CHAPTER 18

Mass, Force, and Torque Measurement

Chapter Outline

18.1 Introduction

Mass, force, and torque are covered together within this chapter because they are closely related quantities. Mass describes the quantity of matter that a body contains. Force is the product of mass times acceleration, according to Newton's second law of motion:

$$\text{Force} = \text{Mass} \times \text{acceleration}.$$

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Forces can be applied in either the horizontal or vertical direction. A force applied in a downward, vertical direction gives rise to the term *weight*, which is defined as the downward force exerted by a mass that is subject to a gravitation force:

$$\text{Weight} = \text{Mass} \times \text{acceleration due to gravity.}$$

The final quantity covered in this chapter, torque, can be regarded as a rotational force. When applied to a body, torque causes the body to rotate about its axis of rotation. This is analogous to the horizontal motion of a body when a horizontal force is applied to it.

$$\begin{aligned}\text{Torque} = {} & \text{Force applied} \\ & \times \text{radial distance between the application point of force and the axis of rotation.}\end{aligned}$$

18.2 Mass (Weight) Measurement

The *mass* of a body is always quantified in terms of a measurement of the *weight* of the body, this being the downward force exerted by the body when it is subject to gravity. Three methods are used to measure this force.

The first method of measuring the downward force exerted by a mass subject to gravity involves the use of a *load cell*. The load cell measured the downward force F, and then the mass M is calculated from the equation:

$$M = F/g, \quad \text{where } g \text{ is the acceleration due to gravity.}$$

Since the values of g vary by small amounts at different points around the earth's surface, the value of M can only be calculated exactly if the value of g is known exactly. Nevertheless, load cells are in fact the most common instrument used to measure mass, especially in industrial applications. Several different forms of load cells are available. Most load cells are now electronic, although pneumatic and hydraulic types also exist. These types vary in features and accuracy, but all are easy to use since they are deflection-type instruments that give an output reading without operator intervention.

The second method of measuring mass is to use a spring balance. This also measures the downward force when the measured mass is subject to gravity. Hence, as in the case of load cells, the mass value can only be calculated exactly if the value of g is known exactly. Like a load cell, the spring balance is also a deflection-type instrument and so easy to use.

The final method of measuring mass is to use some form of mass-balance instrument. This provides an absolute measurement, since they compare the gravitational force on the mass being measured with the gravitational force on a standard mass. Since the same gravitational force is applied to both masses, the exact value of g is immaterial. However, being a null-type instrument, any form of balance is tedious to use.

The following paragraphs explain these various forms of mass-measuring instrument in more detail.

18.2.1 Electronic Load Cell (Electronic Balance)

The electronic load cell is now the preferred type of load cell in most applications. Within an electronic load cell, the gravitational force on the body being measured is applied to an elastic element. This deflects according to the magnitude of the body mass. Mass measurement is thereby translated into a displacement measurement task.

The elastic elements used are specially shaped and designed, some examples of which are shown in Figure 18.1. The design aims to obtain a linear output relationship between the

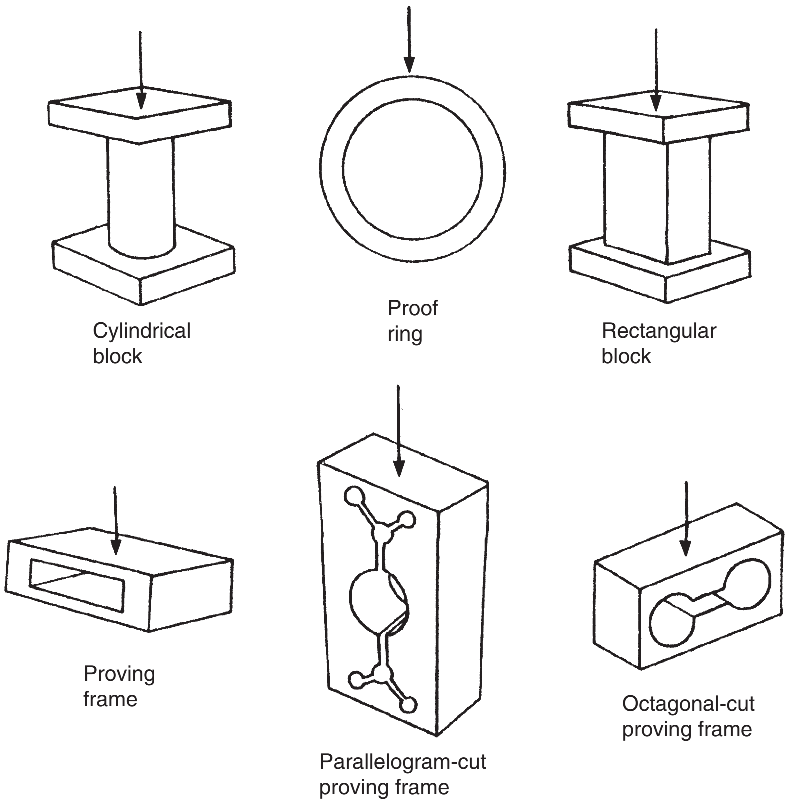

Figure 18.1
Elastic elements used in load cells.

applied force and the measured deflection and to make the instrument insensitive to forces that are not applied directly along the sensing axis. Load cells exist in both compression and tension forms. In the compression type, the measured mass is placed on top of a platform resting on the load cell, which therefore compresses the cell. In the alternative tension type, the mass is hung from the load cell, thereby putting the cell into tension.

Various types of displacement transducer are used to measure the deflection of the elastic elements. Of these, the strain gauge is used most commonly, since this gives the best measurement accuracy, with an inaccuracy figure of less than ±0.05% of full-scale reading being obtainable. Load cells including strain gauges are used to measure masses over a very wide range between 0 and 3000 tonne. The measurement capability of an individual instrument designed to measure masses at the bottom end of this range would typically be 0.1–5 kg, whereas instruments designed for the top of the range would have a typical measurement span of 10–3000 tonne.

Elastic force transducers based on differential transformers (linear variable differential transformers (LVDTs)) to measure defections are used to measure masses up to 25 tonne. Apart from having a lower maximum measuring capability, they are also inferior to strain gauge-based instruments in terms of their ±0.2% inaccuracy value. Their major advantage is their longevity and almost total lack of maintenance requirements.

The final type of displacement transducer used in this class of instrument is the piezoelectric device. Such instruments are used to measure masses in the range of 0–1000 tonne. Piezoelectric crystals replace the specially designed elastic member normally used in this class of instrument, allowing the device to be physically small. As discussed previously, such devices can only measure dynamically changing forces because the output reading results from an induced electrical charge whose magnitude leaks away with time. The fact that the elastic element consists of the piezoelectric crystal means that it is very difficult to design such instruments to be insensitive to forces applied at an angle to the sensing axis. Therefore, special precautions have to be taken in applying these devices. Although such instruments are relatively cheap, their lowest inaccuracy is ±1% of full-scale reading, and they also have a high-temperature coefficient.

Electronic load cells have significant advantages over most other forms of mass-measuring instrument in terms of their relatively low cost, wide measurement range, tolerance of dusty and corrosive environments, remote measurement capability, tolerance of shock loading, and ease of installation. However, one particular problem that can affect their performance is the phenomenon of creep. Creep describes the permanent deformation that an elastic element undergoes after it has been under load for a period of time. This can lead to significant measurement errors in the form of a bias on all readings if the instrument is not recalibrated from time to time. However, careful design and choice of materials can largely eliminate the problem.

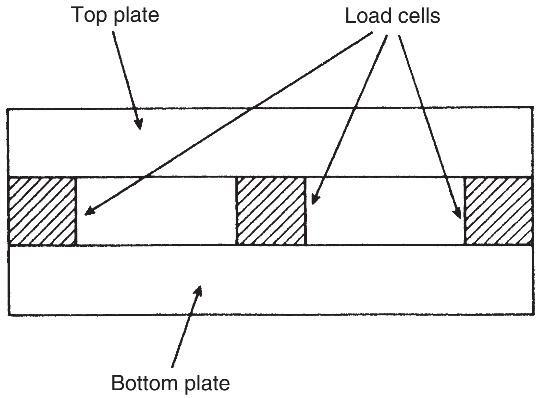

Figure 18.2
Load cell-based electronic balance.

Several compression-type load cells are often used together in a form of instrument known as the *electronic balance*. This is shown schematically in Figure 18.2. Commonly, either three or four load cells are used in the balance, with the output mass measurement being formed from the sum of the outputs of each cell. Where appropriate, the upper platform can be replaced by a tank for weighing liquids, powders etc.

18.2.2 Pneumatic and Hydraulic Load Cells

Pneumatic and hydraulic load cells translate mass measurement into a pressure measurement task, though they are now less common than the electronic load cell. A pneumatic load cell is shown schematically in Figure 18.3. Application of a mass to the cell causes deflection of a diaphragm acting as a variable restriction in a nozzle-flapper mechanism. The output

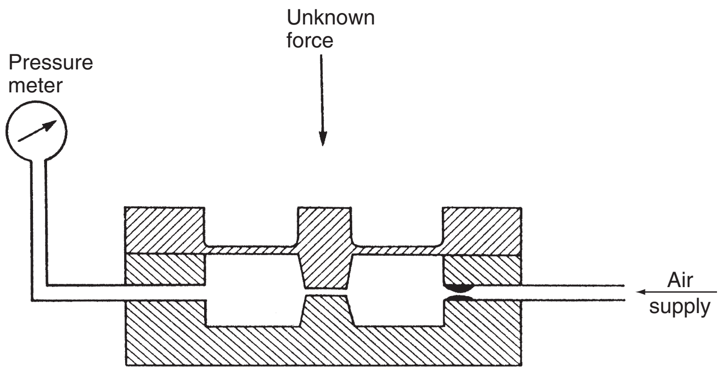

Figure 18.3
Pneumatic load cell.

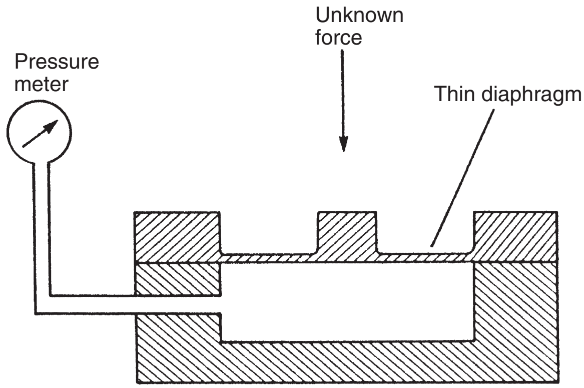

Figure 18.4
Hydraulic load cell.

pressure measured in the cell is approximately proportional to the magnitude of the gravitational force on the applied mass. The instrument requires a flow of air at its input of around 0.25 m^3/hour at a pressure of 4 bar. Standard cells are available to measure a wide range of masses. For measuring small masses, instruments are available with a full-scale reading of 25 kg, while at the top of the range, instruments with a full-scale reading of 25 tonne are obtainable. Inaccuracy is typically ±0.5% of full scale in pneumatic load cells.

The alternative, hydraulic load cell is shown in Figure 18.4. In this, the gravitational force due to the unknown mass is applied, via a diaphragm, to oil contained within an enclosed chamber. The corresponding increase in oil pressure is measured by a suitable pressure transducer. These instruments are designed for measuring much larger masses than pneumatic cells, with a load capacity of 500 tonne being common. Special units can be obtained to measure masses as large as 50,000 tonne. Besides their much greater measuring range, hydraulic load cells are much more accurate than pneumatic cells, with an inaccuracy figure of ±0.05% of full scale being typical. However, in order to obtain such a level of accuracy, correction for the local value of g (acceleration due to gravity) is necessary. A measurement resolution of 0.02% is attainable.

18.2.3 Intelligent Load Cells

Intelligent load cells are formed by adding a microprocessor to a standard cell. This brings no improvement in accuracy because the load cell is already a very accurate device. What it does produce is an intelligent weighing system that can compute total cost from the measured weight, using stored cost per unit weight information, and provide an output in the form of a digital display. Cost per weight values can be prestored for a large number of substances, making such instruments very flexible in their operation.

In applications where the mass of an object is measured by several load cells used together (for example, load cells located at the corners of a platform in an electronic balance), the total mass can be computed more readily if the individual cells have a microprocessor providing digital output. In addition, it is also possible to use significant differences in the relative readings between different load cells as a fault detection mechanism in the system.

18.2.4 Mass-Balance (Weighing) Instruments

Mass-balance instruments are based on comparing the gravitational force on the measured mass with the gravitational force on another body of known mass. This principle of mass measurement is commonly known as *weighing*, and is used in instruments like the beam balance, weigh beam, pendulum scale, and electromagnetic balance. Various forms of mass-balance instrument are available, as discussed below.

Beam balance (Equal-arm balance): In the beam balance, shown in Figure 18.5, standard masses are added to a pan on one side of a pivoted beam until the magnitude of the gravity force on them balances the magnitude of the gravitational force on the unknown mass acting at the other end of the beam. This equilibrium position is indicated by a pointer that moves against a calibrated scale.

Instruments of this type are capable of measuring a wide range of masses. Those at the top end of the range can typically measure masses up to 1000 g, whereas those at the bottom end of the range can measure masses of less than 0.01 g. Measurement resolution can be as good as 1 part in 10^7 of the full-scale reading if the instrument is designed and manufactured very carefully. The lowest measurement inaccuracy value attainable is $\pm 0.002\%$.

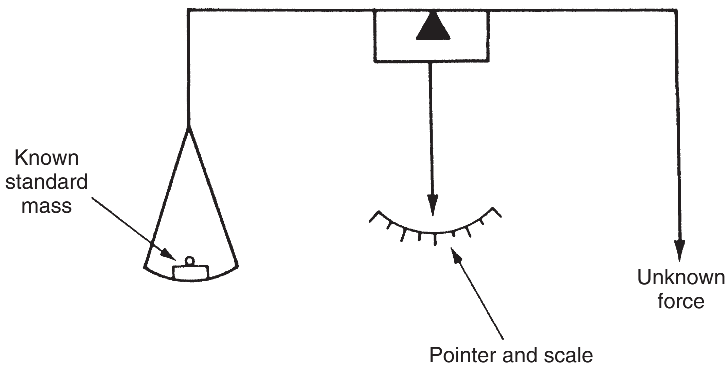

Figure 18.5
Beam balance (Equal-arm balance).

One serious disadvantage of this type of instrument is its lack of ruggedness. Continuous use and the inevitable shock loading that will occur from time to time both cause damage to the knife edges, leading to a deterioration in the measurement accuracy and measurement resolution. A further problem affecting their use in industrial applications is that it takes a relatively long time to make each measurement. For these reasons, the beam balance is normally reserved as a calibration standard and is not used in day-to-day production environments.

Weigh beam: The weigh beam, sketched in two alternative forms in Figure 18.6, operates on similar principles to the beam balance but is much more rugged. In the first form, standard masses are added to balance the unknown mass, and fine adjustment is provided by a known mass that is moved along a notched, graduated bar until the pointer is brought

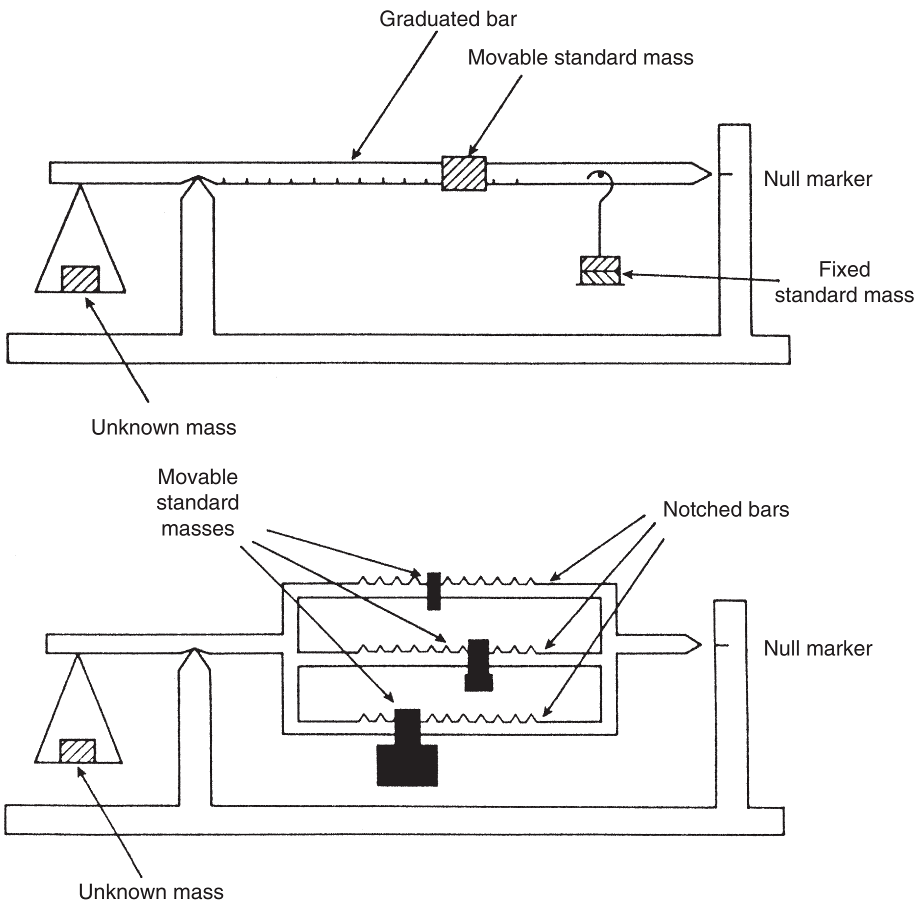

Figure 18.6
Two alternative forms of weigh beam.

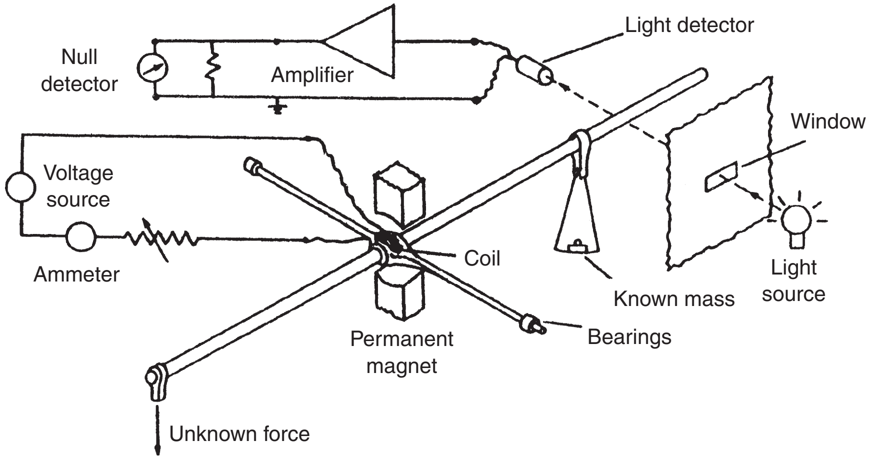

Figure 18.7
Electromagnetic balance.

to the null, balance point. The alternative form has two or more graduated bars (3 bars shown in Figure 18.6). Each bar carries a different standard mass and these are moved to appropriate positions on the notched bar to balance the unknown mass. Versions of these instruments are used to measure masses up to 50 tonne.

Electromagnetic balance: The electromagnetic balance uses the torque developed by a current-carrying coil suspended in a permanent magnetic field to balance the unknown mass against the known gravitational force produced on a standard mass, as shown in Figure 18.7. A light source and detector system is used to determine the null balance point. The voltage output from the light detector is amplified and applied to the coil, thus creating a servosystem where the deflection of the coil in equilibrium is proportional to the applied force. Its advantages over beam balances, weigh beams, and pendulum scales include its smaller size, insensitivity to environmental changes (modifying inputs), and electrical form of output. Despite these apparent advantages, it is no longer in common use because of the development of other instruments, particularly electronic balances.

18.2.5 Spring Balance

Spring balances provide a method of mass measurement that is both simple and cheap. The mass is hung on the end of a spring, and the deflection of the spring due to the downwards gravitational force on the mass is measured against a scale. Because the characteristics of the spring are very susceptible to environmental changes, measurement accuracy is usually relatively poor. However, if compensation is made for the changes in spring characteristics, then a measurement inaccuracy less than ±0.2% is achievable.

According to the design of the instrument, masses between 0.5 kg and 10 tonne can be measured.

18.3 Force Measurement

This section is concerned with the measurement of horizontal forces that either stretch or compress the body that they are applied to according to the direction of the force with respect to the body. If a force of magnitude, F, is applied to a body of mass, M, the body will accelerate at a rate, A, according to the equation:

$$F = MA.$$

The standard unit of force is the *Newton*, this being the force that will produce an acceleration of 1 m/s squared in the direction of the force when it is applied to a mass of 1 kg. One way of measuring an unknown force is therefore to measure the acceleration when it is applied to a body of known mass. An alternative technique is to measure the variation in the resonant frequency of a vibrating wire as it is tensioned by an applied force. Finally, forms of load cell that deform in the horizontal direction when horizontal forces are applied can also be used as force sensors. These techniques are discussed below.

18.3.1 Use of Accelerometers

The technique of applying a force to a known mass and measuring the acceleration produced can be carried out using any type of accelerometer. Unfortunately, the method is of very limited practical value because, in most cases, forces are not free entities but are part of a system (from which they cannot be decoupled) in which they are acting on some body that is not free to accelerate. However, the technique can be of use in measuring some transient forces and also for calibrating the forces produced by thrust motors in space vehicles.

18.3.2 Vibrating Wire Sensor

This instrument, illustrated in Figure 18.8, consists of a wire that is kept vibrating at its resonant frequency by a variable-frequency oscillator. The resonant frequency of a wire under tension is given by:

$$f = \frac{0.5}{L}\sqrt{\left(\frac{M}{T}\right)}.$$

where M is the mass per unit length of the wire, L is the length of the wire, and T is the tension due to the applied force, F. Thus, measurement of the output frequency of the oscillator allows the force applied to the wire to be calculated.

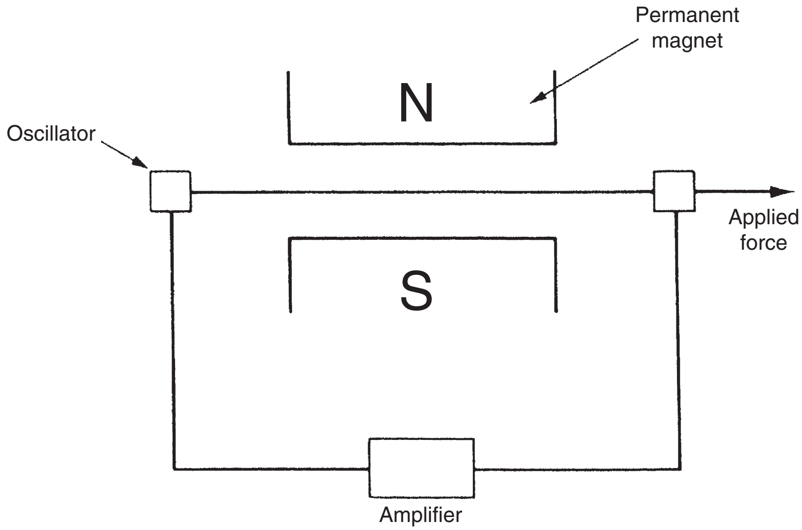

Figure 18.8
Vibrating wire sensor.

18.3.3 Use of Load Cells

Special forms of electronic load cell that are designed to deflect in the horizontal direction are used to measure horizontal forces that are applied to them.

18.4 Torque Measurement

Torque can be thought of as a rotational force. If a circumferential force F is applied to a shaft of radius r, the torque produced in the shaft is given by:

$$T = F \times r.$$

The effect of the torque applied to a shaft is to produce a shear stress in the shaft, this stress being maximum at the surface of the shaft. The maximum shear stress in a rotating shaft is given by $\tau_{max} = \frac{T \times r}{J}$, where J is the moment of inertia of the shaft.

It is obviously important that the design of any rotating shaft, or any other form of rotating element, is such that it can withstand the maximum shear stress applied to it. If this condition is not met, the shaft will fail during service. Torque measurement is therefore of fundamental importance in all rotating bodies and applies to the rotation of shafts in many things like pumps, rotational cutting equipment, gearbox shafts, vehicle axles, and electric motors. Torque measurement is also a necessary part of measuring the power transmitted by rotating shafts.

The three methods of measuring torque now commonly used consist of either (1) measuring the strain produced in a rotating body due to an applied torque, (2) measuring torque by an optical method, and (3) measuring torque using surface acoustic wave (SAW) devices. The latter are MEMS-scale devices. Historically, two other methods were also used which were mentioned in the first edition of this book. These were (1) measuring the reaction force in cradled shaft bearings and (2) a using equipment known as the “Prony brake.” These have now been omitted from this latest edition since the these two old methods are very rarely used nowadays.

18.4.1 Measurement of Induced Strain

Measuring the strain induced in a shaft due to an applied torque has been the most common method used for the torque measurement in recent years. The method involves bonding four strain gauges onto the shaft as shown in Figure 18.9, where the strain gauges are arranged in a DC bridge circuit. The output from the bridge circuit is a function of the strain in the shaft and hence of the torque applied. It is very important that the positioning of the strain gauges on the shaft is precise, and the difficulty in achieving this makes the technique relatively expensive.

The technique is ideal for measuring the stalled torque in a shaft before rotation commences. However, a problem is encountered in the case of rotating shafts because a suitable method then has to be found for making the electrical connections to the strain gauges. One solution to this problem found in many commercial instruments is to use a system of slip rings and brushes for this, although this increases the cost of the instrument still further. An alternative solution recently developed is to use wireless telemetry to transmit the signals from the strain gauges.

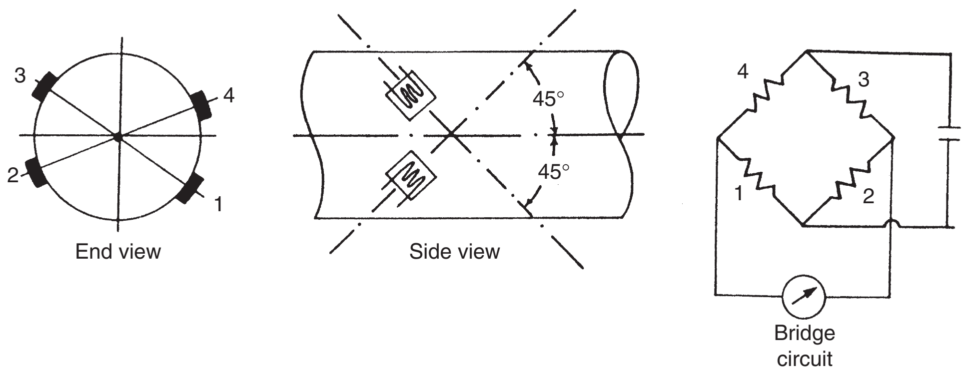

Figure 18.9
Position of torque-measuring strain gauges on the shaft.

18.4.2 Optical Torque Measurement

Optical techniques for torque measurement have become available recently with the development of laser diodes and fiber-optic light transmission systems. One such system is shown in Figure 18.10. Two black-and-white striped wheels are mounted at either end of the rotating shaft and are in alignment when no torque is applied to the shaft. Light from a laser diode light source is directed by a pair of optic fiber cables onto the wheels. The rotation of the wheels causes pulses of the reflected light and these are transmitted back to a receiver by a second pair of fiber-optic cables. Under zero torque conditions, the two pulse trains of reflected light are in phase with each other. If torque is now applied to the shaft, the reflected light is modulated. Measurement by the receiver of the phase difference between the reflected pulse trains therefore allows the magnitude of torque in the shaft to be calculated. The cost of such instruments is relatively low, and an additional advantage in many applications is their small physical size.

18.4.3 Torque Measurement Using SAW MEMS Devices

This is a very new technique based on surface acoustic wave (SAW) technology in MEMS devices that is patented. Devices based on the technology are only available from one company at the present time (TorqSense, 2013). The technique involves measuring the resonant frequency change between two SAW devices when torque is applied to the shaft that the SAW devices are attached to. The SAW device consists of an array of thin metal electrodes deposited on a quartz piezoelectric crystal substrate. The electrodes are

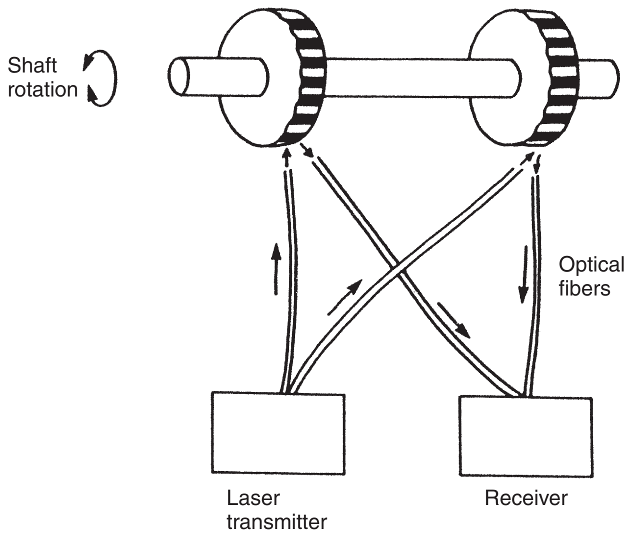

Figure 18.10
Optical torque measurement.

arranged such that their polarities are alternate, and this sets up a surface wave on the crystal when an RF signal of an appropriate frequency is applied to them. This is facilitated by the spacing of the electrodes, which is arranged to be either one half or one quarter of the frequency of the applied RF signal. When a torque is applied to the shaft, this causes strain within it and a corresponding change in the electrode spacing, and this in turn causes a change in the resonant frequency of the SAW devices. The two resonant frequencies are transmitted to a pickup outside the shaft via wireless transmission. The shaft torque is then computed by appropriate electronic signal processing and analysis.

SAW devices are part of the class of MEMS devices, and therefore have obvious size advantages. They have a high immunity to magnetic fields, and are thus applicable to applications where electronic interference is a serious problem, such as close to electric motors. They also have a fast electrical and mechanical response time. The fact that the measurement technique is a noncontact one is also advantageous in many applications.

18.5 Calibration of Mass-, Force-, and Torque-Measuring Sensors

One particular difficulty that arises in the calibration of mass-, force-, and torque-measuring instruments is the variability in the value of g (the acceleration due to gravity). Apart from instruments like the beam balance and pendulum scale which directly compare two masses, all other instruments have an output reading that depends on the value of g.

The value of g is given by Helmert's formula:

$$g = 980.6 - 2.6 \cos \phi - 0.000309h.$$

where ϕ is the latitude and h is the altitude in meters.

It can be seen from this formula that g varies with both latitude and altitude. At the equator ($\cos\phi = 0°$) $g = 978.0$, whereas at the poles ($\cos\phi = 0°$) $g = 983.2$. Typical working values for g are 980.3 in New York, 980.0 in San Francisco and 980.7 in the UK. Where necessary, the exact value of g can be established by measuring the period and length of a pendulum.

Another difficulty that arises in calibrating mass, force, and torque sensors is the presence of an upward force generated by the air medium in which the instruments are tested and used. According to Archimedes' principle, when a body is immersed in a fluid (air in this case), there is an upward force proportional to the volume of the fluid displaced. Even in pure mass-balance instruments, an error is introduced because of this unless both the body of unknown mass and the standard mass have the same density. This error can be quantified as:

$$\text{Error} = \frac{SG_a}{SG_u} - \frac{SG_a}{SG_m}.$$

where SG_a is the specific gravity of air, SG_u is the specific gravity of the substance being measured, and SG_m is the specific gravity of the standard mass.

Fortunately, the maximum error due to this upward force (which has the largest magnitude when weighing low-density liquids such as petrol) will not exceed 0.2%. Therefore, in most circumstances, the error due to air buoyancy can be neglected. However, for calibrations at the top of the calibration chain, where the highest levels of accuracy are demanded, either correction must be made for this factor or it must be avoided by carrying out the calibration in vacuum conditions.

18.5.1 Mass Calibration

The primary requirement of mass calibration is the maintenance of a set of standard masses, which are applied to the mass sensor being calibrated. Provided that this set of standard masses is protected from damage, there is little reason for the value of the masses to change. Despite this, the values of the masses must be checked at prescribed intervals, typically annually, in order to maintain the traceability of the calibration to reference standards. The instrument used to provide this calibration check on the standard masses is either a beam balance, a weigh beam, an electromagnetic balance, or a proof-ring-based load cell.

Beam balance

The beam balance is used for calibrating masses in the range between 10 mg and 1 kg. The measurement resolution and accuracy achieved depend on the quality and sharpness of the knife edge that the pivot is formed from. For high-measurement resolution, friction at the pivot must be as close to zero as possible, and hence a very sharp and clean knife-edge pivot is demanded. The two halves of the beam on either side of the pivot are normally of equal length and are measured from the knife edge. Any bluntness, dirt, or corrosion in the pivot can cause these two lengths to become unequal, causing consequent measurement errors. Similar comments apply about the knife edges on the beam that the two pans are hung from. It is also important that all knife edges are parallel, otherwise displacement of the point of application of the force over the line of the knife edge can cause further measurement errors. This last form of error also occurs if the mass is not placed centrally on the pan.

Great care is therefore required in the use of such an instrument but, provided that it is kept in good condition, particularly with regard to keeping the knife edges sharp and clean, high-measurement accuracy is achievable. Such good condition can be confirmed by applying calibrated masses to each side of the balance. If the instrument is then exactly in balance, all is well.

Weigh beam

In order to use it as a calibration standard, a weigh beam has to be manufactured and maintained to a high standard. However, provided that these conditions are met, it can be used as a standard for calibrating masses up to 50 tonne.

Electromagnetic balance

Various forms of electromagnetic balance exist as alternatives to the three instruments just described for calibration duties. A particular advantage of the electromagnetic balance is its use of an optical system to magnify motion around the null point, leading to higher measurement accuracy. Consequently, this type of instrument is often preferred for calibration duties, particularly for higher measurement ranges. The actual degree of accuracy achievable depends on the magnitude of the mass being measured. In the range between 100 g and 10 kg, an inaccuracy of ±0.0001% is achievable. Above and below this range, the inaccuracy is worse, increasing to ±0.002% measuring 5 tonne and ±0.03% measuring 10 mg.

Proof-ring-based load cell

In a proof-ring-based load cell used for calibration, the displacement of the proof ring in the instrument is measured by either an LVDT or a micrometer. As the relationship between the applied mass/force and the displacement is not a straight-line one, a force/deflection graph has to be used to interpret the output.

The lowest measurement inaccuracy achievable is ±0.1%. The proof-ring-based load cell is used for calibration in the range between 150 kg and 2000 tonne.

18.5.2 Force Sensor Calibration

Force sensors are calibrated by using special machines that apply a set of known force values to the sensor. The machines involved are very large and expensive. For this reason, force sensor calibration is normally devolved to either specialist calibration companies or manufacturers of the measurement devices being calibrated, both of whom will give advice on the frequency of calibration necessary to maintain traceability of measurements to national reference standards.

18.5.3 Calibration of Torque-Measuring Systems

As for the case of force sensor calibration, special machines are required for torque measurement system calibration that can apply accurately known torque values to the system being calibrated. Such machines are very expensive. It is therefore normal to use the services of specialist calibration companies or to use similar services provided by the manufacturer of the torque measurement system. Again, the company to which the calibration task is assigned will give advice on the required frequency of calibration.

18.6 Summary

We have covered the measurement of all three quantities: mass, force, and torque, in this chapter as the three quantities are closely related. We also learned that weight was another related quantity since this describes the force exerted on a mass that is subject to gravity.

Mass of measured in one of three distinct ways, using a load cell, using a spring balance, and using one of several instruments working on the mass-balance principle. Of these, load cells and spring balances are deflection-type instruments whereas the mass balance is a null-type instrument. This means that a balance is somewhat tedious to use compared with other forms of mass-measuring instrument.

In respect of load cells, we looked first at the electronic load cell since this is the type that is preferred in most applications where masses between 0.1 kg and 3000 tonne in magnitude are measured. We learned that pneumatic and hydraulic load cells represent somewhat older technology that is used much less frequently nowadays. However, special types of hydraulic load cell still find a significant number of applications in measuring large masses, where the maximum capability is 50,000 tonne. We noted that variations in the local value of g (the acceleration due to gravity) have some effect on the accuracy of load cells but it was observed that the magnitude of this error was usually small. Before leaving the subject of load cells, we also made some mention of intelligent load cells.

Looking next at mass-balance instruments, we saw that a particular advantage that they had was their immunity to variations in the value of g. We studied the various types of balance: the beam balance, weigh beam, and electromagnetic balance.

We then ended the review of mass-measuring instruments by looking at the spring balance. Our conclusion about this was that, while simple and cheap, its measurement accuracy is usually relatively poor.

Moving onto force measurement, we noted that transient forces could be measured by an accelerometer. However, static forces were measured either by a vibrating wire sensor or by a special form of load cell.

Finally, looking at torque measurement, we saw that the main current methods for measuring the torque were to measure the induced strain in a rotating shaft, to measure the torque optically, and to measure torque using SAW technology. It was noted that two older techniques that were discussed in edition one of this text (measuring the reaction forces in the bearings supporting a rotating shaft, and using a Prony brake) are now largely obsolete and have not been covered in this revised edition. We then concluded the chapter by examining the techniques used for calibrating the measuring devices covered in the chapter. We noted that calibration of mass-measuring sensors involved the use of a set of standard masses. As regards the calibration of force and torque sensors, we saw that both of these required the use of special machines that generate a set of known force or torque values. Because such machines are very expensive, we noted that it was normal to use the services of either specialist calibration companies or the manufacturers of the measurement devices being calibrated.

18.7 Problems

18.1 What is the difference between mass and weight? Discuss briefly the three main methods of measuring the mass of a body.

18.2 Explain, using a sketch as appropriate, how each of the following forms of load cell work: (a) electronic, (b) pneumatic, (c) hydraulic, (d) intelligent.

18.3 Discuss the main characteristics and applications of the four kinds of load cell mentioned in question 18.2. Which form is most common and why?

18.4 Briefly discuss the working characteristics of each of the following: (a) beam balance, (b) weigh beam.

18.5 How does a spring balance work? What are its advantages and disadvantages compared with other forms of mass-measuring instruments?

18.6 What are the available techniques for measuring a force acting in a horizontal direction?

18.7 Discuss briefly the three main methods used to measure torque.

18.8 Discuss the general principles of calibrating mass-measuring instruments.

18.9 Which instruments are used as a reference standard in mass calibration? What special precautions have to be taken in manufacturing and using such reference instruments?

Reference

TorqSense, 2013. Product Literature. Sensor Technology Ltd, Banbury, UK. OX15 6AY, 2013.