TORQUEMETERS

Torque, or moment about an axis, is measured in several industrial situations and, increasingly, in consumer products. A common experience of torque measurement is the use of a torque spanner for tightening a wheel-nut on an automobile. The torque being applied is indicated on a scale, and the device usually operates through the bending of a rod. The meaning of torque as the product of a force and lever length is clear in this situation, and it is measured in Nm (newton meters). The axis about which the torque is applied is that of the stud on which the nut is tightened. Usually, the term torquemeter is taken to mean a device for the measurement of the torque in a rotating shaft, but this is not necessarily so, and other situations need to be instrumented. Measurement may be required in testing small motors or in aircraft or tanks, and in many other situations. Thus the range of requirements is very large in terms of torque range, sensitivity, accuracy, physical size, and, increasingly, of cost. Because of this, several different techniques have been developed successfully for different applications. Continuing work is mainly in the search for low-cost high performance devices for use in industrial control systems and consumer products. The overall picture is complicated because it is not always appropriate to purchase a torquemeter but rather to design it as an integral part of the experimental rig or commercial product, and there are well-established principles for doing this. In some cases, the torquemeter will also be required to act as a mechanical load, absorbing energy. In other cases, it will be important that the device does not change the operation of the system significantly through loading or through its own mechanical flexibility. There are torquemeters in use which were installed a long time ago and which continue to give good service because of their ruggedness and reliability. The user needs to be aware of these, although generally, many of these would not be installed today on grounds of cost and lack of operational flexibility. This is particularly true for the measurement of shaft torque, and this is the type of measurement which is considered first.

THE MEASUREMENT OF SHAFT TORQUE

A typical application of a shaft torquemeter incorporating a mechanical load is for the measurement of the torque/speed characteristics of a motor or engine in performance testing. In older, mechanical instruments, the integration of the two functions, the measurement and the loading, often forms an essential part of the design. The simplest and most direct de-

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vice is the Prony Brake (Fig. 1), in which the rotating shaft carries a narrow drum. Braking is applied to this by means of a brake band, or possibly by friction blocks, and a screw mechanism, A, tightens this to increase the braking effect. The torque applied by the brake mechanism is measured in a number of ways, the traditional way being to use a spring balance as shown in the Fig. 1. The torque acting on the drum is $(F_1 - F_2)r$ Nm and is transferred to the lever which has a fulcrum midway between the points where the belt is attached. The belt is tightened by the screw mechanism indicated in order to increase the braking torque. The torque is then balanced by the force F which is shown on the balance and which acts on a lever of length R. Thus, the torque is FR Nm. Normally, this would be plotted against the shaft speed as the brake is tightened to give a characteristic of the motor or engine driving the shaft for a particular supply voltage or fuel supply. The Prony Brake is generally used for small power levels at lower speeds because of the problems of conducting the heat away and sustaining the large forces involved at high power levels.

In essence, the Prony Brake transfers the torque in the rotating member to a static member where it is more easily measured. Other methods are also utilized to carry out this transfer. These include a hydraulic device, essentially an inefficient centrifugal pump, an air fan, various electromagnetic techniques, depending, for example, on eddy current losses, and the use of a generator with a resistive or other load to absorb the energy. Again, in each case, the reaction torque is measured. In these cases, a spring balance is not normally used but rather strain gauge load cells in the supports with the advantage that the torque can then be recorded automatically. Some of the methods depend on nonlinear properties in carrying out the power transfer and can be difficult to use over wide ranges of torque. Currently, the more basic devices such as the Prony Brake have applications, but it is now simpler to use a commercially available torquemeter which is inserted into the shaft, the energy being absorbed in an appropriate way which for higher powers would be an electrical generator. This also has the advantage of being easily incorporated into an automated test system. It should not be forgotten that the simplest method may be to measure the reaction torque on the motor. This has the drawback that the inertia of the motor spoils the response of the measurement to fast changes in the torque.

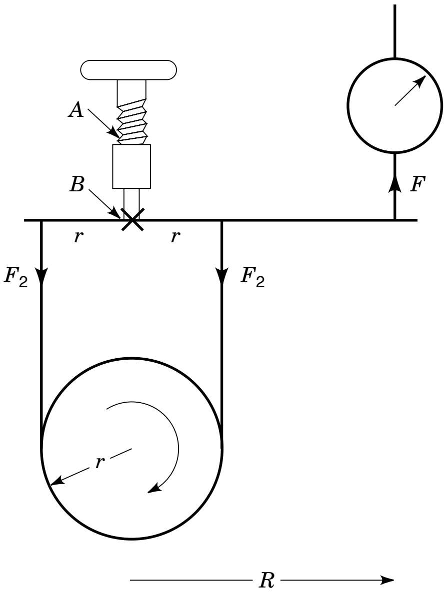

Figure 1. The Prony Brake. In this type the screw arrangement "A" is used to tighten the belt. "B" is the fulcrum of the lever. The force F shown on the spring balance is a measure of the torque.

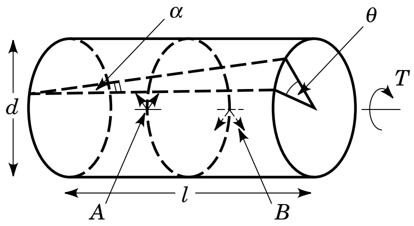

Figure 2. Shaft torsion. The torque T causes the torsion θ and shear α. The principal axes are shown at "A" and at the concealed point "B". Strain gauges would be placed at these positions.

Transmission Torque Measurement

In applications where the energy is transmitted rather than being absorbed in the measuring instrument, a commercial device inserted in the shaft is again the simplest solution, but in many laboratory situations and consumer products, it is better to integrate the device into the overall design. In the latter case, this would usually be on the grounds of convenience, physical size, or cost. The techniques used depend on measuring the small distortions caused by the stresses related to the applied torque. Figure 2 shows the torsion, which is evaluated either by measuring the distortion of the surface or the twist between the ends. The former can be measured using strain gauges attached to the surface, this being a well-developed technology, and suitable gauges exist tailored to this situation. When a shaft is twisted, the directions of greatest stretch and compression on the surface are at 45° to the axis of the shaft, these being known as the principal axes of the surface strain. Figure 2 shows these, and strain gauges would be applied to take account of these. Combination gauges are available to measure strains in more than one direction at a point and are called rosettes. It is important that the gauges are attached to the surface in such a way that a signal can be derived which represents the torque but which does not respond to shaft bending, compression, or stretching. Attaching gauges on opposite sides of the shaft as indicated and differencing the signals eliminates the spurious responses, and standard electronics is available to process the signals. The problem is passing power and signals to and from the rotating shaft. In the past, sliprings have been used satisfactorily, but noncontacting methods are preferred for avoiding electrical noise and for long-term reliability. This has been achieved electromagnetically and optically. Usually, it is best to mount some of the electronics on the shaft so that the overall performance can be independent of the efficiency of the transmission across the gap. For example, the signal can be coded in a digital form. Alternatively, the magnetostrictive effect is exploited to measure the surface strain. This effect is the compression (or possibly extension) experienced when a ferromagnetic material is magnetized. The application of a stress to the material modifies this effect, and this can be measured. If the material is isotropic, that is, uniform in all directions, then there is no preferred direction to the effect, but for materials in a crystalline form, there are preferred directions. If the shaft, or a ribbon wrapped round it, is of suitable material, the effect can be exploited to measure the strain. Considering the principal axes of the strain, the magnetic permeability of isotropic materials is usually increased along the direction of greatest compression and decreased along the direction of greatest stretch. This can be detected by a coil system in close proximity to the shaft, placed and oriented to take account of the directions of principal strain shown in Fig. 2.

If the shaft is known to be rotating, then direct measurement of the twist between the ends of the shaft section is most simply carried out by detecting the time difference for corresponding points on each end to pass fixed points. The methods used are electromagnetic, optical, and capacitive. It would be simplest to place small magnets on the shaft and pick up signals in coils as they passed. However, it has been found to be better to use gear teeth on the shaft surrounded by static internal teeth. For ferromagnetic materials, the rotation changes the magnetic properties of the system through the ease with which the magnetic flux passes between the outer and the inner parts. This is detected by a coil. Optically, the path of a light beam is interrupted by lines on a disk mounted on the shaft. If electrical capacity is used, then some protrusion on the shaft can be detected as it passes an electrode. In the applications where the shaft may sometimes be stationary, it is still possible to arrange for signals to be generated in similar ways, but the interpretation is more difficult, and greater care is needed to obtain good performance. It should not be forgotten that for some electric motors the measurement of the input current, possibly allowing for the phase in the case of alternating current may give a sufficiently good measure of the torque supplied.

STATIC TORQUE MEASUREMENT

There are applications which are essentially static and are exemplified by a robot wrist. To apply feedback in the control of a robot arm, it is useful to know the forces and torques in the wrist connecting the arm to the gripper. Tasks which require feedback include the insertion of a peg in a hole, force-controlled assembly of mechanical parts, and screwing parts together. It also allows the detection of jamming. In general, the measurement of torque is more important than that of force, and this is discussed here; Fig. 3 shows the three torques about the three axes. The methods used depend on the small distortion of the wrist caused by the forces and torques. Because the movement is limited, the connections are by flexible cables, and there is no problem of power and signal transfer. Strain gauges are normally used, and the design skill lies in applying these to a suitable mechanical structure in such a way that the various forces and torques can be distinguished, possibly using a microcomputer. Again, the use of rosettes helps in this. There are many works on strain gauge technology, and the reader is referred to Ross (1) for a helpful introduction. Workers have also used magnetic inductance to detect the small distortions, magnetic circuits being sensitive to small changes in air gaps. Other workers have explored the use of electrical capacity in order to make compact devices at low cost. In all these cases, the possibility of integrating the electronics and incorporating it in the wrist is attractive. Falkner (2) has established that this is possible for driving a capacitor type of wrist sensor. In this, a remote host computer interrogates the sensor and receives a digital signal in return. Workers in this field usually design and instrument their own devices. Static torque may also be measured on a large scale, including heavy machinery, industrial processes and construction equipment, and in these situations strain gauge technology is well-tried and usually most appropriate.

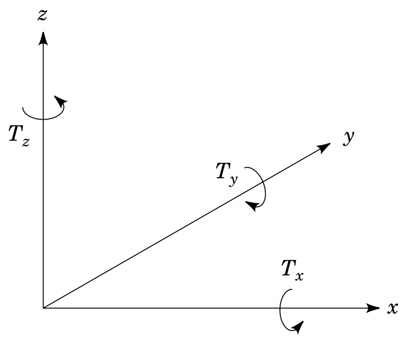

Figure 3. Torques about the three axes.

PRINCIPLES OF OPERATION

In this section, torquemeters are discussed in fuller detail with more detailed analysis of the principles. As pointed out earlier, it is necessary to understand instruments which may no longer be current but which continue in use and which are perfectly satisfactory. This is certainly the case for many of those which absorb the power, and these are the first to be considered.

Power Absorbing Torquemeters

The Prony Brake has been discussed in the introduction and demonstrates the principle very clearly, the torque being transferred to a stator where it can be measured more easily. The hydraulic and electrical types are discussed more fully here, the former transferring the torque in one of two ways. There is the friction type in which disks on the rotor rotate between disks on the stator. The gaps are designed to be small to increase the friction, the velocity gradient in the fluid then being large. The friction is controllable by the quantity of fluid, usually water, in the device, although it will depend on the speed. The water will also be used for cooling to remove the heat generated. The nonlinearity of the effect can make operation difficult as speed instabilities are possible for some power sources. The second type works through agitation of the fluid and is essentially an inefficient centrifugal pump, the rotor comprising a disk with vanes on each side. This operates as a centrifugal pump for the fluid which is impelled into the stator vanes from where it is recirculated. The fluid gains and loses kinetic energy, thus generating heat. Control of the braking effect can be through varying the quantity of fluid and valves for controlling the fluid flow. Again, water is usually used and is circulated for cooling. The rotor revolves between fixed stator blades to which the torque is transferred. Again, the device is nonlinear and may not be easy to control. But in each case, relatively small devices can absorb large

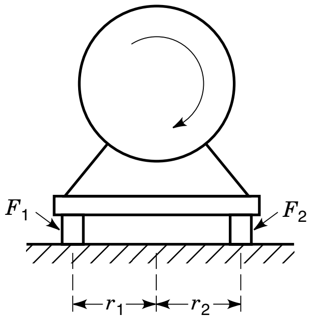

Figure 4. The reaction torque on the motor mounting. The torque is $(F_1r_1 - F_2r_2)$.

powers because of the cooling facility. The outer casing is mounted in bearings so that it would be free to rotate but for the constraints of the mounting which is instrumented to measure the forces. In Fig. 4, the torque is $(F_1r_1 - F_2r_2)$ Nm. For simplicity, the principle is demonstrated by showing only two of the mounts. Devices have also been used which employ a fan working with air in a situation in which heat is generated, and the energy is absorbed.

The use of electrical braking for the torque transfer offers greater flexibility and the simplest method is that in which the shaft drives a generator which has a variable resistive load. Reducing the resistance increases the output current and increases the load and torque transmitted. It is also possible to feed the power into the mains. The casing of the generator is mounted in bearings, and the torque is measured as above. An alternative method of transferring the torque is through eddy current loading and, in devices using this principle, the rotor comprises a metallic disk of magnetic material. There are large teeth on this rotor which sweep past the inner surface of the field magnet during rotation. The relative motion causes rapid fluctuations in the magnetic flux passing between the rotor and the stator depending on whether they are opposite one another. This, in turn, causes eddy currents which flow near the surface in the stator. This process absorbs energy, and the eddy currents flow in such a way as to retard the rotor. The torque transferred is controlled by varying the magnetization of the stator through variation of the current in the stator coils. The torque will also depend on the speed of the rotor at lower speeds, but a useful feature is that the torque saturates above a critical speed and is then mainly dependent on the field current. This makes for smooth, controllable operation. The dissipation of the heat generated is usually achieved through water cooling, adding a complication in use. As in other devices, the reaction torque on the stator is measured using a strain gauge load cell or a linear voltage differential transformer to give the output. In the latter case, there is a spring to resist motion, and the small compression or extension is measured. Care must be exercised to ensure that the electrical leads and the cooling pipes do not contribute to the torque and cause an error. The reader is referred to Ambrosius (3) for further details of these instruments.

Direct Shaft Torque Measurement

These methods all depend on the torsion, or twist, of a length of shaft when the torque is applied. No power is absorbed. In Fig. 2, the torsion θ is given by

$$\theta = (32/\pi)(l/Gd^4)T \text{ rad} \tag{1}$$

with the shear angle α given by

$$\alpha = (16/\pi G d^3)T \text{ rad} \tag{2}$$

where

d = the shaft diameter (m)
l = the shaft length (m)
G = the modulus of rigidity (N/m^2)
and T = the applied torque (Nm)

As an example, for steel, $G = 7.7\ 10^{10}$ N/m^2 so that a length 100 mm of a shaft of diameter 25 mm would twist approximately 3.3 mrad when a torque of 100 Nm was applied. This is equivalent to a movement of approximately 0.33 mm at the surface. A sensitivity of 1% of this corresponds to a surface movement of 3.3 μm. Clearly, if the shaft is made thinner at this section or a longer section is used, then the twist is greater, and the measurement is easier. The problem is that excessive flexibility causes distortion of the system being measured. In some cases, depending on the characteristics of the power source and the load, flexibility may lead to resonances building up. In other cases, the flexibility might reduce the response to higher frequencies in the measurement. For the use of strain gauges or magnetostriction, which depend on the local surface distortion, the angle α is critical but not the length l. Strain gauges are considered first.

Strain Gauges. This is a well established technology, and the correct use in this application takes account of the strain pattern in a twisted shaft. There is a shear on the surface which is perpendicular to the axis and if there is no bending of the shaft or any axial strain, then there is a strain system which has maximum and minimum values along the principal axes at 45° to the axis of the shaft. These are shown in Fig. 2 and are the most sensitive directions for detecting the surface distortion with strain gauges. The strain theory is discussed in Ross (1), and for the strain angle α, the principal strains σ_1 and σ_2 are $\pm(\alpha/2)$. In the example given above, these are ± 163 microstrain. Details of the operation of strain gauges are given in the appropriate section of this encyclopedia, and the gauges are placed to detect the principal strains, probably using a rosette which comprises more than one element. The gauges on the opposite side of the shaft are utilized to avoid spurious operation when the four gauges are connected into a bridge as shown in Fig. 5. The bridge output is

$$V = [(R_2R_3 - R_1R_4)/4R^2]E \tag{3}$$

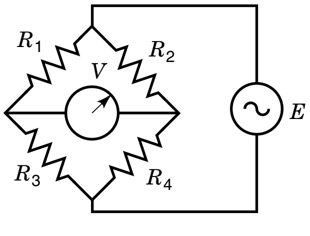

Figure 5. The strain gauge bridge. Unbalance between the resistances $R_1 - R_4$ of the strain gauge elements causes an output voltage V.

where the resistors all have nominal value R, and the small size of the increments due to the strain are taken into account. For pure torsion, the strains $\pm(\alpha/2)$ cause proportional changes in the resistors of $\pm K(\alpha/2)$ where K is the gauge factor of approximate value 2 for most materials used. Thus, R_1 becomes $R(1 + K\alpha/2)$ etc., and

$$V = (K\alpha/2)E \tag{4}$$

The torque is given by

$$T = (\pi G d^3/8K)(V/E) \tag{5}$$

If the shaft is under longitudinal tension or compression, the output is unaffected because all the gauges are affected in the same proportion. Similarly, bending of the shaft affects the resistances in such a way that there is no contribution to the output. The required gauges are readily available but require care in mounting, and the electronics units are also available. The problem is how to connect the power and signals to the rotating shaft. The most direct method is through sliprings, but these can cause electrical noise and would not be considered reliable in the long term. IML (Table 1) manufactures a range of noncontacting strain gauge torquemeters. Electromagnetic coupling has proven successful, and Zabler, Dukart, Heintz and Krott (4) describe a system for detecting the torque in the steering column of an automobile as part of a power assisted steering system. The particular requirements are low cost associated with high reliability and high performance. The last mainly concerns the stability of the null position because the output forms the error signal for the servo system. The noncontacting power and signal transfers are achieved through annular transformers. The inner annulus rotates, but the outer one is static, and the transformer action is unaffected by the rotation. The researchers decided against the simplest configuration in which the ac power supply was transmitted by one transformer and then fed the bridge. The other would take the output of the bridge, and the electronics would all be off the shaft. This arrangement was considered sensitive to noise for the low output signal and to the variations in sensitivity during rotation when the gap would vary using normal manufacturing tolerances. Rather, the electronics was mounted on the shaft supplied by one of the transformers. The bridge output was amplified and converted to a pulse width modulated form for minimum noise sensitivity when transmitted across the gap. In this application, special strain gauge elements were used to reduce cost. This approach resulted in a robust and high performance system.

Table 1. Manufacturers of Torquemeters

Torquemeters Ltd., Ravensthorpe, Northampton, NN6 8ET, UK, +1604 770232

Vibro-Meter SA, Rte de Moncor 4, CH-1701, Fribourg, Switzerland, +37 87 11 11

Industrial Measurements Limited, Melbourne, Derby, DE73 1DY, UK, +1332 864 0000

6-Axis Torque Sensor: Lord Industrial Automation Division, Lord Corporation, 407 Gregson Drive, Cary, NC 27511, +919-469-2500

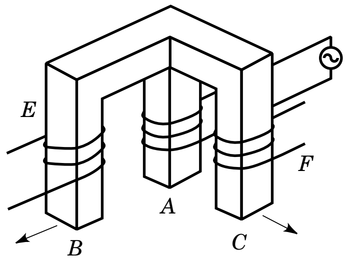

Figure 6. Magnetostrictive torque measurement. This device compares the properties of the surface along AB and along AC. Unbalance is detected by the difference in the signals in coils E and F. This figure is reproduced from *A Survey of Torque Transduction Methodologies for Industrial Applications* by B. Beihoff in the Proceedings of the 1996 Annual Pulp and Paper Industrial Technology Conference. © 1996 IEEE.

Magnetostrictive Devices. In these devices the change in the magnetic permeability of certain materials when stressed is exploited. In principle, the effect is considerably more sensitive to strain than the strain gauge effect. This is discussed by Beihoff (5). Exploiting this depends on successfully subjecting the material to the strain. With strain gauges, the technology for attaching the gauges is well developed, but attaching a thicker, more rigid, material is more difficult. The alloys which are useful in this context are nickel–iron, nickel–cobalt, and high nickel steels. One solution is to manufacture a section of shaft from this material and give it the required thermal mechanical pretreatment. This appears to be expensive, and there may be a compromise over the mechanical properties. More usually, a layer is attached in the form of a ribbon. As explained earlier, the directions of maximum positive and negative stress are in directions at 45° to the axis, and the physical arrangement needs to take account of this. The simplest approach is the coil arrangement shown in Fig. 6. If there is no torsion, then the inductances of the two arms B and C are balanced, and there is no output from the electrical bridge. If there is torsion present, one inductance is increased, and the other decreased, unbalancing the bridge and resulting in an output signal that depends linearly on the torsion over a useful range. Koga and Sasada (6) report an instrument using a more advanced coil system. Figure 7

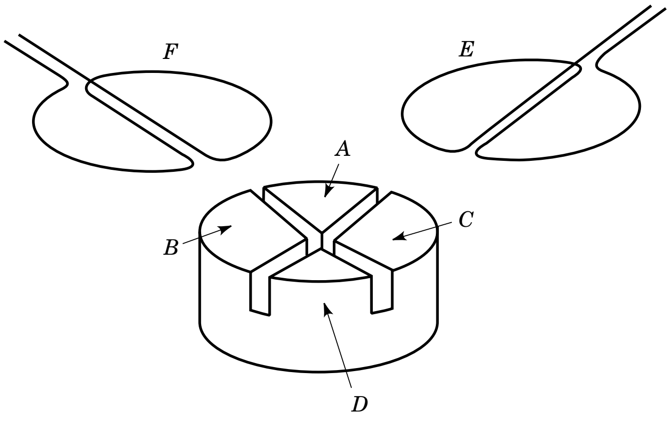

Figure 7. A more compact arrangement for magnetostrictive torque measurement. This figure is reproduced from *Static Characteristics of Torque Detection from Carburised Steel Shafts* by F. Koga and I. Sasada in the IEEE Transactions on Magnetics, **31** (6): 1, 1995. © 1995 IEEE.

shows the figure of eight coils and their orientation with respect to the principal axes on the adjacent shaft. This ensures that the overall measurement of the effect is localized. Sections A and B with sections C and D of the magnetic core form one inductor with coil E. Sections A and C with sections B and D with coil F form the other, and the lack of balance again gives the required signal. The compact design is mainly to reduce the effects of variations in the gap between the sensor and the shaft and variations in the magnetic properties of the shaft. The effective sensor for each of the principal axes uses the same region of the shaft surface. The inductance is particularly sensitive to very small variations in the gap because of the high relative permeability of the core material. In the work described, two sensors are used on opposite sides of the shaft which is of carburized steel. They use a carrier frequency of 60 kHz, and for a torque range of ±400 Nm with a 25 mm shaft, the linearity is ±0.6%. In this first work, there are fluctuations in the performance, including those which are caused by rotation of the shaft. An alternative way of measuring the magnetostrictive effect is to exploit the coupling between two adjacent coils as suggested by Sasada and Koga (7). One sets a magnetizing field parallel to the axis, and the other detects any magnetization of the shaft at right angles to the axis. When there is no torsion, there is no signal, but the torsion causes anisotropy in the permeability and magnetisation at right angles to the axis. This has been found to be proportional to the torsion over a useful range.

Phase Measurement. Devices which depend on the time difference in signals picked up from the two ends of the shaft section when it is rotating use electromagnetic, optical, or capacitive pick-ups. This may also be thought of as the measurement of the phase difference between the two signals. In general, such devices will not operate while the shaft is stationary or rotating very slowly. An example of an electromagnetic system is the range of Torquetronic torquemeters manufactured by Torquemeters Ltd. (Table 1). The essential mechanism comprises internal and external gears with teeth. The outer contains a coil, and the magnetic circuit around the coil changes as the teeth rotate and pass through positions in which they are opposite to each other. If, for example, there is a constant current fed into the coil, then a voltage is generated as the magnetic circuit changes. The manufacturers point out that the use of several teeth in this way compensates for problems associated with any radial movements. The possible torque range of this device depends on the shaft dimensions, and meters with ranges as high as 75,000 Nm are available. These particular devices also record the speed. The problem of lack of signal if the shaft is stationary will not matter in many applications, but it is overcome in a range of devices in which the outer teeth are rotated, the coil still being stationary.

The simplest optical system suitable in a laboratory situation is the use of a stroboscope enabling the twist to be seen visually. A commercial instrument by Amsler is described in Ambrosius (3) with particulars of its source. The power is transmitted through the torsion rod which, at one end, has a disc attached with gradations around the edge. Concentric with this rod and outside it is a tube which is not subject to any torque. This carries the information about the angular position of the other end to another smaller flat ring which also has a graduated edge. The two scales are adjacent, and the torsion causes relative motion of the two scales, a vernier scale being used for accuracy. To inspect the scales during rotation, a synchronized stroboscope is used. Clearly, it would not be feasible to inspect the scales for a general static position, and the device depends on rotation. Measurements are best made for steady torques, and it is not possible to automate the operation of the device.

Other Optical Devices. Another type of optical torquemeter uses mirrors. Again, rotation is required for successful operation. The principle is that if a light beam is reflected off two parallel mirrors in sequence, then the direction of the ray is unaltered; although, of course, it will be shifted sideways. The meter is designed so that one mirror is attached to one end of the flexible shaft and the other to an outer cylinder which is connected to the other end in a similar manner to the optical instrument described above. The two mirrors are at the same position at the end of the shaft. A collimated light ray, possibly from a laser, strikes the mirrors in turn for a small part of the time of rotation. During this time, the change in direction depends on the lack of parallelism, equivalent to the angle of twist of the shaft. The transmitted ray is focused onto a scale, and the position of the light spot corresponds to the twist in a linear manner. Further details are given in Adams (8).

Beyond this, the simplest system is one that depends on the rotation of the shaft and uses a disk mounted axially on the shaft at each of the two positions. Each contains a pattern of radial lines and is otherwise transparent. Units comprising light-emitting diodes and photo cells detect the motion of a disk, and the twist in the shaft gives a phase difference at the two positions. This is measured as described above. A different approach is required if the shaft is stationary or slow moving, and to overcome this problem, Hazelden (9) has developed an optical sensor for use in an electrical power assisted steering system. In this, the light passes through both the disks which are close to each other, the patterns being designed so that there are two outputs whose ratio determines the torsion, taking account of sign. This arrangement makes the signal independent of the light intensity. An optical sensor is suited to the electrically noisy environment. The performance is not claimed to be suitable for general instrumentation but it is adequate for this application and capable of being manufactured at the low cost which is demanded.

Inductive Devices. The principle of these instruments is the variation of the transformer coupling between two coils through the variation in the magnetic circuit caused by the distortion of the shaft. There are concentric cylinders attached to each end of the flexible section of the shaft. These contain slots arranged so that when there is no twist, they just do not overlap so that there is no coupling between the coils. The deformation caused by twisting causes overlap and creates the magnetic circuit allowing coupling. With careful design, the coupling is proportional to the applied torque, and it is also possible to make the system detect the direction of the torque so that the electronics generates a dc output signal of sign depending on the direction. This device has no lower speed limit. Vibro-meter (Table 1) manufactures a range of instruments using this principle with measurement ranges of ±1 to ±500 Nm. The bandwidth is 1 kHz. The linearity is of the order of ±0.2% over a wide range of environmental conditions.

Capacitive Devices. Capacity has been exploited to detect the shaft torsion, and the methods to be described are ones in which the variable capacitor or capacitors form part of the rotating shaft. An older design developed by the Royal Aircraft Establishment, Farnborough, is described in (10). In this, there are two concentric cylinders, one connected to each end of the shaft so that one is inside the other with a small gap. The torsion causes a small relative twist which is detected by teeth, or serrations, on the outside of the inner element and on the inside of the outer element. When these coincide, the capacity between the inner and outer is a maximum and reduces as the relative angular position moves from this state. By using square teeth and a very small gap, there is a region in which the capacity varies linearly with the angle, and this is used. The capacity is measured from outside the device through sliprings and a bandwidth up to 80 kHz is reported. On those applications where vibrations are being looked at, long-term drift will not matter. In other cases, it is better to use a bridge technique to remove temperature and other effects. The technique is also sensitive to stray capacities. Today, sliprings would be considered a possible source of unreliability.

An alternative use of capacity is that developed by Falkner (11). The torsion between the ends of the flexible section of shaft is detected through two capacitors. The plates of these are connected to the ends in such a way that the torsion increases the gap in one and decreases it in the other. Capacitors are more sensitive to gap changes than to relative lateral motion of the plates. The two capacitors form a bridge and the three connections to the bridge are connected capacitively to the stator through rings with small gaps, thus maintaining the requirement for no contact. Such bridges have been found to be very stable and sensitive at the submicrometer level. In this situation, the performance is affected by these coupling capacitors, but it is the stability of their values which is critical. They are made as large as practical, which can be shown to reduce these effects. The prototype is extremely sensitive and has a range of ±0.9 Nm with nonlinearity better than ±1% of full scale. There is some residual variation in the readings as the shaft is rotated, the sensitivity and zero reading each varying ±1% of full scale. There would be no difficulty in designing a stiffer torsion device to operate at higher torque levels.

Static Torque Measurement

The situation has already been described above in the introduction and represented diagrammatically in Fig. 3, and again the robot wrist example is considered first. The most obvious approach is to use strain gauges on an appropriate mechanical configuration. For example, gauges could be arranged around a metal wrist block. In this case, the signals obtained would each contain information about more than one of the torques and forces present, but the use of the appropriate rosettes and bridges as described above would help the situation. There is also the possibility of using a microprocessor program to distinguish the individual outputs. More satisfactory is the use of a metal cross, in which case the arm and the gripper are joined to the center and the outside of the unit which is designed to give enough flexibility for useful signals. In this case, the arms are instrumented with the gauges on all the faces, and inevitably, there is some mixing of the signals so that it becomes essential to use a microprocessor. Such a device has been made commercially by Lord Automation (Table 1) with an accuracy of approximately ±2% and some residual cross-coupling. Other workers have used inductance and capacity to detect strain in the wrist. An example of the former is by Piller (12), the compliant element being essentially three helical springs between two plates. Any force or torque applied to this causes a small distortion, and the signals from a set of inductive pick-offs are interpreted to distinguish the forces and torques. Falkner (2) has used capacity in a wrist in which the compact mechanical design allows complete separation of the three forces and the three torque signals. Small distortions occur, each of which depends solely on one of these parameters. Each measurement is made capacitively. Figures 8 and 9 show the two types of basic ele-

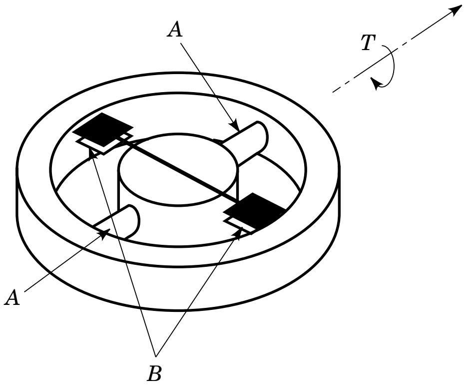

Figure 8. A capacitive torque sensing element. "A" is a torsion bar and torque unbalances the capacitor bridge "B." This material has been reproduced from the Proceedings of the Institution of Mechanical Engineers, Part C, *Journal of Mechanical Engineering,* **206**: 1992, by A. H. Falkner by permission of the Council of the Institution of Mechanical Engineers.

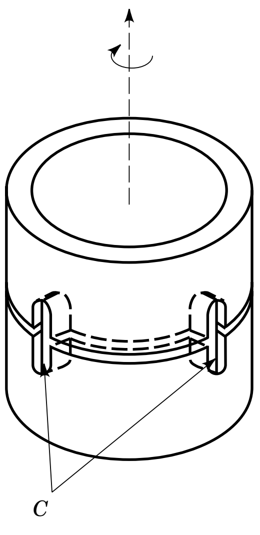

Figure 9. In this configuration, axial torque causes torsion through the flexing of the leaves "C." This material has been reproduced from the Proceedings of the Institution of Mechanical Engineers, Part C, *Journal of Mechanical Engineering Science,* **206**: 1992, by A. H. Falkner by permission of the Council of the Institution of Mechanical Engineers.

ments used for the torque measurement. That, in Fig. 8, works on a torsion bar which the applied torque twists, unbalancing the capacitor bridge comprising the two capacitors shown. The antiphase drive signals are applied to the two fixed plates, and the signal pick-off is the moving element A. In Fig. 9, the device responds to twist about the axis to unbalance the capacitor bridge. Again, the two moving plates are connected together to form the pick-off. In each case, torsion increases one capacitor and reduces the other, and the signal measures the amplitude of the torque and, through the phase, the sign. A compact three-axis torque sensor has been built using two elements of the type shown in Fig. 8 and one of the type shown in Fig. 9. To simplify the electronics, it is possible to multiplex the drive signals to the bridges and make the outputs common. The use of square waves makes the multiplexing simple using integrated electronic circuits of the complementary metal-oxide-semiconductor family. A prototype application specific integrated circuit has been made to drive the circuit and interface to a computer with the objective of fitting the electronics in the device and having the simplest possible electrical connections. Otherwise, it is possible to use long leads with no electronics in the device. It has been found that the capacitor bridges are extremely stable in this situation, and overall performance is at the 1% level. The correct mechanical design results in complete isolation of the axes. For larger scale applications, including heavy equipment, the robust, well-tried techniques based on strain gauges are most appropriate.

CURRENT DEVELOPMENTS

The above shows that there are a number of well-tried methods available for measuring shaft torque and for measuring torque in static situations, such as the robotic wrist. The requirements vary, but the present emphasis in research is towards low-cost devices with high performance. The latter includes accuracy, sensitivity, and linearity as well as noise immunity and wide bandwidth. Environmental conditions vary, but there may be a requirement for operation over a wide temperature range and for ruggedness. In the case of an automobile power assisted steering system, for example, the device is expected to operate with little maintenance over many years in a hostile environment. The system must be designed so that any failure is safe in the sense that no assistance would be supplied, rather than a false turning which the driver could not control. To meet these challenges, there is work in the development of existing techniques and in the investigation of new ideas. It is difficult to predict which will be most successful, but it is always likely to be the case that a range of techniques will be used. The availability of application specific integrated circuits in electronics, which are inexpensive even in small quantities, means that as much complication as possible should be in the electronics with the simplest possible electrical and mechanical components. It is possible to incorporate a microprocessor to measure nonlinearities and temperature and compensate for these. This can remove the need for tight mechanical tolerances and materials specifications. These developments have led to falling costs across instrumentation in general and have made possible the use of new techniques. There is also interest in fully integrated sensors for many purposes. In these, micromachining of mechanical parts is undertaken on the silicon chip which contains the electronic circuitry. The wide range of adhesives now available may make an important contribution. Below is a survey of the current research which appears to be of most promise.

Magnetostrictive Devices

There is considerable activity in the field of the magnetostrictive sensors. This centers around the selection of the material itself and the use of ribbons as well as treatment of an existing shaft. Otherwise, compact pick-ups are being developed. For ribbons, the work is directed to the choice of material and the problem of attachment to the shaft. An example is work by Hase, Shoji and Wakamiya (13). The gluing process requires raising the temperature, and during the cooling, the differential coefficient of expansion results in a compressive stress in the ribbon. This compression is biased in direction, and this direction will coincide with a principal axis. The magnetic properties are affected in a way which can be exploited to arrive at a device with uniform characteristics over a wide temperature range. Hirose, Takagi, Mori and Imura (14) describe the following process for the fabrication of an amorphous magnetic alloy layer. A crystalline layer of the alloy is attached to the surface by silver brazing and then melt quenched by laser irradiation. It is found that the easy direction of magnetization is along the direction of the laser scanning. This feature is exploited by making this direction along one of the principal axes at 45° to the shaft axis (Fig. 2). A further refinement is to make the treated area in stripes in this direction. The coil structures required are described above in the section on magnetostrictive devices, and research is directed to making these more compact. In particular, Rombach, Steiger and Langheinrich (15) have developed a micromachined torque sensor in which a magnetic layer and coils are deposited on the slice of silicon containing the electronic circuitry. The magnetic layer becomes the core of the coil and this is the equivalent of the Torquemaster (Table 1) devices which are described above. The manufacture could be highly automated. One objective is the compensation for variations in the gap between the shaft and the sensor which occur with normal machining tolerances. This is achieved by measuring the field in different positions around the sensor head to allow compensation.

Surface Acoustic Waves

Devices are being developed based on the effect on the propagation of surface acoustic waves of strain in the material used. The purpose is to develop instruments which require the minimum part on the rotating shaft and which can be treated as a part of an electrical circuit on the stator. In this case, the signal is connected by the electrical capacity of the gap, this being easy at the very high frequencies used. The corresponding impedances are relatively low, and the overall system is robust. It has been known for a long time that sound waves propagate in the surface of isotropic, elastic materials. It is possible to interface from electrical signals to the acoustic signals using a piezoelectric substrate, and devices which include resonators and filters can be fabricated in a small space because the wavelengths are small. A strain sensor depends on the effect of strain in the substrate on the wave velocity and is mounted on the shaft along one of the principal axes. For the case of a resonator, this affects the frequency, independently of the gap spacing. Typical frequencies are 200 MHz to 400 MHz corresponding to convenient physical dimensions of 1 or 2 mm. Hall, Wang and Lonsdale (16) describe how they have mounted the resonant element on the shaft. The coupling is capacitive as described above so that the resonator forms part of the circuit. Inductive coupling would be an alternative. The overall resonant frequency is measured using well established electronic techniques to give a measure of the strain. In the work reported, the emphasis has been on overcoming the sensitivity of the sensor to the temperature by using various configurations and cements for attaching the sensor. The current situation is that successful development would result in a very useful instrument, but further work is needed.

Other Developments

In the devices in which the sensor is mounted on a rotating shaft, the use of light to transfer the signal, and even the operating power, is attractive. The system can be designed so that variations in the light intensity are not important. In the case of the power, a simple regulated power supply is needed on the shaft. Electronic circuitry is available that consumes an extremely small amount of power of the order of a few mW or less, and the main user of power will be the light emitting diode which transmits the signal back. The whole system becomes feasible with small standard optical devices. To ensure the noise immunity and tolerance to light power variations, a pulse code or digital code is used. The practical problem is arranging for light to be transmitted at all angular positions of the shaft. An example is given by Mu and He (17) in which they use a standard strain gauge bridge and report that the signal is transmitted in Hamming code using infrared light. The overall accuracy for measuring the torque is ±0.1%. Dezhong and Zesheng give another example (18). They use light in the visible spectrum, and the power is picked up by a ring of photocells which allows operation in daylight or through an optical fiber. The modulation technique is to use a multivibrator with two strain elements switched alternately into the timing circuit leading to a form of pulse width modulation. The signal is transmitted by a light emitting diode back to a ring of photo diodes and the demodulator compares the width of alternate pulses. The electronics uses standard low power integrated circuits, and the linearity is of the order of ±1%.

There are current developments in the capacitor techniques for measuring the torsion. Cooper (19) describes an instrument in which a variable capacitor on the shaft forms part of a tuned circuit, all the other elements being on the stator, and the coupling being capacitive. The capacity variation is achieved by using the torsion to move a dielectric material in the gap of the capacitor, thus varying its value. The units have been designed to fit in a small, hand-held electric screwdriver, the signal being required for feedback in the control of the operation. To achieve a linear relationship between the torsion and the overall output, the capacitance forms part of a multivibrator circuit so that simple digital counting leads to the torque value. The sensitivity is 0.005 Nm and the linearity is ±0.6% but the reported results show that further work is required to remove sensitivity to environmental conditions and to the angular position. It is suggested that a bridge technique might be helpful in this respect. Falkner (20) has investigated how capacity can be exploited with the minimum changes to the shaft. From the point of view of ease of manufacture, splines which already exist, in many cases, are suggested, but if the shaft may sometimes be stationary, then a timing method will not work. The only signals available are capacities to the grounded shaft, these varying with angular position. These can be measured at the two ends from internal splines on the stator. Although these readings will, in general, be different, there is ambiguity in the interpretation, and readings at or near the peak values are not very dependent on the position. To overcome this, a system of four external elements at each end is proposed which generates a signal whose phase depends on the angular position passing through 360° for each spline pitch. Then, the phases are compared at each end to give the torsion without ambiguity. Assessment of this proposal awaits the making of a prototype. Other techniques which have been investigated include the Faraday effect, the piezoelectric effect, and the use of the Hall effect to measure unbalance in magnetic bridges.

BIBLIOGRAPHY

1. C. T. F. Ross, Ch. 7, *Applied Stress Analysis,* Chichester: Ellis Horwood, 1987.
2. A. H. Falkner, The measurement of force and torque using capacitor devices, *J. Mech. Eng. Sci.,* C, **206**: 385–390, 1992.
3. E. A. Ambrosius, *Mechanical Measurement and Instrumentation,* New York: Ronald Press, 1966, p. 280–303.
4. E. Zabler et al., A noncontact strain-gage torque sensor for automotive servo-driven systems, *Sensors Actuators,* A, **A41-A42**: 39–46, 1994.
5. B. Beihoff, A survey of torque transduction methodologies for industrial applications, *Proc. IEEE Annu. Pulp Paper Ind. Technol. Conf.,* 1996, Birmingham, AL, 220–229.
6. F. Koga and I. Sasada, Static characteristics of torque detection from carburized steel shafts, *IEEE Trans. Magn.,* **31**: 1, 3143–3145, 1995.
7. I. Sasada and F. Koga, A new structure of torque sensors using thin pick-up head—use of mutual coupling modulation, *J. Appl. Phys.,* **75** (2A): 5916–5918.
8. L. F. Adams, *Engineering Measurements and Instrumentation,* London: Hodder and Stoughton, 1981, p. 128–129.
9. R. J. Hezelden, Application of an optical torque sensor to a vehicle power steering system. In J. Giber et al. (ed.), *Proc. Eurosensors VII,* **2**: 39–46, Lausanne: Elsevier, 1994.
10. M. Hetényi, *Handbook of Experimental Stress Analysis,* New York: Wiley, 1950, p. 287–293.
11. A. H. Falkner, A capacitor-based device for the measurement of shaft torque, *IEEE Trans. Instrum. and Meas.,* **45**: 835–838, 1996.
12. G. Piller, A compact six-degree-of-freedom sensor for assembly robots, *12th Int. Symp. Ind. Robots,* 1982.
13. H. Hase, R. Shoji, and M. Wakamiya, Torque sensor using amorphous magnetostrictive ribbons, *Mater. Sci. Eng.,* A, **A181-A182**: 1378–1382, 1994.
14. F. Hirose et al., Characteristics of an amorphous magnetic alloy layer prepared by laser quenching, *Mater. Sci. Eng.,* A, **A181-A182**: 1359–1362, 1994.
15. P. Rombach, H. Steiger, and W. Langheinrich, Planar coils with ferromagnetic yoke for a micromachined torque sensor, *J. Micromech. Microeng.,* **5** (2): 136–138, 1995.
16. D. A. Hall, H. W. Wang, and A. Lonsdale, Torque Measurement by Means of a SAW Resonator, *Sensors VI. Technology Systems and Applications,* 201–206, 1993. Manchester, UK.

17. N. X. Mu and S. S. He, The infrared transmitting torquemeter, *Conf. Proc. IEEE Conf. Advanced Technol. Instrum. Meas.,* **1**: 384–5, 1994. Hamamatsu.
18. Z. Dezhong and D. Zesheng, A new torque instrument driven by light power with two rings, *Proc. IEEE Int. Conf. Industrial Technol.,* New York, 510–513, 1994.
19. J. D. Cooper, Novel torque sensor for mechatronic applications, *4th IAESTED Int. Conf. Robotics Manuf.,* Honolulu, August 1996.
20. A. H. Falkner, Non-contact shaft torque measurement—A new technique, *Proc. 12th Int. Conf. Syst. Eng.,* Coventry, UK, 1997.

Reading List

References 4 and 5 in the Bibliography contain useful surveys which would be helpful in selecting the appropriate technique for a particular application. Reference 3 surveys older equipment which may still be encountered. Reference 1 gives the mathematical background to the stresses generated when torque is applied. Most technical libraries hold several books on instrumentation and measurement and many contain work on torque sensing. It is also suggested that information from the first three manufacturers listed in Table 1 is very helpful.

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TORQUE SENSORS. See DYNANOMETERS.

TORSION. See TORQUEMETERS.

TOTAL HARMONIC DISTORTION. See POWER SYSTEM HARMONICS.

TOTAL QUALITY MANAGEMENT. See QUALITY CONTROL.

TOUCH. See TACTILE SENSORS.

TRACK AND HOLD, CIRCUITS. See SAMPLE-AND-HOLD CIRCUITS.

TRACKING, RADAR. See RADAR TRACKING.

TRACKING, TARGET. See TARGET TRACKING.

TRADEMARKS. See INTELLECTUAL PROPERTY.

TRADE SECRETS. See INTELLECTUAL PROPERTY.

TRAFFIC, TELECOMMUNICATION. See TELECOMMUNICATION TRAFFIC.

TRAFFIC THEORY. See NETWORK PERFORMANCE AND QUEUEING MODELS.

TRANSACTION MANAGEMENT. See TRANSACTION PROCESSING.