of mass of the earth.

A body supported on the surface of the earth senses the acceleration of gravity but does not move. Instead it exerts a force on its support. This force is what we call weight. In the absence of an atmosphere the weight of a body is equal to the product of its mass and the gravitational acceleration it is subjected to. (The earth's atmosphere complicates matters by creating an upward force proportional to the volume of the body, effectively reducing its weight. We shall discuss this issue in detail below).

So we have seen that while mass is a fundamental quantity of a body, weight is dependent on mass and on the presence of a gravitational field. In common usage the term "weight" is often used incorrectly to mean "mass," a practice that causes much confusion when discussing the measurement of mass by weighing. For the remainder of this article we shall carefully distinguish these two quantities and use the correct term for each.

However, we must also be aware that the word "weight" can have another meaning. We have already seen that it can mean the attracting force between a body and the earth. It can also mean an artifact used in weighing as a reference standard of mass. This can lead to confusion, so care must be taken to ensure that the meaning is clear (1).

A BRIEF HISTORY OF WEIGHING AND MASS STANDARDS

A History of Weighing

Weighing, by which we mean using a balance to measure the weight of a body or to compare the weight of two bodies, has been done for thousands of years. Images from the earliest civilizations in the Middle East show weighing using a beam balance. The process has continued almost unchanged until the present day. As recently as the medieval times, monetary value was measured by weighing. The coin in use in Britain was the silver penny, chiseled in two for a halfpenny and in four for a quarter-penny or farthing (fourthing). The pennyweight was $\frac{1}{240}$ of the "pound of Troyes" (named after a city in France which was the center of mercantile trade in the twelfth century). This pound was 5760 grains—barleycorn grains selected in a precise manner. The *troy* weight system (20 pennyweights to the troy ounce and 12 ounces to the pound) was used for all precious materials and for bread, the price of which was controlled by law from the twelfth until the nineteenth century. (In 1280, a "farthing loaf" weighed about $3\frac{1}{2}$ pounds.)

A later system of weights introduced the "haber de peyse" or *avoirdupois* pound, which was eventually fixed at 7000 grains, and divided into 16 ounces each of 16 drams. The only direct connection between the values of the troy and avoirdupois systems is the grain of barleycorn.

Another important measure of wealth in Britain was wool, which by the fifteenth century accounted for over half of the country's export trade. For this, larger measures of weight were needed, and the lowest value in common use was the stone, which varied in value for many years but eventually settled at 14 avoirdupois pounds. Two stones made a quarter, and four quarters a hundredweight. Three hundredweights made a sack.

Fine weighings were needed for medicines, and for that purpose the *apothecaries'* measure was based on the Troy ounce—20 grains to the scruple, three scruples to the drachm, and eight drachms to the ounce (2).

When dealing with all these different systems of weight measurement, the benefit of a single, universally accepted system soon becomes apparent. The metric system, based on the kilogram, is now in use in most of the world.

The Birth of the Metric System

In 1790 King Louis XVI of France commissioned his country's leading scientists to recommend a consistent system for weights and measures. The report that the French scientists (Lagrange, Lalande, Laplace, Borda, Monge, and Condorcet) presented to the Academy of Sciences on March 19, 1791 recommended a system based on a unit of length, the meter, equal to one ten-millionth part of the arc of the Earth's quadrant, pole to Equator. The unit of mass would be equal to the mass of a defined volume of water *in vacuo* at its freezing point. Legislation authorizing construction of this new system of units was passed on March 26, 1791, and the metric system of measurement was born (2).

After the 1791 report, measurements were made to decide an appropriate volume of water for the standard of mass. In 1775 it was agreed that the unit would be the mass of one cubic decimeter of water at a temperature of 4°C (which is approximately the temperature at which the density of water has a maximum value). This unit would be called a kilogram, and the mass of one cubic centimeter of water would be called a gram.

Brass weights were made whose mass was equal to the new unit, the kilogram, then later a weight of platinum was made, and adjusted to the value for the new unit (18,827.15 French grains). This platinum weight became known as the *Kilogramme des Archives,* and was effectively the standard of mass for most of Europe. It was soon realized that the mass of this kilogram artifact was not exactly that of a cubic decimetre of water; thus the link between mass and volume measurements was effectively broken.

International interest in measurement standards grew quickly, and in 1870 and again in 1872 the French government called meetings to discuss the construction and distribution of new metric standards. At a third meeting, in 1875, eighteen countries subscribed to a treaty, called the *Convention du Metre,* by which the *Comité International des Poids et Mesures* (CIPM) and the *Bureau International des Poids et Mesures* (BIPM) were set up, to be responsible for the custody and verification of metric standards. The convention agreed that a new kilogram weight should be made using an alloy of platinum and iridium (90% : 10%). After many attempts in France, a successful casting of the alloy was made by George Matthey of Johnson, Matthey and Co. of London, and in 1879 three cylindrical pieces of the alloy were delivered to a French metallurgist, St-Claire Deville. The cylinders were hammered in a press, and then polished and adjusted and finally compared with the *Kilogramme des Archives* by M. Collot, a maker of weights and balances. By 1883 the CIPM were convinced that one of the cylinders "was indistinguishable in mass from that of the *Kilogramme des Archives,*" and this weight was chosen as the international prototype of the kilogram (3).

A further 40 one-kilogram weights had been ordered from Johnson, Matthey & Co. in 1882 and were delivered in 1884. After reheating and hammering to increase their density, these were adjusted to be close in mass to the newly selected international prototype. In 1889 each signatory of the *Convention du Metre* (by now 20 countries) was allocated one of these weights. The allocation was made by lot, the United States being given Copy No. 20 and the United Kingdom receiving Copy No. 18. The certificate that accompanied Copy No. 18 on its first journey to the United Kingdom gives its mass as 1 kg + 0.070 mg, with an uncertainty of ±0.002 mg, and its volume as 46.414 ml at 0°C. To this day Kilogram 18 is the cornerstone of measurements of mass in the United Kingdom. At its last calibration at the BIPM in 1997 its mass was found to be 1 kg + 0.061 mg ±0.004 mg, and its volume at 0°C (calculated from the original value in milliliters) as 46.4149 cm^3.

The Unit of Mass in the SI System

The unit of mass in the International System of Units (SI) is the kilogram, which is abbreviated kg. The value of the kilogram is defined as being "equal to the mass of the international prototype of the kilogram" (4). The kilogram is unique in the SI system of units in being the only unit whose definition is based on a physical artifact.

GRAVITY AND DENSITY

Gravity

Sir Isaac Newton described gravity in terms of the attracting force between two bodies, which is proportional to their masses and inversely proportional to the square of the distance between them. However, in considering the gravitational field of the earth and its effects on bodies that we are weighing, we need only consider the attraction of the body to the earth, which depends on the mass of the body and its distance from the center of the earth.

The earth is not quite spherical, having its greatest diameter at the equator. In addition, the earth is rotating on its axis, which creates a "centrifugal" force acting at 90° to the direction of spin and proportional to the speed of rotation. It therefore follows that the value of gravitational acceleration will be smaller at the equator than at the poles. The value of gravitational acceleration at any latitude, at sea level, may be calculated using the following formula:

$$g = g_e(1 + 0.005\,302\,4\sin^2\Phi - 0.000\,005\,8\sin^2 2\Phi)\ \mathrm{m\cdot s^{-2}} \quad (1)$$

where

g = gravitational acceleration at desired location ($\mathrm{m\cdot s^{-2}}$)
g_e = gravitational acceleration at the equator = 9.780 327 $\mathrm{m\ s^{-2}}$
Φ = latitude of location (deg)

The correction for altitude is $-3.088 \times 10^{-6}\ \mathrm{m\cdot s^{-2}}$ per meter above sea level. The above formulae give the best simple method of calculating the gravitational acceleration at a location where it has not been measured, and will almost always give results within $1 \times 10^{-3}\ \mathrm{m\cdot s^{-2}}$ and usually within $5 \times 10^{-4}\ \mathrm{m\cdot s^{-2}}$ (5).

The actual value of gravitational acceleration at a particular point will differ from that given by the equation above, due principally to the variability of the density of the earth from place to place. If an accurate determination at a particular location is required, a measurement can be made using appropriate apparatus. Also, in many countries the value of gravitational acceleration has been mapped for the entire country (by the British Geological Survey for the British Isles), and a value can be obtained on request.

Density

Density is the mass per unit volume of a substance, expressed in kilograms per cubic meter ($\mathrm{kg\cdot m^{-3}}$). All substances, whether solid, liquid, or gas, have density, and an accurate knowledge of the density of the body being weighed and the density of the air at the time of weighing is essential to the accurate measurement of mass.

The density of a solid object can be determined by weighing it suspended in a liquid of known density and noting the apparent loss in weight by comparison with its weight in air. The density of a liquid or gas can most easily be measured by reference to the apparent loss in weight of an artifact of known mass and volume immersed in it (often the change in apparent mass difference between two bodies of similar mass but different volume is used to give a smaller uncertainty of measurement).

The density of air can be measured as for other gases, but is commonly derived from a knowledge of the composition of the air and measurements of physical parameters. Air is composed of oxygen, nitrogen, water vapor, and a host of minor constituent gases, the most abundant of which are argon and carbon dioxide. A formula for the calculation of air density has been recommended by the CIPM and is internationally recognized (6).

Use of this formula requires measurement of temperature, pressure, and humidity, and for the highest accuracy of carbon dioxide content. The uncertainty of the calculated value of air density will depend on the uncertainty of measurement of the contributing parameters and on the uncertainty of the formula itself.

WEIGHING IN AIR—THE BUOYANCY EFFECT AND THE CONVENTIONAL VALUE

Archimedes' Principle and the Buoyancy Effect

The *weight* of a body is equal to the attractive force between it and the earth. We could measure this force and then divide it by the gravitational acceleration to determine the body's mass. We can measure the force by putting the body on the pan of a balance. But there is a complication.

Many centuries ago, the Greek philosopher Archimedes realized (while sitting in his bath, it is said) that when a body is immersed in a fluid, the fluid exerts an upward force on it that is equal to the weight of the fluid displaced by the body. When the upward force from the fluid is greater than the downward force due to gravity, the body will float on the surface of the fluid; otherwise it will sink, but part of its weight will be supported by the fluid. This discovery has since become known as Archimedes' principle. The magnitude of the upward force experienced by the immersed body is proportional to its volume and to the density of the fluid. We call this upward force the buoyancy force, or simply buoyancy.

When we think of fluids, we usually imagine liquids. But gases are also fluids and behave in the same way. We live immersed in a gas, which we call air. Air has a density, which, although only about one-thousandth of that of water, causes a significant buoyancy on most materials, the effect being greater on materials of lesser density. For any body in the earth's atmosphere, the force exerted on its support (= mass × gravitational acceleration) is reduced by the upward buoyancy force [= volume × density of air × gravitational acceleration, or (mass × density of air/density of body) × gravitational acceleration].

The result of this buoyancy effect is that a given mass of a more dense material exerts a greater force on its support than the same mass of a less dense material. Thus the two identical masses have different "weights." Hence one may deduce that to use the principle of weighing to determine mass, one must have a knowledge of the density of the materials being weighed and of the density of the air at the time of weighing. But it is unusual to have any accurate knowledge of the density of most items that are to be weighed, and the measurement of air density requires sophisticated instrumentation or calculation.

Conventional Value of Mass

To solve this problem a *conventional value of mass* has been defined. In doing so it is supposed that all items have the same density, and the air density in which the weighing is made is also assumed to have a fixed value. The conventional value of mass will not always be the same as the true mass, but for most practical purposes it will be close enough. The chosen density values on which the conventional mass value is based are 8000 $kg \cdot m^{-3}$ for the item's density (because this is close to the density of stainless steel, iron, and brass, materials that are commonly used to manufacture weights) and 1.2 $kg \cdot m^{-3}$ for the air density (because this is typical of the air density at sea level in most parts of the world). Put simply, "For a weight taken at 20°C the conventional value of mass is the mass of a hypothetical reference standard weight of density 8 000 kg m^{-3} which it balances in air of density 1.2 kg m^{-3}" (7).

For many practical purposes, weighings whose result is stated in conventional-value terms are quite satisfactory, although the true mass of the object being weighed may differ from the reported conventional mass. In particular, for the purposes of trade, commodities may be bought and sold using conventional mass with no net gain to the manufacturer, wholesaler, or buyer, provided the convention is consistently applied.

It is sometimes necessary to make a correction to the measured conventional value of mass, to allow for the difference in the density of the object being weighed or the difference in the density of the air at the time of weighing from the conventionally agreed values. Then we have

$$M_c = M_i\left[1 + \left(\frac{1}{\rho_w} - \frac{1}{8000}\right)(\rho_a - 1.2)\right] \quad (2)$$

where

M_c = corrected conventional mass value (kg)
M_i = indicated conventional mass value (kg)
ρ_w = density of artefact being weighed ($kg \cdot m^{-3}$)
ρ_a = density of air at the time of weighing ($kg \cdot m^{-3}$)

From Eq. (2) it can be seen that the correction is zero when either the density of the object or the air density at the time of weighing is equal to the conventionally agreed value. Knowing the normal range of air density (from meteorological data) and the range of density of materials to be weighed, it is possible to determine the limit of uncertainty for which there is no need to apply the correction.

It is also possible to deduce the true mass of an object from its conventional mass provided the density of the object is known:

$$M = M_c\left[1 + 1.2\left(\frac{1}{\rho_w} - \frac{1}{8000}\right)\right] \quad (3)$$

where

M = true mass of object (kg)
M_c = conventional value of mass (kg)
ρ_w = density of object ($kg \cdot m^{-3}$)

From Eq. (3) it can be verified that the conventional mass value of an object whose density is 8000 $kg \cdot m^{-3}$ is identical to its true mass.

WEIGHING METHODS AND EQUIPMENT

Weighing is performed for a variety of purposes, ranging from retail trade activities such as selling food to the public, through food preparation and packaging, chemical analysis, and wholesale trading to industrial product preparation and process control. For simple trade and analytical weighing the requirement is usually to have a suitable balance or weighing machine available for a variety of weighing tasks, while for industrial applications the weighing system is more likely to be a purpose-built, permanently installed part of the processing plant.

In many cases the design of balances and simple weighing systems does not differ greatly from the design of process weighing plants, but from the user's viewpoint the purchase of a balance is a very different issue from the specification of an industrial processing plant. A balance can be purchased directly, and is usually selected on the basis of a manufacturer's specification, whereas the design of processing plant requires specialist engineering skills.

Force measurement systems and industrial weighing applications are discussed later. Let us first consider the use of a balance for simple weighing activities.

Balances and Weights

A balance may be based on mechanical principles, such as the position of a loaded beam or the extension of a spring element, or on electrical principles linked to the measurement of force, or on a combination of both. Types of balances are discussed in detail elsewhere in this encyclopedia (see BALANCES), so here we shall concentrate on the method of use of a balance, rather than on the detail of its design and operation.

A mechanical balance may involve a balanced beam offering two weighing pans, one on either side of the balance point, or it may be of single-pan design. An electronic balance will usually be a single-pan device. On a two-pan balance it is possible to measure the difference between the masses of two bodies directly, while a single-pan device can be used to give an indication of the mass of a single body. The single-pan device may also be used to measure mass difference by sequentially weighing one object and then the other. Typically a two-pan balance is used to compare the mass of an unknown weight with that of a calibrated reference weight, whereas with the single-pan device the reference weight is used to calibrate the balance, after which the unknown weight can itself be calibrated. The majority of balances currently available for purchase are single-pan electronic devices, so these will be examined in depth. But a large number of two-pan balances are still in use, so these are also discussed below.

Two-Pan Balances. Two-pan balances may be *damped* so that the swing of the beam quickly dies away, but more commonly they are *free-swinging,* so that the beam continues to swing for a period of time before finally coming to rest. On a damped balance a reading can be obtained quickly but the sensitivity to very small changes of load may be much reduced. The free-swinging balance may be allowed to come to rest before a reading is taken, but that is very time-consuming. An alternative approach is to record the extremes of the beam swing in each direction and predict the final resting point from these. With care this method can produce satisfactory results with a significant saving of time. The same number of swings must be recorded for each weighing. Typically the first swing in either direction is ignored to allow the oscillating system time to establish a free oscillation; then three swings to one extreme interspersed with two to the other extreme are recorded. Analysis of the resulting data predicts the eventual rest point of the beam.

The most common method of use for a two-pan balance is to place a known reference weight in one pan and the unknown weight in the other pan. If the two weights are similar, the balance will indicate the mass difference, usually by means of a mechanical pointer or an optical scale. The balance must be calibrated so that the user can interpret the reading of the scale in terms of mass difference, and the calibration must be repeated regularly because the mechanical characteristics of the balance may change with time. Calibration of a two-pan balance is most easily achieved by observing the change in reading when a small, known mass is added first to one pan and then to the other.

If the lengths of the arms of the balance beam differ, the measurement result will be biased to one pan or the other. On a perfect balance, if the loads in the two pans are exchanged, the balance indication should remain the same except for a change of sign. But it is rarely the case that a balance is so perfectly set up, so it is common to take two readings, exchanging the weights between the pans before the second reading. The resulting mass difference is the mean of that obtained from the two readings. However, this method places some reliance on the stability of the balance during the time of the weighings, and two-pan mechanical balances are subject to a number of time-dependent effects. Therefore, for the smallest uncertainty of measurement the second weighing can be made a second time, before the weights are returned to their original pans and a fourth weighing is made. This *double–double weighing* method offers the best measurement uncertainty for a balance of this type.

Single-Pan Balances. Single-pan balances may be purely mechanical in operation, or involve electric force measurement. They may have a pan suspended below the weighing system, in which case access to the pan is hindered by the suspension mechanism, or be of "top-pan" design where the loading receptacle is freely accessible from above. Regardless of the operating principle, the method of use is similar.

The balance will be equipped with an indicator system to display the measured value. This may be as simple as a pointer attached to a spring or lever, observed against a printed scale, or as complex as an electronic digital display. The display mechanism will probably indicate in a unit of mass; nevertheless, all such systems require calibration to ascertain the difference between the displayed value and the true mass of the weight in the scale pan. Calibration can be performed using a suitably calibrated external weight, or may be dependent on the use of one or more weights built in to the weighing system (the "auto-cal" feature of many modern electronic balances). In either case it is necessary to know the uncertainty of the calibration weight, and where internal weights are used it is prudent to calibrate the device, or at least make occasional checks, using an external reference weight.

It is important to realize that, once calibrated, a single-pan balance is making measurements of force, and the indicated value will be dependent on the buoyancy effect, but more importantly on the value of gravitational acceleration. For this reason the balance should be calibrated in the location in which it will be used. (One major distribution company, selling balances manufactured and calibrated high in the mountains of China, received complaints of inaccuracy from a purchaser in a sea-side town in northern England.) The use of an internal reference weight to reset the *span* (the reading corresponding to full load) helps to overcome these problems, but if the internal weight is used to set the span of the balance, it cannot also be used to provide a calibration. Transportation of a balance is likely to affect its performance, hence adding further impetus to the requirement to calibrate in the location of use.

Other factors affecting the performance of single-pan balances are *hysteresis* (a difference in reading for the same load approached from a smaller load and from a larger load) and *eccentricity* (a difference in reading arising from placing the load toward one side of the pan, rather than centrally). These issues can be investigated during the calibration of the balance, while at the same time the sensitivity, linearity, and repeatability of loading are assessed.

The measurement uncertainty obtained using a calibrated balance to make measurements of unknown loads can often be improved significantly by using the same balance, together with an appropriate set of calibrated reference weights, to make comparison measurements. If done properly this approach can eliminate the uncertainties arising from nonlinearity, hysteresis, and long-term drift of the measuring system, and careful loading will minimize eccentricity effects. A measurement of the unknown weight is followed immediately by measurement of one or a group of reference weights of similar value. The closer the value of the reference weight(s) to the unknown, the less reliance is placed on the linearity of the balance. Repeated measurements allow assessment of repeatability, and comparison with a second reference weight adds confidence in the measurement. This method of substitution weighing is often referred to as *Borda's method.*

Weights. Weights, or reference mass standards, are available in a range of accuracy classes. The most widely recognized international classification of weights is that recommended by the International Organization of Legal Metrology in International Recommendation 111, "Weights of Classes E_1, E_2, F_1, F_2, M_1, M_2, and M_3," (8). Class E_1 weights are of the very highest metrological quality, typically used only by calibration laboratories of the highest order. These weights are made of nonmagnetic stainless steel, and handled with extreme care, using tongs or gloved hands to avoid contamination. Class E_2, and F_1 weights, also made of nonmagnetic stainless steel and handled only with gloved hands, are commonly used as transfer standards to calibrate weights of lesser classes. Class F_2 weights are typically used as working standards in an industrial laboratory, while class M weights, commonly made from cast iron, are used as working standards in the field.

Weights of any class require periodic recalibration to ensure that they have not become damaged or contaminated. Weights should be handled with an appropriate amount of care—greater for the higher-class weights. Weights of class F_2 and below will often be recorded as being within a given tolerance of their nominal value, and this must be taken into account when assessing the uncertainty of measurement of any weighings made with reference to them. Weights of the higher classes will usually be accompanied by a certificate stating their measured conventional values with associated uncertainties. The certified values should be used in all calculations associated with these weights.

Industrial and Process Weighing

For routine weighing of a variety of objects it is a simple task to purchase a balance and a set of weights from a supplier. But for weighings associated with industrial processes it is necessary to design the weighing apparatus as an integral part of the process equipment, which requires expertise both in the functional issues of the particular process, and in the selection, installation, use, and maintenance of appropriate force-measuring devices and systems. The remainder of this article is devoted to force measurement systems and transducers and their application to industrial and process control weighing.

FORCE

Force is a measure of the interaction between bodies. Force takes a number of forms, including short-range atomic forces, electromagnetic, and gravitational forces. Force is a vector quantity, with both direction and magnitude. If the forces acting on a body in equilibrium are summed around the periphery of the body, then they add to zero. If there is any resultant force acting, then the body is not in equilibrium and it will accelerate so that the rate of change of the body's momentum is equal to the force. If the body is held stationary in some way, then there will be a reaction acting on the body from the support structure that is equal in magnitude and opposite in direction to the force imposed. Although the definition of force units is based on acceleration of a free body, most force measurements are made on bodies in equilibrium, and are therefore measures of forces within a structure. The basis of most force measurements is that a physical support or link in a structure is replaced with a device that measures the forces acting at that point.

The SI unit of force is the newton (N); this is defined as the force that would give to a mass of one kilogram an acceleration of one meter per second per second. In practice, it is not convenient to accelerate 1 kg at $1\ \mathrm{m \cdot s^{-2}}$ to generate 1 N. Instead, the practical realization of the unit of force makes use of known masses that, when subjected to the effect of local gravitational acceleration, exert a known force on an earth-located support. The mechanical structure to handle and control such masses is known as a deadweight machine.

FORCE MEASUREMENT SYSTEMS

A force measurement system is made up of a transducer and associated instrumentation. The transducer is subjected to the force to be measured, and some resultant change in the sensing element of the transducer is measured by the associated instrumentation. The instrumentation may power the transducer in some way and may also process the output from the transducer before it is shown on an indicator. For many types of force measurement system, the term "load cell" is in common usage in place of "force transducer."

The instrumentation may be as simple as a dial gauge or as complex as a computer with associated analog-to-digital converters and excitation circuitry. The indicated value is the output of the force measurement system, which may be in units of force or other units such as volts. If the indicated value is not in units of force, then the user may need to perform a calculation based on a calibration to calculate the force value.

For the measurement made using a force device to be of any use, the uncertainty of that measurement must be known. Performance criteria for a force measurement system are described by the manufacturer in terms of a specification, which gives limits within which the behavior of the instrument can be expected to fall. However, this performance is generally given for a production series, and cannot be relied upon for a specific device unless verified by calibration.

Characteristics of Force Measurement Systems

Many physical principles are involved in the operation of different force measurement systems. The performance of these systems can, however, be described by a number of common characteristics, and the behavior of the system may be expressed graphically by plotting the indicated output value against the force applied to generate that value. It is then usual to fit a straight line to the resulting curve; deviation from this line is referred to as *nonlinearity,* and generally the largest such deviation is the value given for nonlinearity in the system specification. The difference of readings between the increasing and decreasing forces at any given force is called the *hysteresis.* The largest value of hysteresis is usually at the midrange of the system. Sometimes it may be useful to combine the nonlinearity and the hysteresis in a single figure. This is usually done by drawing two lines parallel to the best-fit line such that these lines enclose the increasing- and decreasing-force curves. The difference of output between the lines is halved and stated as combined error.

Any difference between the indicated value of force and the true value is an *error* of measurement, and may be expressed as percentage of actual force applied or percentage of full-scale output. *Full-scale output,* also known as *span* or *rated output,* is the output at rated capacity minus the output at zero applied force. *Sensitivity* is defined as the full-scale output divided by the rated capacity of a given load cell.

The ability of a force measurement system to measure force consistently is covered by the concept of *repeatability.* Repeatability is defined as the measure of agreement between the results of successive outputs of a force measurement system for repeated applications of a given force. The tests should be made by the same observer, with the same measuring equipment, on the same occasion, without mechanical or electrical disturbance, and calibration conditions such as temperature, alignment of loading, and the timing of readings held constant as far as possible. Although many manufacturers quote a value for repeatability as a basic characteristic of a transducer, it should not be considered as such. The value obtained for a transducer in a given machine will depend not only on the characteristics of the device itself, but also on temperature gradients, the resolution and repeatability of the electric measuring equipment, and the degree to which the conditions of the tests are held constant, all of which are characteristics of the test procedure.

In contrast to repeatability, *reproducibility* is defined as the closeness of agreement between the results of measurements of the same force carried out under changed conditions of measurement. Note that a valid statement of reproducibility requires specification of the conditions changed and may include changes in the principle of measurement, method of measurement, observer, measuring instrument, reference standard, location, conditions of use, and time.

A force measurement system will take some time to adjust fully to a change in force applied, and *creep* of a force transducer is usually defined as the change of output with time following a step increase in force from one value to another. Most manufacturers specify the creep as the maximum change of output over a specified time after increasing the force from zero to the rated force. *Creep recovery* is the change of output following a step decrease in the force applied to the force transducer, usually from the rated force to zero. For both creep and creep recovery, the results will depend on how long the force applied has been at zero or the rated value respectively before the change of force is made.

The frequency response of a force transducer is affected by the nature of the mechanical structure, both of the transducer itself and of its mounting. A force transducer on a rigid foundation will have a natural frequency of oscillation, and large dynamic errors occur when the frequency of the vibration approaches the natural frequency of oscillation of the system. If dynamic forces (ones that vary with time) are to be measured, the frequency response of the force measurement system must be capable of following the changing force. If a transducer is to be used with fluctuating forces applied, its fatigue life should also be considered.

The temperature coefficients of both the output at zero force and the sensitivity quantify the effect of temperature changes on a given system. A force measurement system may need to be kept at constant temperature, or set up well in advance to settle into the ambient conditions, if high-accuracy measurements are required. In some cases the temperature gradients within the measurement installation can create a problem even when the average temperature is stable.

Other influence quantities such as humidity, pressure, electrical power changes, or radio-frequency interference may have analogous effects to those of temperature and may be considered in a similar manner.

In general, a force transducer has two interfaces through which a force is applied. These may be the upper and lower loading surfaces of a compression force transducer or the upper and lower screw threads of a tension device. At each interface, there will be a force distribution, which will depend on the end loading conditions. A change in these loading conditions may therefore cause a change in the force distribution, resulting in a change of the sensitivity of the transducer, even though the resultant force at the interface remains unchanged. Depending on the design of the transducer, the change of sensitivity caused by a change of end loading conditions can be significant in comparison with all other effects.

The long-term stability of the sensitivity of force measurement systems is clearly important if they are to be used to compare the magnitude of forces at different times, perhaps months or years apart. This stability will be determined by several factors, including the stability of the force transducer's many components, the protection of the sensing components or other parts against humidity, and the conditions under which the system is stored, transported, and used.

FORCE TRANSDUCERS

There are many types of force transducer, and these may be used with instrumentation of varying complexity. Most force transducers employ some form of elastic load-bearing element or combination of elements. Application of force to the elastic element causes it to deflect, and the deflection is then sensed by a secondary transducer, which converts it into an output. The output may be in the form of an electric signal, as in strain-gauge and linear variable differential transformer (LVDT) load cells, or of mechanical indications, as in proving rings and spring balances.

The method of measuring the distortion of the elastic element varies considerably. The most often used method is to make measurements of the surface strain; when this is undertaken with electrical resistance strain gauges, such a transducer is known as a strain-gauge load cell. Strain-gauge load cells are the most common commercially available type of force transducer.

Another commonly used type of force transducer is based on the piezoelectric phenomenon exhibited by certain crystalline materials, where an electric charge is generated on the crystal surface, the amount of charge being proportional to the applied force. Many other physical relationships are also used, and force transducers based on these are described later.

Strain-Gauge Load Cells

Each such load cell contains an elastic element to which a number of electrical resistance strain gauges are bonded. The geometry and modulus of elasticity of the element determine the magnitude of the strain field produced by the action of the force. Each strain gauge responds to the local strain at its location, and the measurement is determined from a combination of these individual strain values.

The rated capacities of strain-gauge load cells range from 1 N to more than 50 MN, and they can be used with high-resolution digital indicators as force transfer standards. The shape of the elastic element used in load cells depends on a number of factors, including the range of force to be measured, dimensional limits, final performance, and production costs.

Figure 1 shows a selection of different elastic elements and gives their typical rated capacities. Each element is designed to measure the forces acting along its principal axis, and to be unaffected by side forces. The arrows in the figure indicate the principal axis of each element.

The material used for the elastic element is usually tool steel, stainless steel, aluminum, or beryllium copper. The ideal material exhibits a linear relationship between stress and strain with low hysteresis and low creep in the working range. There also has to be high level of repeatability between

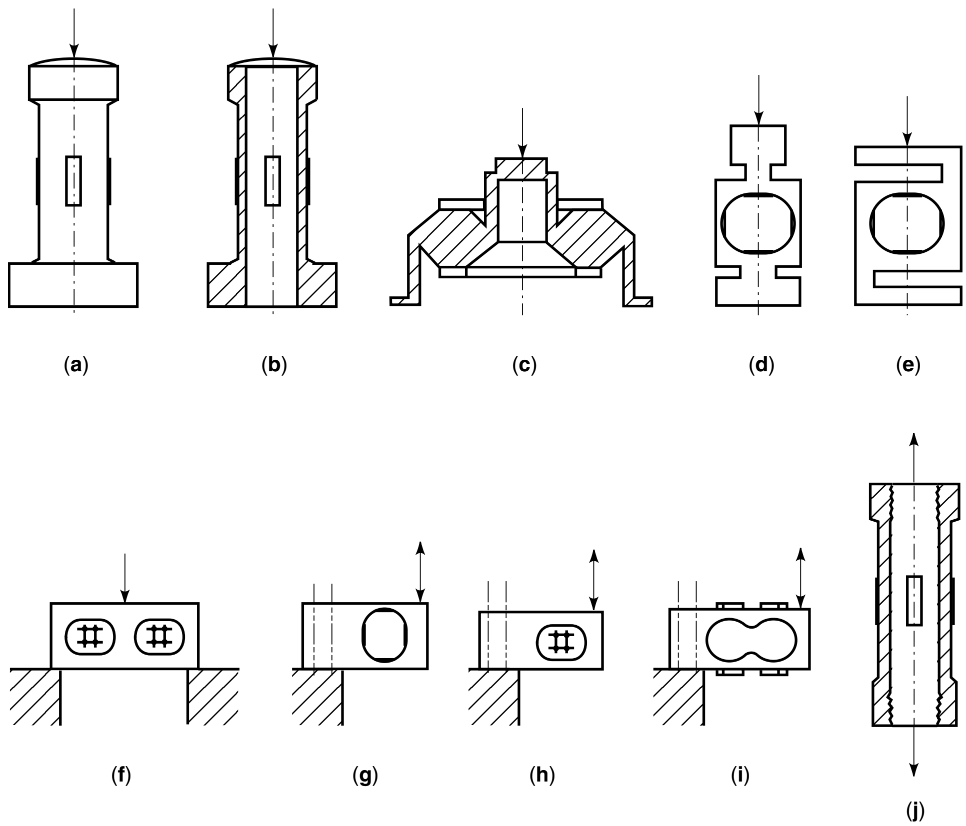

Figure 1. Various types of load cell: (a) compression cylinder, 50 kN to 50 MN; (b) compression cylinder (hollow), 10 kN to 50 MN; (c) toroidal ring, 1 kN to 5 MN; (d) ring, 1 kN to 1 MN; (e) S beam (bending or shear), 200 N to 50 kN; (f) double-ended shear beam, 20 kN to 2 MN; (g) double-bending beam (simplified), 500 N to 50 kN; (h) shear beam, 1 kN to 500 kN; (i) double-bending beam, 100 N to 10 kN; (j) tension cylinder, 50 kN to 50 MN.

force cycles to ensure that the load cell is a reliable measuring device.

In electrical terms, all electrical resistance strain gauges may be considered as a length of conducting material, such as a wire. When a length of wire is subjected to a tension within its elastic limit, its length increases, with corresponding decrease in its diameter and change of its electrical resistance. If the conducting material is bonded to an elastic element under strain, then the change in resistance may be measured and used to calculate the force from the calibration of the device.

The foil strain gauge is the most widely used type. It has significant advantages over all other types of strain gauge and is employed in the majority of precision load cells. It consists of a metal foil pattern mounted on an insulating backing or carrier, which provides electrical insulation between the foil and the elastic element, facilitates handling, and presents a readily bondable surface. A large variety of foil gauges are now commercially available to the transducer designer and general user.

Semiconductor strain gauges are manufactured from strips of semiconducting silicon of either the *n* or the *p* type. The output sensitivity of a semiconductor gauge is very high compared to a foil gauge. It is also, however, nonlinear in strain and highly temperature-sensitive. The gauges exhibit essentially no creep or hysteresis and have an extremely long fatigue life. This type of gauge is widely used on small transducers such as accelerometers and pressure sensors, whose sensing element may be micromachined out of a single piece of silicon.

Thin-film strain gauges are produced by sputtering or evaporating thin films of metals or alloys onto the elastic element. A thin-film strain-gauge system may have up to eight layers of material. There are a number of such force transducers available, covering a range of 0.1 N to 100 N, in the form of a single- or double-bending beam configuration. These devices are highly cost-effective when produced in large quantities due to the manufacturing techniques involved. This makes them ideally suited for use in large-volume products such as shop scales and pressure transducers.

The wire strain gauge was the original type of resistance strain gauge, though now widely replaced by cheaper foil or thin film types. However, the wire strain gauge is still used extensively for high-temperature transducers and stress analysis, and is available in a wide range of materials.

The nominal resistance of a strain gauge varies with the type and application. Wire gauges have resistances in the range of 60 Ω to 350 Ω, foil and semiconductor gauges from 120 Ω to 5 kΩ, and thin-film types around 10 kΩ. Selection criteria may include size, self-heating, and power requirements. If several load cells are to be connected together, then matched resistance may be important.

The strain gauge converts the strain produced by the applied force into resistance change. To maximize the response of the load cell, it is normal to connect one or more strain gauges aligned to respond to a compressive strain and another set aligned with a tensile strain. When connected electrically as a Wheatstone bridge configuration, this has the added advantage of minimizing the effects of environmental changes, such as temperature, which act equally on all the gauges. The resistance change is detected by measuring the differential voltage across the bridge.

A Wheatstone bridge is normally formed by four strain gauges, although it is not uncommon to use two strain gauges for a *half bridge,* or more than four on elastic elements of complex shape. In the latter case, half the total number of strain gauges are subjected to compressive strains and the other half to tensile strains. The voltage output from the bridge, when excited by an input voltage, is linearly related to the resistance change of the strain gauges and is therefore a function of the force applied to the element. The rated output of a load cell is commonly standardized to a nominal level, usually 2 mV/V (2 mV output at rated load per 1 V input), but it can range from 1 mV/V to 5 mV/V.

A shunt resistor may be needed to perform a shunt calibration, and this is often fitted in the signal conditioning unit to be switched across one arm of the bridge when required. Typical shunt calibration resistor values used for a 350 Ω bridge are 40 kΩ and 80 kΩ, which equate to approximately 90% and 45% of full load on a 2 mV/V transducer.

A load cell is part of a measurement chain, and it requires an excitation voltage to be supplied, as well as amplification and conditioning of the output signal, before it can be meaningfully displayed or used in a control system. Normally a system excites the load cell with direct current (dc) voltage and amplifies the output through an instrumentation amplifier. This chain features wide frequency bandwidth, high stability, and relatively low cost.

In industrial applications, the distance between the load cell and the measuring instrument may be considerable, possibly hundreds of meters. The voltage drop along the connecting cable and its dependence upon temperature can contribute to the system error. This additional error can be remedied by the use of a six-wire connection technique. The excitation voltage is measured at the load cell, rather than at the instrument, and maintained at a constant preset level.

An alternative to dc excitation is the alternating current (ac) system, which excites the load cell with an ac signal. The output is processed through an ac amplifier, a synchronous demodulator, a filter, and a dc amplifier. A high-level dc signal is obtained, suitable for direct analog display or for conversion to a digital display with the use of an analog-to-digital converter. Such a system offers higher immunity to thermal effects in the instrumentation and thermoelectric effects in the transducer, high noise rejection, good zero-force output stability, and ease of achieving isolation between the signal output and the load cell. However, in view of the complex measuring chain, these systems tend to be costly.

A strain-gauge load cell has two distinct temperature coefficients, one on zero-load output and one on full-scale output. The former is caused by the effect of temperature on the strain-gauge resistance, the mismatch between the expansion coefficient of the gauge and the spring element to which it is bonded, and the out-of-balance condition in the bridge wiring. The effect on full-scale output is mainly caused by the temperature dependence of the modulus of elasticity of the spring element material. Temperature compensation gauges can reduce the load cell's temperature coefficients to very low levels.

It is usually necessary to protect the elastic element, its strain gauges, and associated electronic components, since many load cells are exposed to harsh industrial environments. The way the load cell is housed depends on its intended application, and there are a wide range of shapes and sizes, including cylinders, rectangular and circular beams, and tension devices like turnbuckles. The housing must allow for suitable fixings such as bolts or cradles and is critical in determining the correct transfer of the force to the elastic element. The housing used for this purpose also fulfils other functions, such as limiting the side forces on the element and protecting the various electric components.

Piezoelectric Crystal Force Transducers

When a force is exerted on certain crystalline materials, electric charges are formed on the crystal surface in proportion to that force. To make use of the device, a charge amplifier is required to integrate the electric charges to give a signal that is proportional to the applied force and big enough to measure. These devices are known as piezoelectric crystal, or quartz, force transducers.

These sensors are different from most other sensing techniques in that they are active sensing elements. No power supply is needed, and the deformation to generate a signal is very small. This provides the advantage of high-frequency response of the measuring system without introducing geometric changes into the force measuring path.

When packaged as a load washer and compressed under a force of 10 kN, a typical piezoelectric transducer deflects only 0.001 mm. The high-frequency response (up to 100 kHz) enabled by this stiffness and the other inherent qualities of the piezoelectric effect makes piezoelectric crystal sensors very suitable for dynamic measurements.

Extremely fast events such as shock waves in solids, or impact printer and punch press forces, can be measured with these devices. Piezoelectric sensors operate with small electric charge and require high impedance cable for the electrical interface. It is important to use the matched cabling supplied with a transducer.

Piezoelectric crystal sensors are primarily designed for applications using a pretensioned bolt that allows the measurement of forces in both tension and compression. The preloading is important to ensure optimum linearity, and the sensor must be calibrated after mounting. An extension of this principle is the use of force-measuring pins, which are placed within the structure of a machine and respond to the forces within the structure.

There is a small leakage of charge inherent in the charge amplifier, which is called *drift* of the signal. So while piezoelectric force transducers are ideally suited for dynamic measurements, they cannot perform truly static measurements.

Piezoelectric crystal sensors are suitable for measurements in laboratories as well as in industrial settings. The measuring range is very wide, and the transducers survive high overload (typically $>$ 100% of full-scale output). The sensors' small dimensions, large measuring range, and rugged packaging make them very easy to use. They can operate over a wide temperature range and survive temperatures of up to 350°C.

Hydraulic Load Cells

The hydraulic load cell is a device filled with a liquid (usually oil), which has a preload pressure. Application of the force to the loading member increases the fluid pressure, which is measured by a pressure transducer or displayed on a pressure gauge dial via a Bourdon tube.

When used with a pressure transducer, hydraulic load cells are inherently very stiff, deflecting only about 0.05 mm under full force conditions. Although capacities of up to 5 MN are available, most devices fall in to the range of 500 N to 200 kN. The pressure gauge used to monitor the force can be located several meters away from the device by the use of a special fluid-filled hose.

Hydraulic load cells are self-contained and need no external power. They are inherently suitable for use in potentially explosive atmospheres and can be tension or compression devices, but are sensitive to temperature changes.

Pneumatic Load Cells

The operating principles of the pneumatic load cell are similar to those of the hydraulic load cell. The force is applied to one side of a piston or a diaphragm of flexible material and balanced by pneumatic pressure on the other side. This counteracting pressure is proportional to the force and is displayed on a pressure gauge.

Other Elastic Devices

The *loading column* is probably the simplest elastic device, being simply a metal cylinder subjected to a force along its axis. The change in length of the cylinder is measured directly by a dial gauge and lever system, or other technique. The *proving ring* is functionally very similar except that the element is a circular ring, and the deformation is usually measured across the inside diameter. These transducers have the advantage of being simple and robust; their main disadvantage is the strong effect of temperature on the output.

An LVDT may be used within a load cell to measure the displacement of an elastic element instead of using strain gauges. The LVDT is essentially a transformer that provides an ac output voltage as a function of the displacement of a separate movable magnetic core. The lack of friction and the low mass of the core result in high resolution and low hysteresis, making this device ideal for dynamic measurement applications.

Capacitive load cells use a capacitance sensor to sense the displacement of an elastic element. In most cases the sensor consists of two parallel plates standing opposite each other. The changing length of a spring member produces a change in the gap between two plates, and hence a change in electric capacitance. In the case of small weighing instruments, such as domestic scales, the spring also provides parallel guidance of the scale's platform.

An optical strain gauge can be formed in a manner similar to a wire strain gauge by the use of optical fibers. The deflection of the elastic force-bearing member with the optical strain gauge bonded to it will result in length changes in the optical fibers. If monochromatic light is used to feed two optical strain gauges experiencing different strains, then the phase difference between the two beams emerging from the gauges is a function of the applied force.

The interference optical load cell uses a high-resolution displacement measuring method. A fork-shaped spring is deformed by the force, the deformation being in the region of 40 μm, and the change of the aperture of the fork is measured by a Michelson interferometer. For the same resolution, the maximum elastic deformation, and with it the strain of the material, need not be as large as in the case of the strain-gauge load cell. The deformation element is made of quartz, which has a very low temperature dependence. The hysteresis and creep of these systems are both particularly small.

Vibrating Elements

In the case of the tuning-fork load cell, the force transducer consists of two parallel band splines, which are connected at their ends and vibrate in opposite directions in resonance. The mode of vibration is like that of a tuning fork and the resonance frequency changes if the element is subjected to a tensile or compressive force. The excitation of the vibration and the reciprocal reception of the vibration signals are carried out by two piezoelectric elements close to the vibration node of the tuning fork.

The vibrating-wire transducer consists of a taut ferromagnetic wire that is excited into transverse vibrations by a drive coil. These vibrations are detected using a pickup coil. Both coils have permanent magnet cores, and once the wire has been excited to its resonance frequency for a given tension, it is maintained at this frequency by connecting the two coils through an amplifier to form a self-oscillating system. Each resonance frequency is a measure of the wire's tension and, hence, the applied force at that instant. The advantage of the vibrating-wire transducer is its direct frequency output, which can be handled by digital circuitry, eliminating the need for an analog-to-digital converter.

Magnetoelastic Devices

The magnetoelastic force transducer is based on the effect that when a ferromagnetic material is subjected to mechanical stress, the magnetic properties of the material are altered and the change is proportional to the applied stress. Due to its sturdy construction, high signal level, and small internal resistance, the magnetoelastic load cell can be used in rough and electrically disturbed environments such as rolling mills. The rated capacities of these devices are in the range from 2 N to 5 MN.

Dynamic Balance Devices

Gyroscopic load cells exploit the force sensitivity of a gyroscope mounted in a gimbal or frame system. A commercially available gyroscopic load cell incorporates a dynamically balanced heavy rotor on a spindle, itself mounted in the inner frame of a two-gimbal system. The arrangement has three orthogonal axes of rotational freedom and has the axis of origin at the center of gravity of the rotor. The force to be measured by the transducer is applied through the lower swivel, and a couple is produced on the inner frame, causing the gimbals to precess. The time taken for the outer gimbal to complete one revolution is then a measure of the applied force. The gyroscopic load cell is essentially a fast-responding digital transducer and is inherently free of hysteresis and drift.

The force balance uses a feedback circuit to compare the electrical output with the force input. A typical system has attached to the force input member an electric coil, which operates in the flux gap of a permanent magnet. An electric current passed through the coil generates a restoring force in opposition to the applied force. A displacement transducer is used to sense the displacement of the force input member, its output being amplified and used to control the current in the coil until the restoring force exactly balances the applied force and restores the force input member to its original position. The coil current to achieve this balance is proportional to the applied force and is measured as a voltage sensed across a resistor in series with the coil. These types of device have good dynamic performance, small deflection, and relative insensitivity to environmental conditions. They are inherently stable and accurate, and as a result are often considered for use as secondary standards. This type of device is mainly a competitor for the mechanical analytical balance in mass determination.

APPLICATIONS

There are many different applications of force measurement systems in industry, too numerous to describe here. One of the main applications is the weighing of products during manufacturing—this is known as process weighing. Batch mixing, truck loading, packing, and vessel filling of liquids, gases, or solids are all processes requiring accurate determination of weight. Many process weighing situations use load cells to measure forces, from which the weight of product is derived. One pitfall is that, while determination of the force may be straightforward, the interpretation of the gravitational component acting on the mass may not be so simple, as described in the following example of vessel weighing.

If a vessel can be mounted at all support points on force transducers, and if the associated pipework and fittings do not take some of the force, the weight may be derived from the total force measured. Often, however, to reduce cost, the vessel may be mounted on one load cell and two dummies, or two load cells and two dummies, and the force is assumed to be equally distributed between the active and nonactive points.

Weighing of a three-legged tank/vessel with one active force transducer in this way leaves the measurement at the mercy of variations in center of gravity due to nonlevel loads, nonuniform vessel cross section, agitation of the contents, and external wind forces. Accuracy of weighing with these systems is usually poor (although acceptable sometimes for level measurement) even if the material in the tank is self-leveling or a liquid. The effects of pipework, fittings, and nonlinear deformation of the tank will cause movement of the center of gravity between the empty and full conditions, as well as affecting the total force seen by the measurement devices (9).

System Design

The choice of force measurement system can only be made after considering the specific details of the application. The designer should consider the range of force to be measured, the number of loading points, the direction of the forces (and whether in tension, compression, or both), and the duration and rate at which the force is applied to the transducer. As a result of these considerations, the choice can be made on what type of transducers can be used, how many will be required and of what capacity, whether uni- or bidirectional, and whether single or multiaxis.

The choice of instrumentation also needs to be made. The frequency and number of data to be collected need to be considered, as well as the nature of the indicator and any links to a data acquisition or control system. The environment in which the force measurement system has to work can have a significant effect on its performance. Parameters to be considered include the temperature, vibration, humidity, corrosive nature of the atmosphere, variation in ambient pressure, and freedom of movement required by the displacement of all the force measurement transducers.

The design should also ensure that there are no parallel load paths (known as force shunts) that may take some of the force that is supposed to be measured by the transducer. Force shunts can be present all of the time (as through pipework connections) or may occur when the movement of the system is arrested by overload stops. The end fittings of the transducer should be designed both to minimize side loads and to allow the force to be passed to the transducer along a well-defined axis, normally the principal axis of the transducer.

Calibration and Traceability

Even with good transducers and a good system design, the measurement cannot be relied upon without some check on the performance of the system. Unexpected installation effects, degradation of the equipment over time, or user abuse may all lead to a measurement that has a greater uncertainty than the designer planned. Consequently, calibration is required to ensure that the force measurement meets the needs of the user and achieves the required degree of uncertainty.

Traceability to authoritative standards is the best way to ensure accuracy of measurements, and leads to consistency of measurements among users at different times and locations. A standard force is less easy to visualize than a standard mass and, by its nature, must be created by a machine rather than having a separate existence as an artifact. Not only must the magnitude of the force be known to the required uncertainty, but also its direction and the conditions of its application to the transducer under test (10,11).

Machines capable of undertaking force calibrations are known as force standard machines, and they may be categorized as either primary or secondary. Primary standards in force measurement are generally deadweight machines whose uncertainty can be directly verified through physical principles with respect to the fundamental base units of mass, length, and time. Secondary standards are machines that can reliably reproduce forces and can be compared with primary standards by the use of a force transfer standard. Examples of secondary standards are lever, reference load cell, hydraulic amplification, and hydraulic strain-gauged column machines. The instrumentation used during the calibration must itself have full traceability, either by calibrating the complete force measuring system of transducer and instrumentation together, or by calibrating the instrumentation separately.

Primary standards are usually defined at a national or international level by a single authoritative measuring instrument known as a national standard or international standard. Traceability normally means that the calibrations have been undertaken by the national standards laboratory, by an accredited laboratory, or by a national or accredited laboratory in another country with which there is a reciprocal recognition agreement.

Most documentary standards in the area of force measurement were written to satisfy a need for traceability in materials testing. The procedures contained in these standards are also used for the calibration of force measurement systems in a wide range of other industries. The calibration, or verification, of materials testing machines is covered by ISO 7500 (12) and other national standards. The document dealing with the calibration and classification of transfer standards (or force-proving instruments) is ISO 376 (13).

The above standards have been developed for the calibration of systems to measure static forces acting along a single well-defined axis. Calibrations are also required for multiaxis situations and for systems that measure dynamic forces.

Multiaxis calibration is similar to single-axis calibration, but done once for each axis. The calibration of multicomponent force sensors is more demanding on the equipment, although the principles remain the same.

At the time of writing, dynamic force calibration is not yet an established procedure. The statically derived force transducer sensitivities are assumed to be applicable for dynamic force measurements. This can lead to significant errors, and work is ongoing to produce a dynamic calibration standard.

There are three main calibration options available for establishing the uncertainty of the force measurement system. The first is to leave the force transducer in its permanently installed position and use a transfer standard to carry out the calibrations. The second is to calibrate the force transducer prior to installation and remove it as required for further calibrations. The final option is to calibrate the force transducer prior to its permanent installation in the force measurement system and then not to recalibrate during the life of the installation.

The user also needs to consider how often to calibrate the device, whether to calibrate the whole system or just the transducer, whether adjustment of the instrument is required, and what uncertainty level is required. The end-loading and temperature conditions during the calibration should be similar to those experienced in the application.

Before taking any calibration readings the transducer should be preloaded up to its rated force and back to zero several times. This is to ensure that any mechanical or electric connection, offsets, or mismatches have been allowed to settle in. When taking measurements, the applied force should always be approached from the same direction, and allowed to stabilize before a reading is taken. It is also important that zero force be a well-defined mechanical point at the same level and direction, taking account of backlash and the like.

Analysis of the calibration data will often be carried out by the calibration laboratory and a calibration certificate supplied to the user when the transducer is returned. There are other checks the user can make, such as checking that the worst-case error is within the process needs, checking for any anomalies or bias, checking that the linearity is within process needs, and reviewing the history of the device's calibrations.

QUALITY ASSURANCE OF FORCE AND MASS MEASUREMENTS

Many organizations are granted a recognized certification or accreditation for their activities, covering their overall quality management system. However, a generalized quality certification does not address the details of specialised technical practices. Accreditation, on the other hand, means that certain aspects of their business have been independently assessed, and that they comply with given criteria of competence and quality.

In the United Kingdom, for example, the United Kingdom Accreditation Service (UKAS) undertakes the National Accreditation of Measurement and Sampling (NAMAS). NAMAS accreditation of a calibration or testing laboratory provides assurance that measurements are carried out to the highest standards of technical competence, traceable to recognized national or international standards, using agreed methods, and with realistic statements of uncertainty. The NAMAS regulations are based on international standards for the operation and accreditation of laboratories, such as EN 45000 (14) and ISO Guide 25 (15). NAMAS certificates are widely recognised and accepted throughout the United Kingdom and also world-wide.

Counterparts of NAMAS exist in many other countries, and in many cases are recognized as equivalent. Formal agreements provide for the mutual recognition of certificates from different national accreditation schemes. The European Co-operation for Accreditation (EA) is the body that is the focus for multilateral recognition among national measurement accreditation schemes in Europe.

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WHEATSTONE BRIDGE. See Bridge instruments.