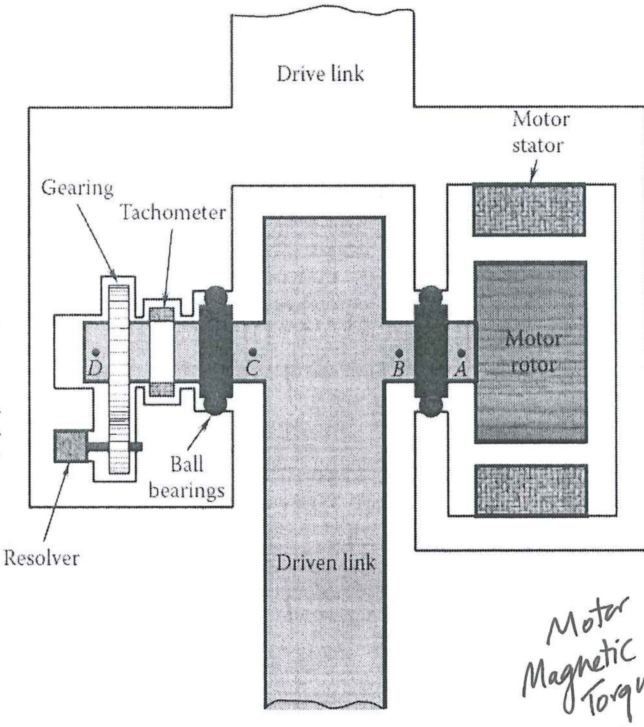
Example:

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.*



T_m: Motor Magnetic Torque

T_i: Rotor Inertia Torque + Motor Frictional Torque T_i

T_{f_1}, T_{f_2}: Frictional Torques of Two bearings

T_L: Net Torque Transmitted

Available Locations A, B, C, D

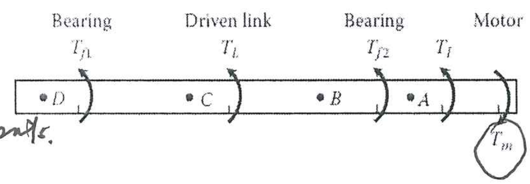
T: @ difference between points B & C.

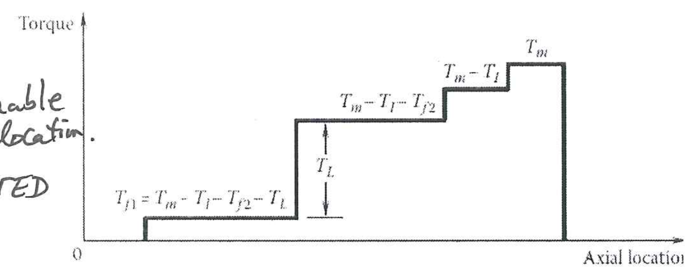
- Strain gauges @ B + C : Accurate Measurements.
- Bearing friction : generall small

Single Torque Sensor @ B is - reasonable good location.

T_m → Approximately equal to TRANSMITTED TORQUE (Assuming Negligible bearing friction + Motor Loading (Inertia + friction)

Motor Magnetic Torque T_m





Read Example 5-13 text Page 381

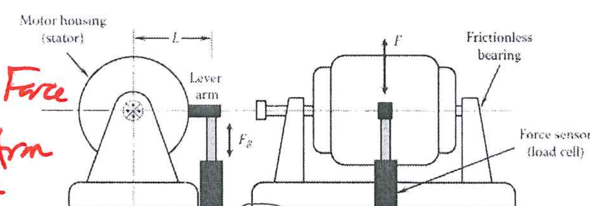
Reaction Torque Sensor:

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.

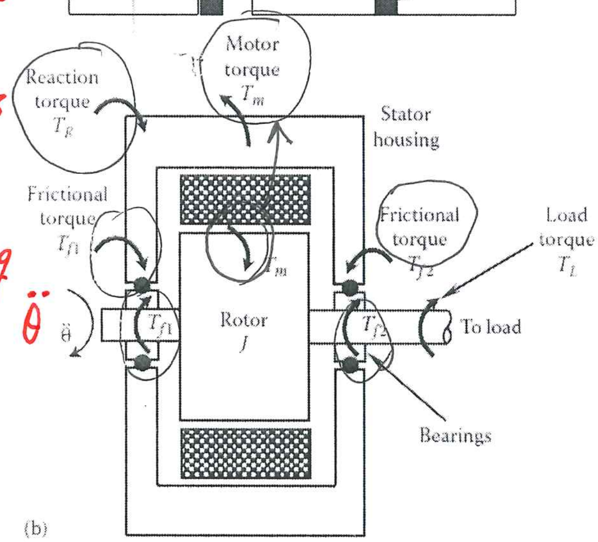
The reaction method of torque sensing eliminates these problems to a large degree. In particular, this method can be conveniently used to measure torque in a rotating machine.

- 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:



$T_R = F_R \cdot L$; F_R = Reaction Force; L = Lever Arm length

- Strain gauges/force sensors can be mounted directly at fixture locations i.e. @ mounting bolts of housing to measure reaction forces without having to cradle the housing
- Reaction Torque is determined with the knowledge of distance of fixture from shaft axis.



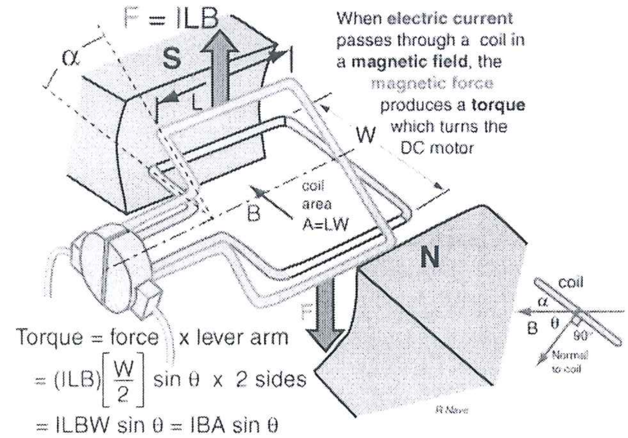
DRAWBACK: Motor of Rotor Inertia – $\ddot{J}$
Rotates at Angular Accel – $\ddot{\theta}$; Newton's Law: ACTION = REACTION
EM. Torque: T_m @ Motor Rotor → Reacted Back ONTO STATOR & HOUSING
T_{f_1}, T_{f_2}: Frictional Torques of 2 bearings. T_L: Torque to driven Load
Frictional Torques & Magnetic Torques CANCEL OUT

$\therefore J\ddot{\theta} = T_R - R_L$ OR $T_L = T_R - J\ddot{\theta}$; (T_L: Must be Measured)

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.



In a DC Motor

- Rotor may have armature windings and stator may have field winding.
- Consider a dc Motor with both ROTOR and STATOR have electro-magnets.

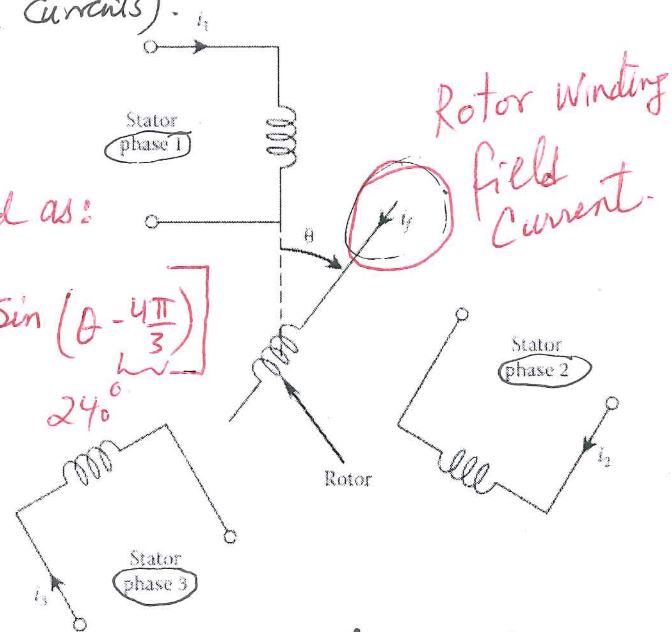
The resulting Magnetic torque $T_m = K i_f i_a$ ← armature current; i_f ← field current; K ← Torque constant

In AC Motors, Torque may also be measured by sensing the motor current. Note that AC motors incorporate frequency control and 'V' control.

→ 3-ϕ synchronous motor shown schematically as: ↓

i_1, i_2, i_3 : currents in 3 ϕ's (Armature currents).

i_f : DC Rotor : field current in Rotor Winding



Motor Torque T_m can be expressed as:

$$T_m = K i_f \left[i_1 \sin\theta + i_2 \sin\left(\theta - \frac{2\pi}{3}\right) + i_3 \sin\left(\theta - \frac{4\pi}{3}\right) \right]$$

($\frac{2\pi}{3}$: 120°; $\frac{4\pi}{3}$: 240°)

K: Torque Constant of Synchronous Motor; i_f: FIXED Value; θ: Angular Rotation of Motor.

For balanced 3-ϕ Supply: $i_1 = i_a \sin\omega t$

$i_2 = i_a \sin(\omega t - 2\pi/3)$, $i_3 = i_a \sin(\omega t - \frac{4\pi}{3})$

$T_m = 1.5 K i_a i_f \cos(\theta - \omega t)$,

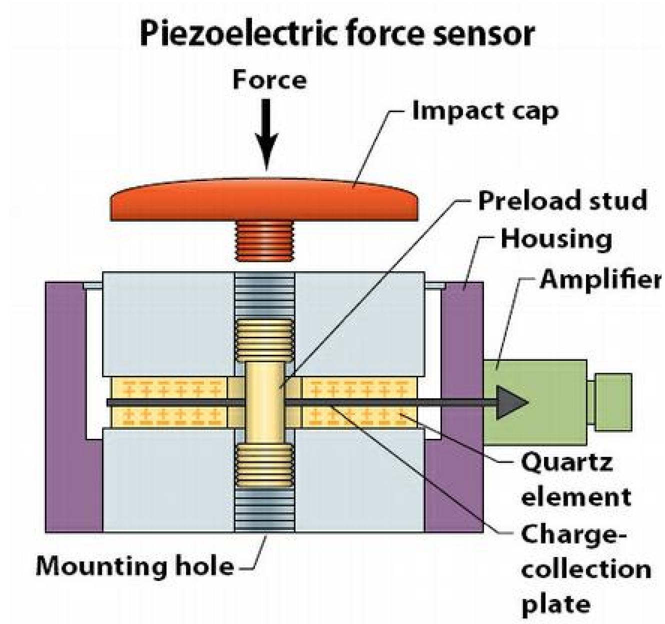
$t = 0, \ \theta = \theta_0 \quad \therefore \ T_m = 1.5 K i_a i_f \cos(\theta_0)$

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.*



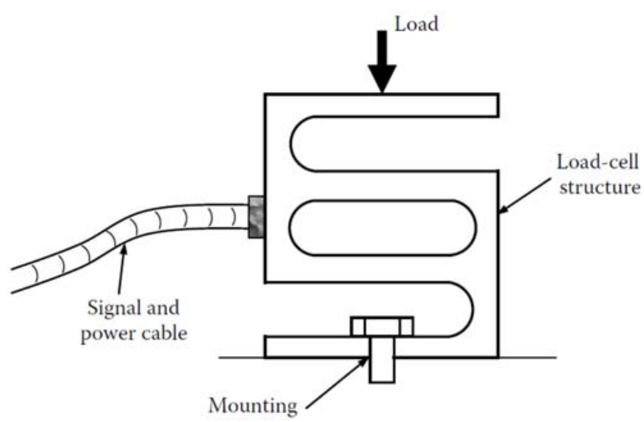
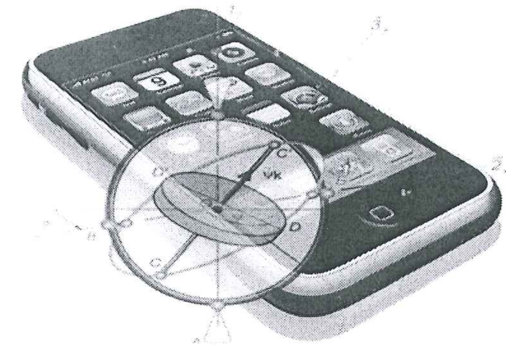
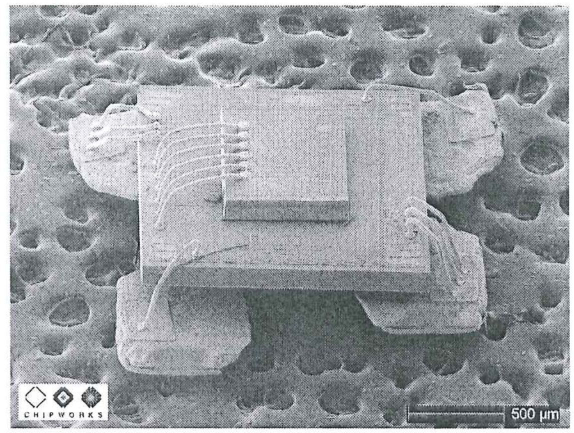


TABLE 5.9 Rating Parameters of Several Sensors and Transducers

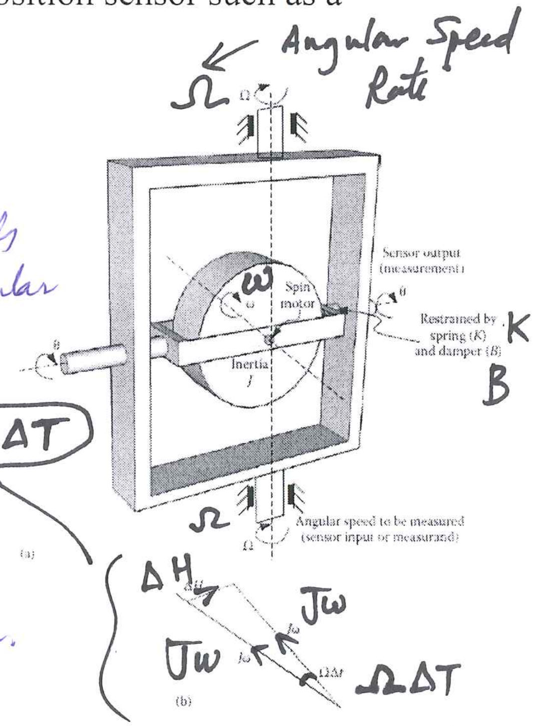
Transducer	Measurand	Measurand Frequency Max/Min	Output Impedance	Typical Resolution	Accuracy	Sensitivity
Potentiometer	Displacement	10 Hz/dc	Low	≤0.1 mm	0.1%	200 mV/mm
LVDT	Displacement	2500 Hz/dc (max, limited by carrier frequency)	Moderate	≤0.001 mm	0.1%	50 mV/mm
Resolver	Angular displacement	500 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.



Rate GYRO: used to measure Angular Speeds

- Gyro disk of Polar Moment (J) is spun at angular speed (ω) about frictionless bearings using constant speed MOTOR, spinning AROUND AXIS

Angular Moment $H = J\omega$ $\quad \Delta H = J\omega . \Omega . \Delta T$

$\therefore \frac{dH}{dt} = J\omega . \Omega$

If restrained by Tortional string of stiffness K, damper with Rotational Const. B.

Torque $= K\theta + B\dot{\theta}$; = Rate of change of Momentum.

$\therefore J\omega\Omega = K\theta + B\dot{\theta}$

$\therefore$ Angular speed: $\Omega = \dfrac{K\theta + B\dot{\theta}}{J\omega}$