Force, Acceleration, & Torque

The fundamental operating principles of force, acceleration, and torque instrumentation are closely allied to the piezoelectric and strain gage devices used to measure static and dynamic pressures discussed in earlier chapters. It is often the specifics of configuration and signal processing that determine the measurement output.

An accelerometer senses the motion of the surface on which it is mounted and produces an electrical output signal related to that motion. Acceleration is measured in feet per second squared, and the product of the acceleration and the measured mass yields the force. Torque is a twisting force, usually encountered on shafts, bars, pulleys, and similar rotational devices. It is defined as the product of the force and the radius over which it acts. It is expressed in units of weight times length, such as lb.-ft. and N-m.

Force Sensors

The most common dynamic force and acceleration detector is the piezoelectric sensor (Figure 6-1). The word piezo is of Greek origin, and it means “to squeeze.” This is quite appropriate, because a piezoelectric sensor produces a voltage when it is “squeezed” by a force that is proportional to the force applied. The fundamental difference between these devices and static force detection devices such as strain gages is that the electrical signal generated by the crystal decays rapidly after the application of force. This makes these devices unsuitable for the detection of static force.

The high impedance electrical signal generated by the piezoelectric crystal is converted (by an amplifier) to a low impedance signal suitable for such an instrument as a digital storage oscilloscope. Digital storage of the signal is required in order to allow analysis of the signal before it decays.

Depending on the application requirements, dynamic force can be measured as either compression, tensile, or torque force. Applications may include the measurement of spring or sliding friction forces, chain tensions, clutch release forces, or peel strengths of laminates, labels, and pull tabs.

A piezoelectric force sensor is almost as rigid as a comparably proportioned piece of solid steel. This stiffness and strength allows these sensors to be directly inserted into machines as part of their structure. Their rigidity provides them with a high natural frequency, and their

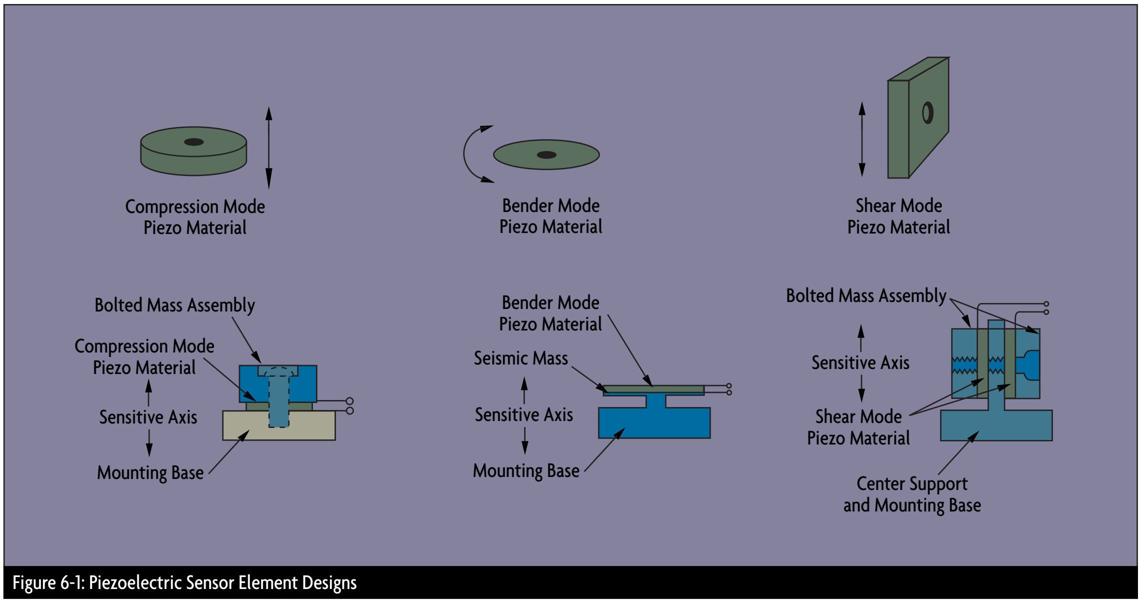

Figure 6-1: Piezoelectric Sensor Element Designs

Tiny accelerometer is useful for low-mass laboratory applications.

corresponding rapid rise time makes them ideal for measuring such quick transient forces as those generated by metal-to-metal impacts and by high frequency vibrations. To ensure accurate measurement, the natural frequency of the sensing device must be substantially higher than the frequency to be measured. If the measured frequency approaches the natural frequency of the sensor, measurement errors will result.

• Impact Flowmeters

The impact flowmeter is also a force sensor. It measures the flow rate of free flowing bulk solids at the discharge of a material chute. The chute directs the material flow so that it impinges on a sensing plate (Figure 6-2). The impact force exerted on the plate by the material is proportional to the flow rate.

The construction is such that the sensing plate is allowed to move only in the horizontal plane. The impact force is measured by sensing the horizontal deflection of the plate. This deflection is measured by a linear variable differential transformer (LVDT). The voltage output of the LVDT is converted to a pulse frequency modulated signal. This signal is transmitted as the flow signal to the control system.

Impact flowmeters can be used as alternatives to weighing systems to measure and control the flow of bulk solids to continuous processes as illustrated in Figure 6-2. Here, an impact flowmeter is placed below the material chute downstream of a variable speed screw feeder. The feed rate is set in tons per hour, and the control system regulates the speed of the screw feeder to attain the desired feed rate. The control system uses a PID algorithm to adjust the speed as needed to keep the flow constant. Impact flowmeters can measure the flow rate of some bulk materials at rates from 1 to 800 tons per hour and with repeatability and linearity within 1%.

Acceleration & Vibration

Early acceleration and vibration sensors were complex mechanical contraptions (Figure 6-3) and were better suited for the laboratory than the plant floor. Modern accelerometers, however, have benefited from the advance of technology: their cost, accuracy, and ease of use all have improved over the years.

Early accelerometers were analog electronic devices that were later converted into digital electronic and microprocessor-based designs. The air-bag controls of the automobile industry use hybrid micro-electromechanical systems (MEMS). These devices rely on what was once considered a flaw in semiconductor design: a “released layer” or loose piece of circuit material in the microspace above the chip surface. In a digital circuit, this loose layer interferes with the smooth flow of electrons, because it reacts with the surrounding analog environment.

In a MEMS accelerometer, this loose layer is used as a sensor to measure acceleration. In today’s

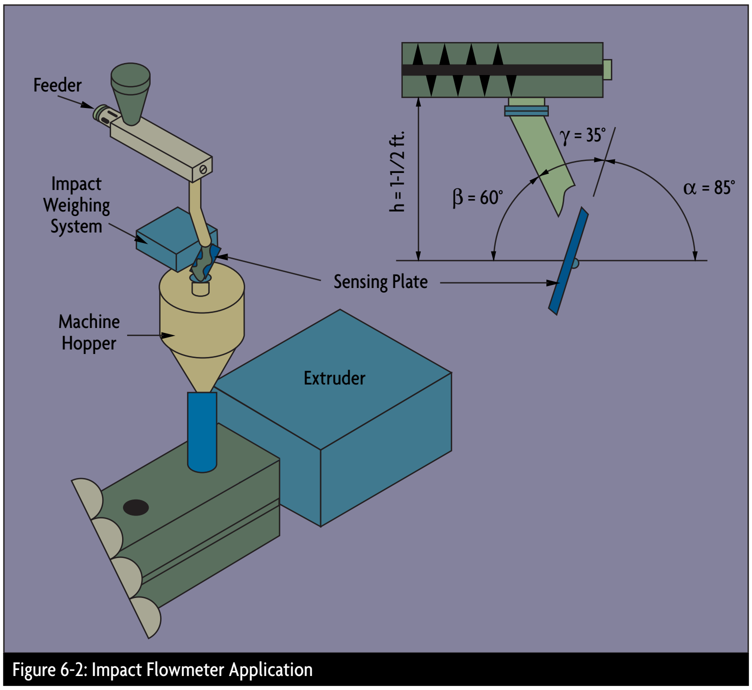

Figure 6-2: Impact Flowmeter Application

autos, MEMS sensors are used in air bag and chassis control, in side-impact detection and in antilock braking systems. Auto industry acceleration sensors are available for frequencies from 0.1 to 1,500 Hz, with dynamic ranges of 1.5 to 250 G around 1 or 2 axes, and with sensitivities of 7.62 to 1333 mV/G.

Industrial applications for accelerometers include machinery vibration monitoring to diagnose, for example, out-of-balance conditions of rotating parts. An accelerometer-based vibration analyzer can detect abnormal vibrations, analyze the vibration signature, and help identify its cause.

Another application is structural testing, where the presence of a structural defect, such as a crack, bad weld, or corrosion can change the vibration signature of a structure. The structure may be the casing of a motor or turbine, a reactor vessel, or a tank. The test is performed by striking the structure with a hammer, exciting the structure with a known forcing function. This generates a vibration pattern that can be recorded, analyzed, and compared to a reference signature.

Industrial accelerometer with associated electronics.

Acceleration sensors also play a role in orientation and direction-finding. In such applications, miniature triaxial sensors detect changes in roll, pitch, and azimuth (angle of horizontal deviation), or X, Y, and Z axes. Such sensors can be used to track drill bits in drilling operations, determine orientation for buoys and sonar systems, serve as compasses, and replace gyroscopes in inertial navigation systems.

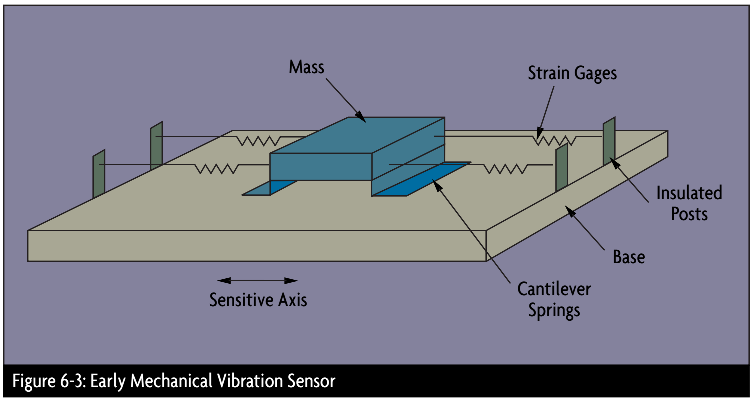

Figure 6-3: Early Mechanical Vibration Sensor

Mechanical accelerometers, such as the seismic mass accelerometer, velocity sensor, and the mechanical magnetic switch, detect the force imposed on a mass when acceleration occurs. The mass resists the force of acceleration and thereby causes a deflection or a physical displacement, which can be measured by proximity detectors or strain gages (Figure 6-3). Many of these sensors are equipped with dampening devices such as springs or magnets to prevent oscillation.

A servo accelerometer, for example, measures accelerations from 1 microG to more than 50 G. It uses a rotating mechanism that is intentionally imbalanced in its plane of rotation. When acceleration occurs, it causes an angular movement that can be sensed by a proximity detector.

Among the newer mechanical accelerometer designs is the thermal accelerometer: This sensor detects position through heat transfer. A seismic mass is positioned above a heat source. If the mass moves because of acceleration, the proximity to the heat source changes and the temperature of the mass changes. Polysilicon thermopiles are used to detect changes in temperature.

In capacitance sensing accelerometers, micromachined capacitive plates (CMOS capacitor plates only

60 microns deep) form a mass of about 50 micrograms. As acceleration deforms the plates, a measurable change in capacitance results. But piezoelectric accelerometers are perhaps the most practical devices for measuring shock and vibration. Similar to a mechanical sensor, this device includes a mass that, when accelerated, exerts an inertial force on a piezoelectric crystal.

In high temperature applications where it is difficult to install microelectronics within the sensor, high impedance devices can be used. Here, the leads from the crystal sensor are connected to a high gain amplifier. The output, which is proportional to the force of acceleration, is then read by the high gain amplifier. Where temperature is not excessive, low impedance microelectronics can be embedded in the sensor to detect the voltages generated by the crystals. Both high and low impedance designs can be mechanically connected to the structure's surface, or secured to it by adhesives or magnetic means. These piezoelectric sensors are suited for the measurement of short durations of acceleration only.

Piezoresistive and strain gage sensors operate in a similar fashion, but strain gage elements are temperature sensitive and require compensation. They are preferred for low frequency vibration, long-duration shock, and constant acceleration applications. Piezoresistive units are rugged, and can operate at frequencies up to 2,000 Hz.

Torque Measurement

Torque is measured by either sensing the actual shaft deflection caused by a twisting force, or by detecting the effects of this deflection. The surface of a shaft under torque will experience compression and tension, as shown in Figure 6-4. To measure torque, strain gage elements usually are mounted in pairs on the shaft, one gauge measuring the increase in length (in the direction in which the surface is under tension), the other measuring the decrease in length in the other direction.

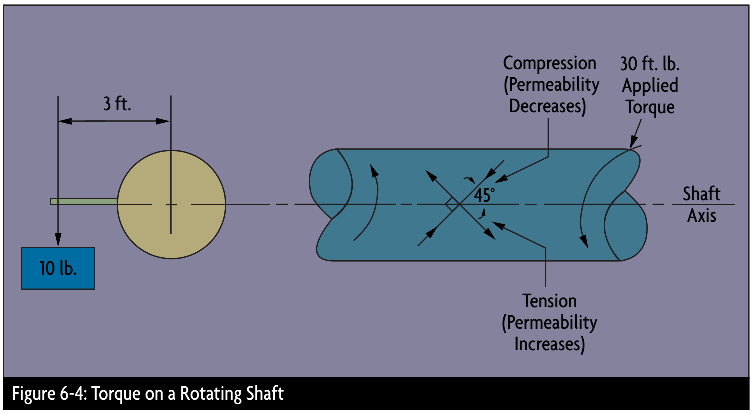

Figure 6-4: Torque on a Rotating Shaft

Early torque sensors consisted of mechanical structures fitted with strain gages. Their high cost and low reliability kept them from gaining general industrial acceptance. Modern technology, however, has lowered the cost of making torque measurements, while quality controls on production have increased the need for accurate torque measurement.

Torque Applications

Applications for torque sensors include determining the amount of power an engine, motor, turbine, or other rotating device generates or consumes. In the industrial world, ISO 9000 and other quality control specifications are now requiring companies to measure torque during manufacturing, especially when fasteners are applied. Sensors make the required torque measurements automatically on screw and assembly machines, and can be added to hand tools. In both cases, the collected data can be accumulated on dataloggers for quality control and reporting purposes.

Other industrial applications of torque sensors include measuring metal removal rates in machine tools; the calibration of torque tools and sensors; measuring peel forces, friction, and bottle cap torque; testing springs; and making biodynamic measurements.

Sensor Configurations

Torque can be measured by rotating strain gages as well as by stationary proximity, magnetostrictive, and magnetoelastic sensors. All are temperature sensitive. Rotary sensors must be mounted on the shaft, which may not always be possible because of space limitations.

A strain gage can be installed directly on a shaft. Because the shaft is rotating, the torque sensor can be connected to its power source and signal conditioning electronics via a slip ring. The strain gage also can be connected via a transformer, eliminating the need for high maintenance slip rings. The excitation voltage for the strain gage is inductively coupled, and the strain gage output is converted to a modulated pulse frequency (Figure 6-5). Maximum speed of such an arrangement is 15,000 rpm.

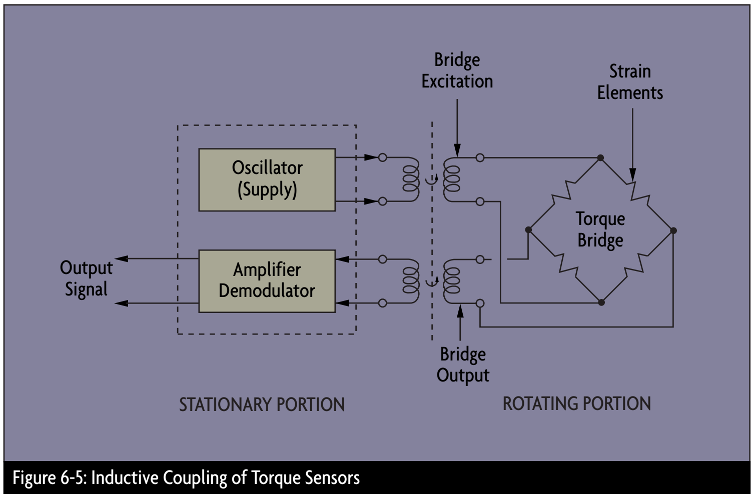

Figure 6-5: Inductive Coupling of Torque Sensors

Strain gages also can be mounted on stationary support members or on the housing itself. These "reaction" sensors measure the torque that is transferred by the shaft to the restraining elements. The resultant reading is not completely accurate, as it disregards the inertia of the motor.

Strain gages used for torque measurements include foil, diffused semiconductor, and thin film types. These can be attached directly to the shaft by soldering or adhesives. If the centrifugal forces are not large—and an out-of-balance load can be tolerated—the associated electronics, including battery, amplifier, and radio frequency transmitter all can be strapped to the shaft.

Reaction torque cell with flange mounts.

Proximity and displacement sensors also can detect torque by measuring the angular displacement between a shaft's two ends. By fixing two identical toothed wheels to the shaft at some distance apart, the angular displacement caused by the torque can be measured. Proximity sensors or photocells located at each toothed wheel produce output voltages whose phase difference increases as the torque twists the shaft.

Another approach is to aim a single photocell through both sets of toothed wheels. As torque rises and causes one wheel to overlap the other, the amount of light reaching the photocell is reduced. Displacements caused by torque can also be detected by other optical, inductive, capacitive, and potentiometric sensors. For example, a capacitance-type torque sensor can measure the change in capacitance that occurs when torque causes the gap between two capacitance plates to vary.

The ability of a shaft material to concentrate magnetic flux—magnetic permeability—also varies with torque and can be measured using a magnetostrictive sensor. When the shaft has no loading, its permeability is uniform. Under torsion, permeability and the number of flux lines increase in proportion to torque. This type of sensor can be mounted to the side of the shaft using two primary and two secondary windings. Alternatively, it can be arranged with many primary and secondary windings on a ring around the shaft.

A magnetoelastic torque sensor detects changes in permeability by measuring changes in its own magnetic field. One magnetoelastic sensor is constructed as a thin ring of steel tightly coupled to a stainless steel shaft. This assembly acts as a permanent magnet whose magnetic field is proportional to the torque applied to the shaft. The shaft is connected between a drive motor and the driven device, such as a screw machine. A magnetometer converts the generated magnetic field into an electrical output signal that is proportional to the torque being applied. Ⓣ

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