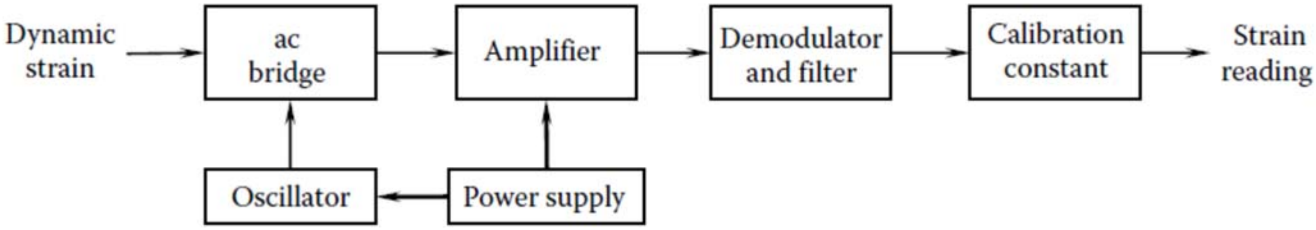
Assignment: Study Example 5.2 on page 363 Textbook Version2.

Data Acquisition:



For measuring dynamic strains:

- Either the servo null-balance method or the imbalance output method should be employed (see Chapter 2).
- A schematic diagram for the imbalance output method is shown in Figure above.
- In this method, the output from the active bridge is directly measured as a voltage signal and calibrated to provide the measured strain. Figure above corresponds to the use of an ac bridge.

- The bridge is powered by an ac voltage. The supply frequency should be about 10 times the maximum frequency of interest in the dynamic strain signal (bandwidth). A supply frequency in the order of 1 kHz is typical. This signal is generated by an oscillator and is fed into the bridge. The transient component of the output from the bridge is very small (typically <1 mV and possibly a few microvolts).

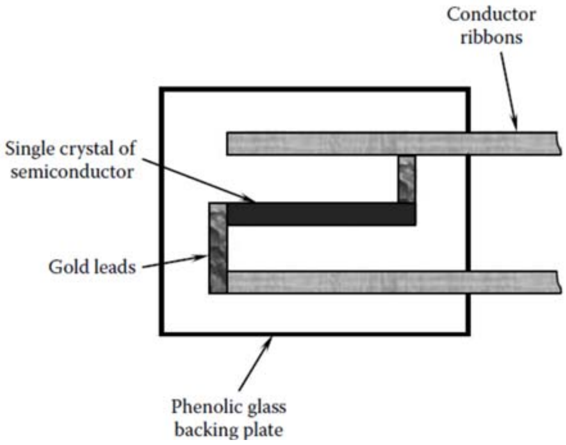
- This signal has to be amplified, demodulated (especially if the signals are transient), and filtered to provide the strain reading.

- The calibration constant of the bridge should be known in order to convert the output voltage to strain. Strain-gauge bridges powered by dc voltages are common.

- However, they have the advantages of simplicity with regard to the necessary circuitry and portability. The advantages of ac bridges include improved stability (reduced drift) and accuracy, and reduced power consumption

Accuracy Considerations:

Semiconductor Strain Gauges:

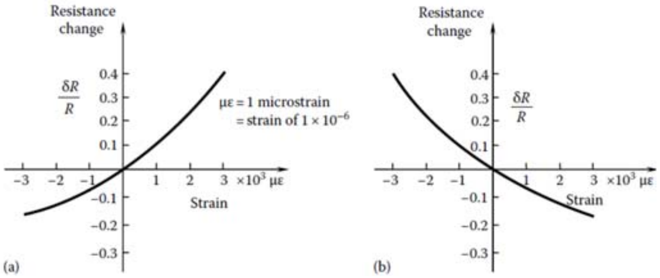


- Low-strain applications (e.g., dynamic torque measurement), the *sensitivity of foil gauges* is not adequate to produce an acceptable strain-gauge signal.
- SC strain gauges are particularly useful in such situations. The strain element of an SC strain-gauge is made of a *single crystal of piezoresistive material such as silicon, doped with a trace impurity such as boron*.
- The gauge factor (sensitivity) of an SC strain gauge is about two orders of magnitude higher than that of a metallic foil gauge (typically, 40–200), as seen for silicon, from the data given below

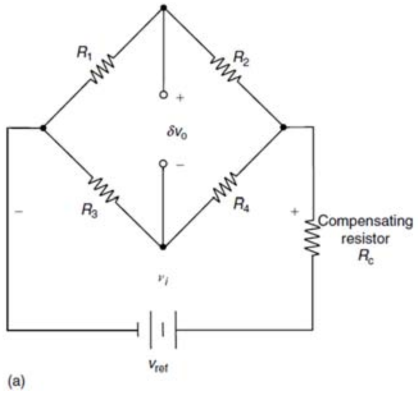
TABLE 5.6 Properties of Common Strain-Gauge Material

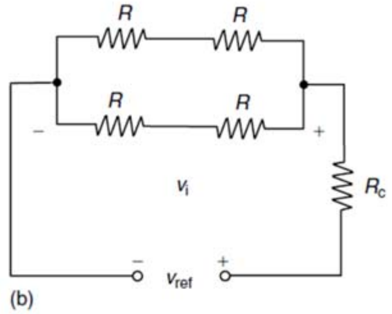
Material	Composition	Gauge Factor (Sensitivity)	Temperature Coefficient of Resistance (10^{-6}/°C)
Constantan	45% Ni, 55% Cu	2.0	15
Isoelastic	36% Ni, 52% Fe, 8% Cr, 4% (Mn, Si, Mo)	3.5	200
Karma	74% Ni, 20% Cr, 3% Fe, 3% Al	2.3	20
Monel	67% Ni, 33% Cu	1.9	2000
Silicon	p-Type	100–170	70–700
Silicon	n-Type	−140 to −100	70–700

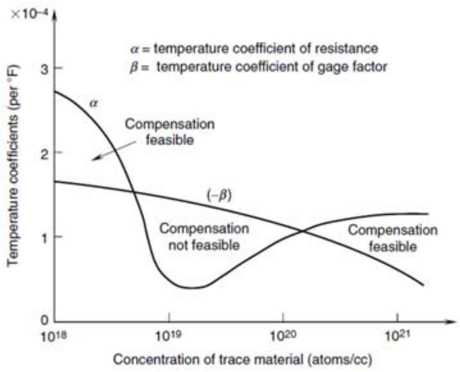
- High resistivity - ∴ low power consumption and lower heat generation.
- Major dvantage of SC strain gauges is that they *deform elastically to fracture*. *Negligible mechanical hysteresis*, *smaller and lighter, providing less cross-sensitivity, and negligible error from mechanical loading*.
- Max-Measureable SC strain gauge is typically 0.003 m/m (i.e., 3000 με).
- Strain-gauge R - can be an order of magnitude greater for an SC strain gauge; for example, several hundred ohms for a metal foil strain gauge (typically, 120 or 350 Ω), while several thousand ohms (5000 Ω) for an SC strain gauge. Disad. associated with SC strain gauges & adv. of foil gauges.
  - *The strain–resistance relationship is more nonlinear.*
  - *Brittle and hard to mount on curvy surface*
  - *The maximum strain that can be measured is one to two orders of magnitude smaller (typically, <0.001 m/m).*
  - *Cost more and have much larger temperature sensitivity.*



Automatic (Self) Compensation for Temperature:
In foil gages the change in resistance due to temperature variations is typically small. Then the linear (first-order) approximation for the contribution from each arm of the bridge to the output signal, as given by Equation







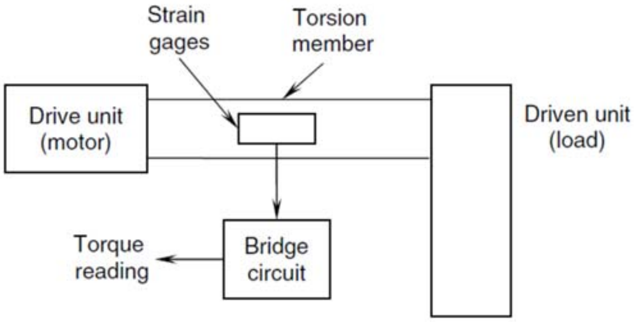
Torque Sensors:

A **torque sensor** or **torque transducer** or **torquemeter** is a device for measuring and recording the torque on a rotating system, such as an engine, crankshaft, gearbox, transmission, rotor, a bicycle crank or cap torque tester.

- Static torque is relatively easy to measure.
- Dynamic torque, on the other hand, is not easy to measure, since it generally requires transfer of some effect (electric or magnetic) from the shaft being measured to a static system.

Commonly, torque sensors or torque transducers use strain gauges applied to a rotating shaft or axle. With this method, a means to power the strain gauge bridge is necessary, as well as a means to receive the signal from the rotating shaft. This can be accomplished using slip rings, wireless telemetry, or rotary transformers. Newer types of torque transducers add conditioning electronics and an A/D converter to the rotating shaft. Stator electronics then read the digital signals and convert those signals to a high-level analog output signal, such as +/-10VDC.

Strain-Gage Torque Sensors:



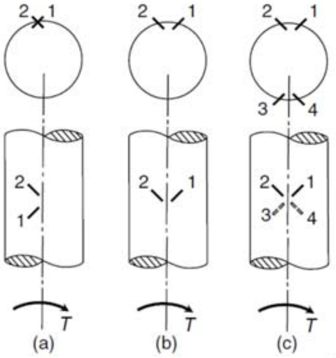
Simple method of torque sensing is:

- To connect a torsion member between the drive unit and the (driven) load in series, as shown in diagram, and to measure the torque in the torsion member.
- If a circular shaft (solid or hollow) is used as the torsion member, the torque–strain relationship becomes relatively simple, and is given by:

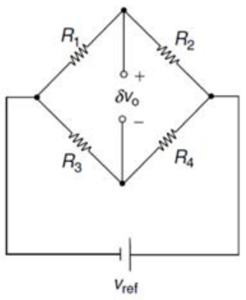
From Last Page: $\boldsymbol{T} = \frac{8GJ}{kS_s r}\frac{\delta v_0}{v_{ref}}$ **;**

- S_s is the gage factor (or sensitivity) of the strain gages and
- The bridge constant k depends on the number of active strain-gages used.

Strain gages are assumed to be mounted along a principal direction and three possible configurations are:



Configuration	(a)		(b)		(c)
Bridge constant (*k*)	2		2		4
Axial loads compensated	Yes		Yes		Yes
Bending loads compensated	Yes		Yes		Yes



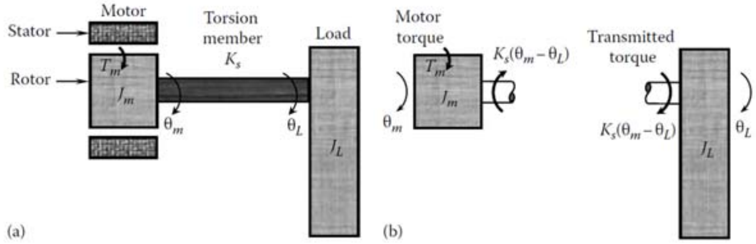
Strain-gage bridge

Example 5.11

Consider a rigid load, which has a polar moment of inertia J_L and driven by a motor with a rigid rotor, which has inertia J_m. A torsional member of stiffness K_s is connected between the rotor and the load, as shown in Figure 5.49a, to measure the torque transmitted to the load.

(a) Determine the transfer function between the motor torque T_m and the twist angle θ of the torsion member. What is the torsional natural frequency ω_n of the system? Discuss why the system bandwidth depends on ω_n. Show that the bandwidth can be improved by increasing K_s, by decreasing J_m, or by decreasing J_L. Give some advantages and disadvantages of introducing a gearbox at the motor output.

(b) If a torsion member of stiffness 0.5 K_s is mounted at the load end of the shaft (in series) by what percentage the original torsional bandwidth of the system (representative of the allowable operating frequency range for the torque sensor) is reduced?



Strain Capacity of the Gauge:
The maximum strain handled by a strain-gauge element is limited by factors such as strength, creep problems associated with the bonding material (epoxy), and hysteresis.

Strain-Gauge Nonlinearity Limit:
For large strains, the characteristic equation of a strain gauge becomes increasingly nonlinear. This is particularly true for SC gauges.

Sensitivity Requirement:
The signal level of the amplifier output has to be sufficiently high so that the SNR is adequate, otherwise, serious noise problems can result.

Stiffness Requirement

The lower limit of the overall stiffness of the system is constrained by:

a. *Speed of response* (represented by system bandwidth) and
b. *Steady-state error* (represented by system gain).

The polar moment of area J should be chosen such that the stiffness of the torsional element does not fall below a specified limit K.

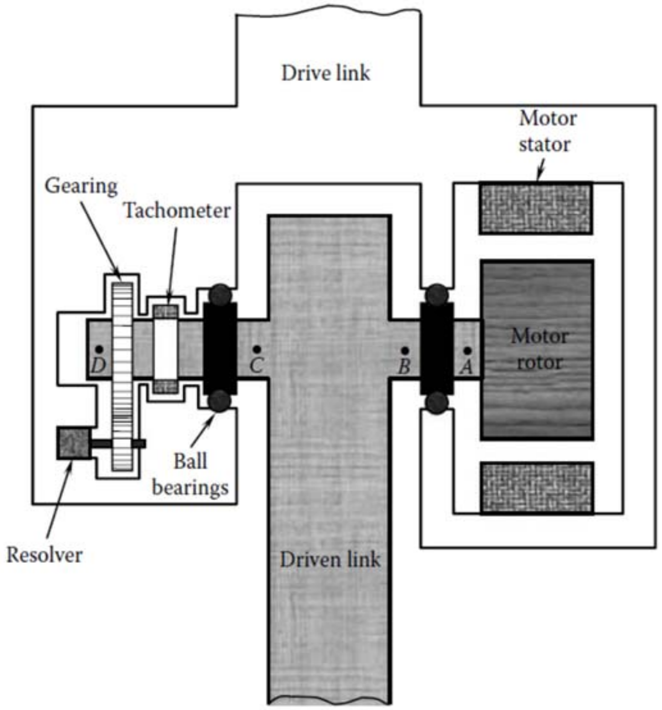
Deflection Torque Sensors:

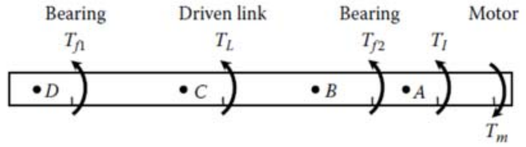
Instead of measuring strain in the sensor element, the *actual deflection or deformation* (twisting or bending) may be measured and used to determine torque, through a suitable calibration constant. For a circular-shaft (solid or hollow) torsional element, the governing relationship for the angle of twist θ for an applied torque T is given by:

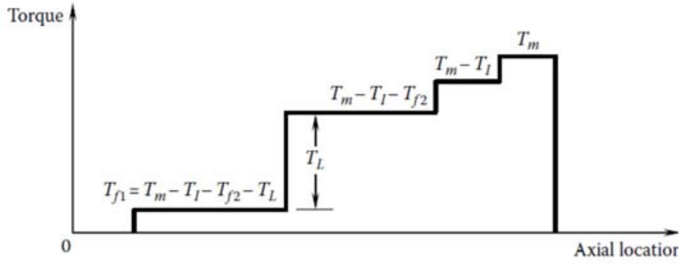
Example:

A joint of a direct-drive robotic arm is sketched in the figure.

- *Rotor is an integral part of the driven link, and there are no gears or any speed reducers. Motor stator is an integral part of the drive link.*
- *Tachometer measures the joint speed (relative), and*
- *Resolver measures the joint rotation (relative).*
- *Gearing is used to improve the performance of the resolver, and it does not affect the load transfer characteristics of the joint.*
- *Neglecting the mechanical loading from the sensors and the gearing, but including the bearing friction,*
    - *Sketch the torque distribution along the joint axis.*
    - *Suggest a location (or locations) for measuring using a strain-gauge torque sensor the net torque transmitted to the driven link.*







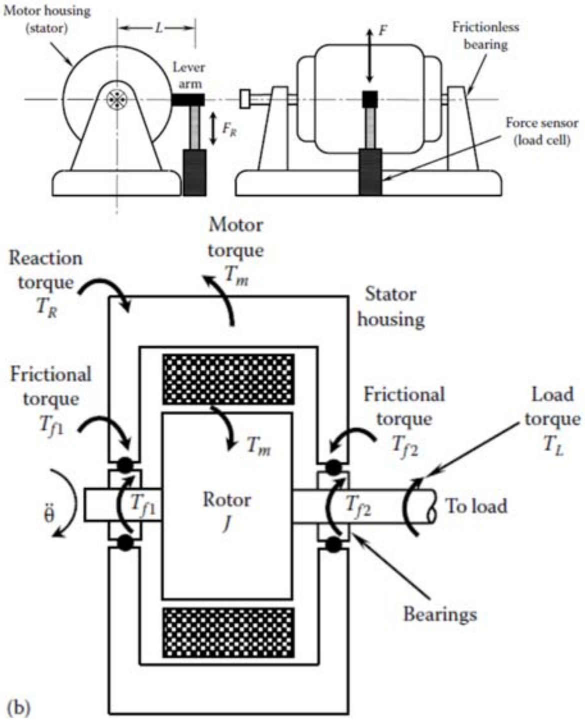
Reaction Torque Sensor:

The methods of torque sensing that were described thus far use a sensing element that is connected between the drive member and the driven member. There are two major drawbacks in this arrangement of torque sensing:

1. The sensing element *modifies the original system in an undesirable manner*, particularly by decreasing the system stiffness and adding inertia. As a result, not only does the overall bandwidth of the system decrease, but the original torque is also changed (due to mechanical loading) *because of the inclusion of an auxiliary sensing element*.
2. Under dynamic conditions, the *sensing element is in motion, thereby making torque measurement more difficult*. Then, some form of commutation (e.g., slip ring and brush), rotary transformer or wireless telemetry would be needed in reading the sensor signal.

The reaction method of torque sensing eliminates these problems to a large degree. In particular, this method can be conveniently used to measure torque in a rotating machine.

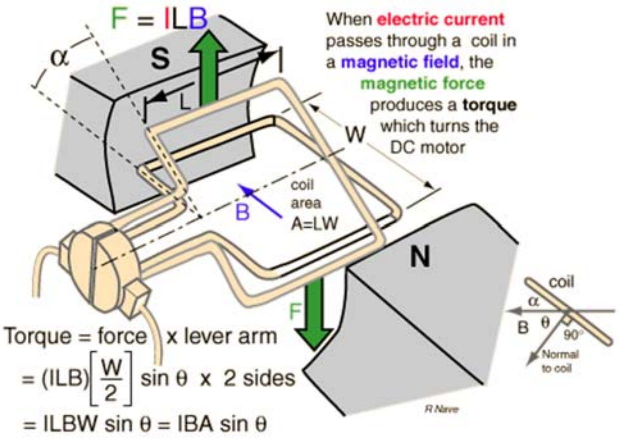
- The supporting structure (or housing) of the rotating machine (e.g., motor, pump, compressor, turbine, generator) is cradled by releasing the fixtures, and the effort that is necessary to keep the structure from moving (i.e., to hold down) is measured.
- A schematic representation of the method is shown in figure. Ideally, a lever arm is mounted on the cradled housing, and the force required to maintain the housing stationary is measured using a force sensor (load cell). The reaction torque on the housing is given by:

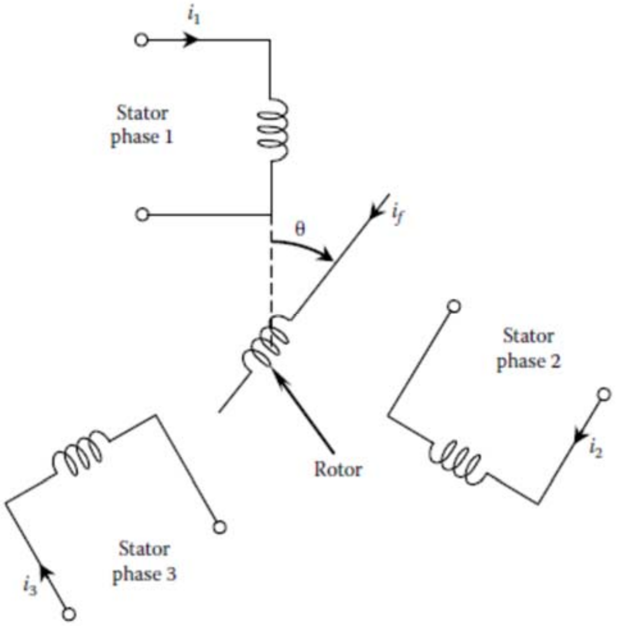


Motor Current Torque Sensors

Torque in an electric motor is generated as:

- Result of the electromagnetic interaction between the rotor magnetic field and the stator magnetic field of the motor.
- Hence, the current that generates the magnetic field may be used to estimate the motor torque.



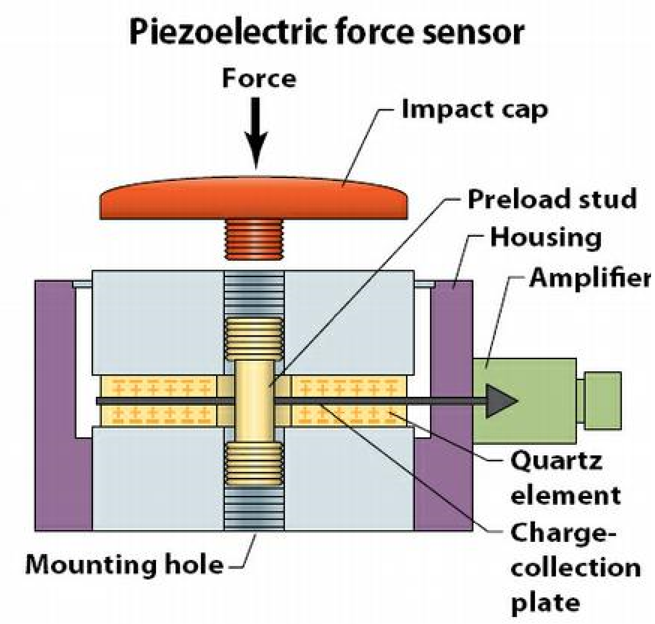


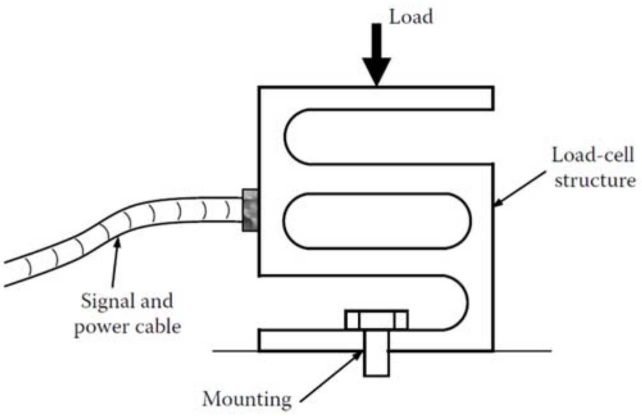
Force Sensors:

Force sensors are useful in numerous applications.

- In vehicle testing, force sensors are used to monitor impact forces on the vehicles and crash-test dummies.

- Force sensors that employ strain-gauge elements or piezoelectric (quartz) crystals with built-in microelectronics are common. For example, thin-film and foil sensors that employ the strain-gauge principle for measuring forces and pressures are commercially available.
- A sketch of an industrial load cell, which uses strain-gauge method, is shown in *figure to the right*.
- Both impulsive forces and slowly varying forces can be monitored using this sensor.
- Some types of force sensors are based on measuring a deflection caused by the force. Relatively high deflections (fraction of a millimeter) would be necessary for this technique to be feasible. Commercially available sensors range from sensitive devices, which can detect forces in the order of 1000th of a newton to heavy-duty load cells, which can handle very large forces (e.g., 10,000 N). The techniques of torque sensing that have been discussed (*e.g., magnetostrictive*) can be extended in a straight-forward manner to force sensing. *Typical rating parameters for several types of sensors are given in Table.*





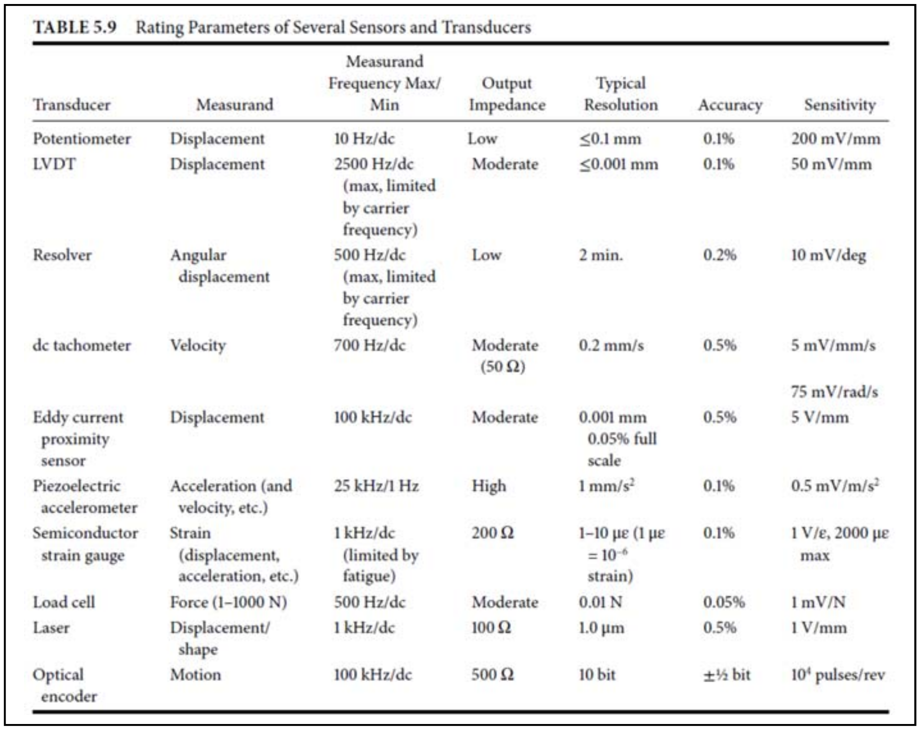
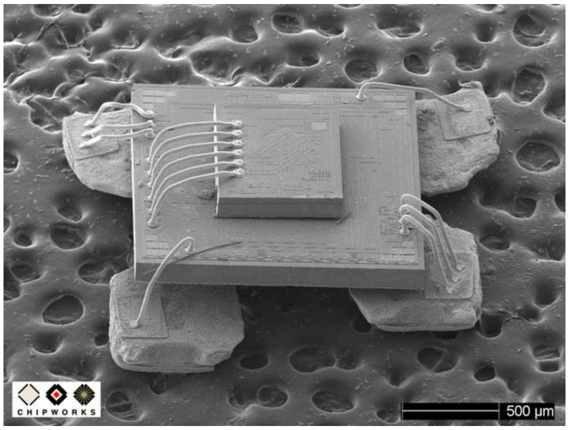


TABLE 5.9 Rating Parameters of Several Sensors and Transducers

Transducer	Measurand	Measurand Frequency Max/Min	Output Impedance	Typical Resolution	Accuracy	Sensitivity
Potentiometer	Displacement	10 Hz/dc	Low	≤0.1 mm	0.1%	200 mV/mm
LVDT	Displacement	2500 Hz/dc (max, limited by carrier frequency)	Moderate	≤0.001 mm	0.1%	50 mV/mm
Resolver	Angular displacement	500 Hz/dc (max, limited by carrier frequency)	Low	2 min.	0.2%	10 mV/deg
dc tachometer	Velocity	700 Hz/dc	Moderate (50 Ω)	0.2 mm/s	0.5%	5 mV/mm/s 75 mV/rad/s
Eddy current proximity sensor	Displacement	100 kHz/dc	Moderate	0.001 mm 0.05% full scale	0.5%	5 V/mm
Piezoelectric accelerometer	Acceleration (and velocity, etc.)	25 kHz/1 Hz	High	1 mm/s^2	0.1%	0.5 mV/m/s^2
Semiconductor strain gauge	Strain (displacement, acceleration, etc.)	1 kHz/dc (limited by fatigue)	200 Ω	1–10 με (1 με = 10^{-6} strain)	0.1%	1 V/ε, 2000 με max
Load cell	Force (1–1000 N)	500 Hz/dc	Moderate	0.01 N	0.05%	1 mV/N
Laser	Displacement/shape	1 kHz/dc	100 Ω	1.0 μm	0.5%	1 V/mm
Optical encoder	Motion	100 kHz/dc	500 Ω	10 bit	±½ bit	10^4 pulses/rev

Gyroscopic Sensors:



- Used for measuring angular orientations and angular speeds in a variety of applications including aircraft, ships, vehicles, robots, missiles, radar systems, machinery, camera stabilization, and various other mechanical devices.
- Commonly used in control systems for stabilizing vehicle systems. *Since a spinning body (a gyroscope) requires an external torque to turn* (precess) *its axis of spin*, if this gyro is mounted (in a frictionless manner) on a rigid vehicle *so that there are a sufficient number of frictionless degrees of freedom (at most three) between the gyro and the vehicle, the spin axis will remain unchanged in space, regardless of the motion of the vehicle*.
- Hence, the *axis of spin of the gyro provides a reference* with respect to which the vehicle orientation (e.g., azimuth or yaw, pitch, and roll angles) and angular speed can be measured.
- The orientation can be measured by using angular sensors at the pivots of the structure that mounts the gyro on the vehicle.
- The angular speed about an orthogonal axis can be determined; for example, by measuring the precession torque (which is proportional to the angular speed) using a strain-gauge sensor; or by measuring using a position sensor such as a resolver, the deflection of a torsional spring that restrains the precession.
- The angular deflection is proportional to the precession torque and hence the angular speed.