MEE303 Sensor Systems

W11
Force And Torque Measurement

Force And Torque Sensing

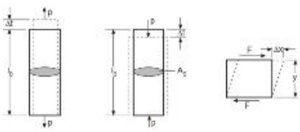
Force sensing

Force sensors are required for a basic understanding of the response of a system.

- cutting forces generated by a machining process.
- Force sensors are used to monitor impact forces in the automotive industry
- Robotic handling and assembly tasks are controlled by detecting the forces generated at the end effector

Strain to force sensing

force sensors are based on measuring a deflection caused by the force. Relatively high deflections. The relation between force and deflection in the elastic region is demonstrated by Hooke’s law:



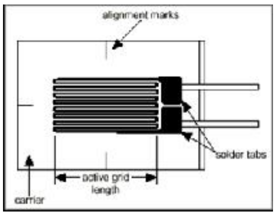
$$\sigma = \varepsilon E \Rightarrow F = \varepsilon E A$$

$$\tau = \gamma G \Rightarrow F = \gamma G A$$

$$\sigma = \frac{P}{A_0} \quad \varepsilon = \frac{\Delta l}{l_0} \quad \tau = \frac{F}{A} \quad \gamma = \frac{\Delta x}{y}$$

Pick ups for effort sensing

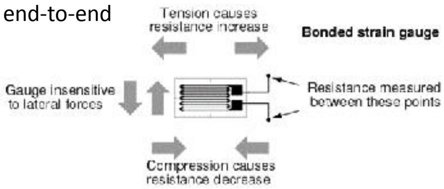
Force sensors employ strain gage elements or piezoelectric materials to obtain force measurements



Strain gauges

Strain gauge is a element whose resistance varies with applied force

If a strip of conductive metal is stretched, it will become skinnier and longer, both changes resulting in an increase of electrical resistance end-to-end



Conversely, if a strip of conductive metal is placed under compressive force (without buckling), it will broaden and shorten.

If these stresses are kept within the *elastic limit* of the metal strip (so that the strip does not permanently deform), the strip can be used as a measuring element for physical force, the amount of applied *force inferred from measuring its resistance*

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Strain gauges

The amount of applied force inferred from measuring its resistance.

$$R = \rho \frac{l}{A}$$

Change of relative dimensions, as the resistance is related to length and cross-sectional area

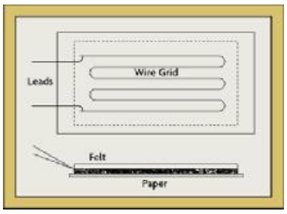
$$dR = \frac{\rho}{A} dL + \frac{L}{A} d\rho - \frac{\rho L}{A^2} dA \qquad \frac{dR}{R} = \frac{dL}{L} + \frac{d\rho}{\rho} - \frac{dA}{A}$$

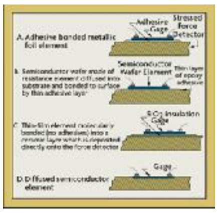
Gauge factor is defined as the ratio of per unit change in resistance to per unit change in length

$$GF = \frac{dR/R}{dL/L} = 1 + \frac{d\rho}{\rho}\frac{L}{dL} + 2\upsilon$$

The unity term, two times poisson ratio and resistivity related term show the resistance change due to change in length, change in area and piezoresistive effect on material, respectively

Typical foil-type strain gages: The gage consists of a grid of very fine metallic wire, foil, material bonded to the strained surface or carrier matrix by a thin insulated layer of epoxy. When the carrier matrix is strained, the strain is transmitted to the grid material through the adhesive. The variations in the electrical resistance of the grid are measured as an indication of strain.





Semiconductor Strain Gauges: For a high sensitivity, a high value of gauge factor is desirable. A high gauge factor means a relatively higher change in resistance which can be easily measured with a good degree of accuracy. Semiconductor strain gauges are used where a very high gauge factor and a small envelope are required. They depend for their action upon piezo-resistive effect i.e. the change in the value of the resistance due to change in resistivity.

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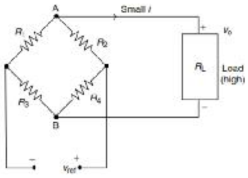
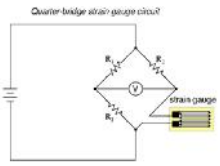
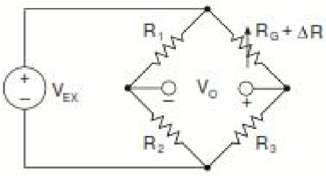
Strain gauge Circuits

The Wheatstone bridge: One or more of the four resistors R1, R2,R3, and R in the bridge may represent strain gages.



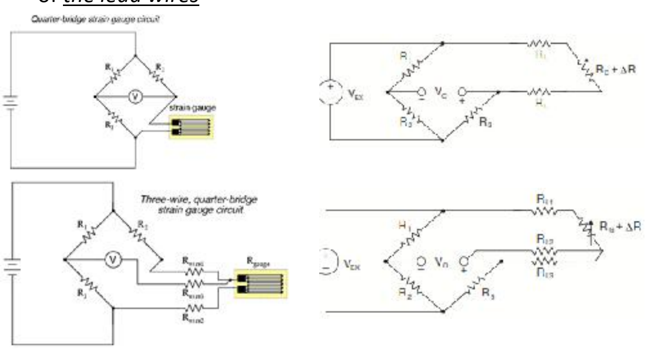
Quarter bridge: One of the four resistors in the bridge may represent strain gages.





$$\frac{V_o}{V_e} = -\frac{GF\varepsilon}{4}\frac{1}{1-\frac{GF\varepsilon}{2}}$$ indicates the nonlinearity of the quarter-bridge output with respect to strain

the preferred connection scheme for quarter-bridge strain gauges is the *three-wire connection* to compensate resistance of *the lead wires*



In this configuration, RL1 and RL3 appear in adjacent arms of the bridge. Therefore, any changes in resistance due to temperature cancel each other.

The lead resistance RL2, is connected to the measurement input. Therefore, this lead carries very little current and the effect of its lead resistance is negligible.

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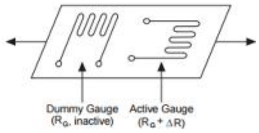
Strain gauge Circuits

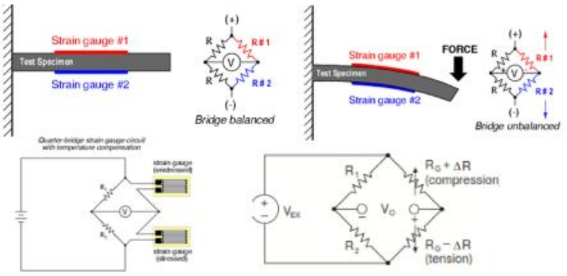
Half bridge: Two of the four resistors in the bridge represent strain gages.

By using two strain gauges in the bridge, the effect of temperature can be avoided. For example, Figure illustrates a strain gauge configuration where one gauge is active (RG + ΔR), and a second gauge is placed transverse to the applied strain. Therefore, the strain has little effect on the second gauge, called the dummy gauge.



Any changes in temperature will affect both gauges in the same way. Because the temperature changes are identical in the two gauges, the ratio of their resistance does not change, the voltage V_O does not change

one can double the sensitivity of the bridge to strain by making both gauges active, although in different directions.
For example, Figure illustrates a bending beam application with one bridge mounted in tension (RG + ΔR) and the other mounted in compression (RG – ΔR).



This half-bridge configuration, whose circuit diagram is also illustrated in Figure 6, yields an output voltage that is ***linear and approximately doubles the output*** of the quarter-bridge circuit.

$$\frac{V_o}{V_e} = -\frac{GF\varepsilon}{2}$$

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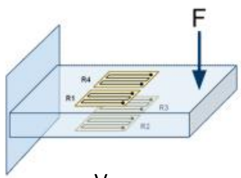
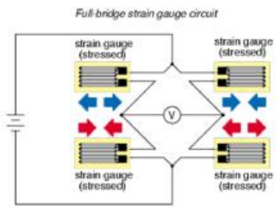
Strain gauge Circuits

Full bridge: All of the four resistors in the bridge represent strain gages.

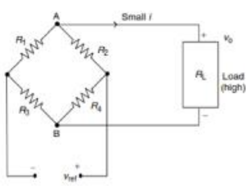
you can further increase the sensitivity of the circuit by making all four of the arms of the bridge active strain gauges, and mounting two gauges in tension and two gauges in compression

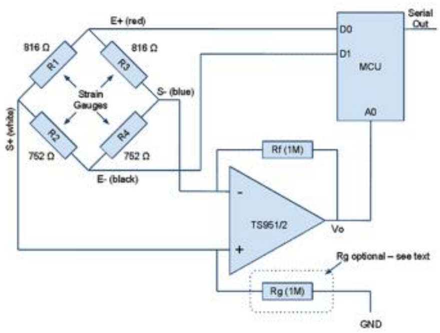




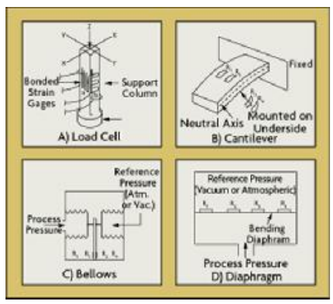
$$\frac{V_o}{V_e} = -GF\varepsilon$$

Implementation Example





Device Examples



Force And Torque Sensing

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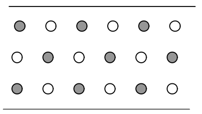
Piezoelectric elements

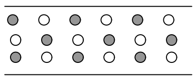
Piezoelectricity is understood as the electricity which is the by product of electromechanical interactions, primarily electrical and mechanical oscillations

These engagements create a transducer effect as per the application of mechanical stress on materials which have no isotropic symmetry such as:

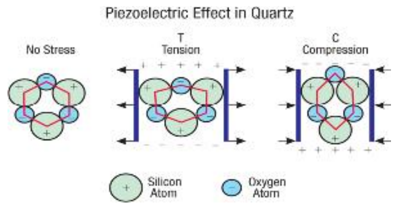
- ZnO: d_{33}=246 pC/N
- Lead zirconate titanate (PZT): d_{33}=110 pC/N
- Quartz: d_{33}=2.33 pC/N
- Polyvinylidene fluoride (PVDF): d_{33}=1.59 pC/N.

Symmetric (centrosymmetric) lattice structure does not produce piezoelectricity when deformed.





Asymmetic lattice structures do



piezoelectric compounds are made of ions hence accumulated electric charge.

Piezoelectric crystals are composed of positive and negative ions in an alternating fashion.

Tension, or pulling, and compression, or squeezing, push and pull these positive and negative away from either other, creating an energy gradient across the crystal and allowing an electric current to flow.

As a result of this centro-symmetric attribute, the reverse piezoelectric effect is plausible; this is, a substance can yield mechanical pressure when subjected to an electric field

In particular, when an electric field is applied to the material to change the ionic polarization, the material will shed the strain and regain its original shape.

Force And Torque Sensing

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Piezoelectric elements

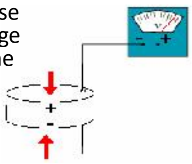
Direct Piezo Effect: a mechanical stress on a material produces an electrical polarization

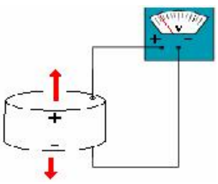
Inverse Piezo Effect: an applied electric field in a material produces dimensional changes and stresses within a material.

Application of the piezoelectric effect is found in piezoelectric torque sensors and force sensors

The direct Effect : Generator

Compression Effect: Decrease in volume and it has a voltage with the same polarity as the material

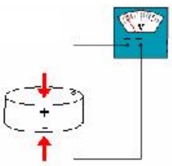


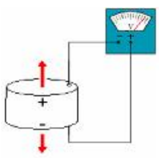


Tension Effect: Increase in volume and it has a voltage with opposite polarity as the material

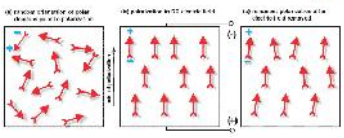
The Inverse Piezoelectric Effect

If the applied voltage has the same polarity then the material expands.





If the applied voltage has the opposite polarity then the material contracts.



Force And Torque Sensing

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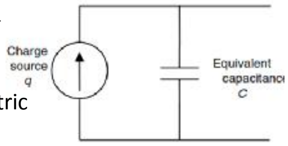
Model of Piezo element

A piezoelectric crystal can be considered to be in the form of a disk with two electrodes plated on the two opposite faces. Since the crystal is a dielectric medium, this device is essentially a capacitor, which may be modeled by a capacitance C.

$$Z = \frac{1}{2\pi fC}$$

According to this fact, Equivalent circuit representation of a piezoelectric sensor is as follows



A quartz crystal may present an impedance of several megaohms at 100 Hz, increasing hyperbolically with decreasing frequencies.

This is one reason why piezoelectric sensors have a limitation on the useful lower frequency

Piezoelectric signals cannot be read using low-impedance devices. The two primary reasons for this are:

- High output impedance in the sensor results in small output signal levels and large loading errors.
- The charge can quickly leak out through the load.

Piezoelectricity is mathematically expressed as a linear relationship between the mechanical factors of strain, compliance and stress, and the electrical factors of electric displacement, permittivity, and the strength of the electric field.

The sensitivity of a piezoelectric crystal may be represented either by its charge sensitivity or by its voltage sensitivity which are defined as:

$$s_q = \frac{dq}{dF} = \frac{1}{A}\frac{dq}{dP} \qquad s_V = \frac{1}{d}\frac{dV}{dP}$$

charge sensitivity — voltage sensitivity

k is the dielectric constant of the crystal capacitor

$$s_q = k s_V$$

Piezoelectric Coefficient

$$[d_{33}] = \frac{[D]}{[T]} = \frac{[\varepsilon][E]}{[T]} = \frac{\frac{F}{m}\frac{V}{m}}{\frac{N}{m^2}} = \frac{\text{Columb}}{\text{N}}$$

Force And Torque Sensing

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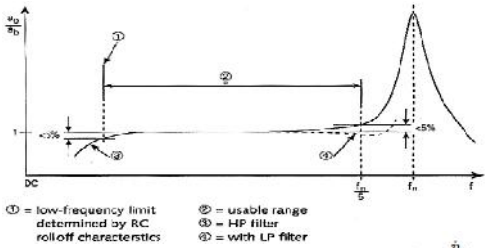
Dynamical Resonse of Piezoelectric elements

Piezoelectric sensors for measuring pressure, force, and acceleration may be regarded as underdamped, spring mass systems with a single degree of freedom

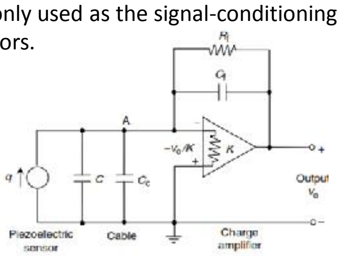


This typical response curve,
1 low-frequency limit determined by RC rolloff characteristics;
2 usable range;
3 high-pass filter
4 with low-pass filter, which can be used to attenuate the effects of the amplitude rise.
Low-pass filtering can be used to attenuate the effects of this

charge amplifier

A charge amplifier is commonly used as the signal-conditioning device for piezoelectric sensors.

Basically the charge amplifier consists of a high-gain inverting voltage amplifier with a MOSFET or JFET at its input to achieve high insulation resistance



$$\dot q + C\frac{\dot v_o}{K} + C_c\frac{\dot v_o}{K} + C_f\left(\dot v_o + \frac{\dot v_o}{K}\right) + \frac{v_o + v_o/K}{R_f} = 0.$$

$$R_f C_f \frac{dv_o}{dt} + v_o = -R_f\frac{dq}{dt}$$

$$\frac{v_o(j\omega)}{q(j\omega)} = -\frac{R_f j\omega}{[R_f C_f j\omega + 1]} \qquad \tau_c = R_f C_f.$$

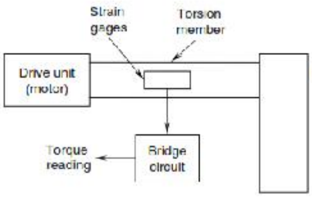
$$M = \frac{\tau_c\omega}{\sqrt{\tau_c^2\omega^2 + 1}}$$

Force And Torque Sensing

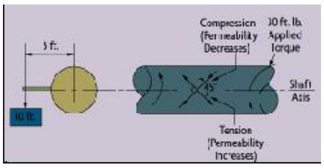
Pick ups for effort sensing

Strain-Gage Torque Sensors

The most straightforward method of torque sensing is to connect a torsion member between the drive unit and the (driven) load in series, as shown in Figure.



If a circular is used as the torsion member, the torque–strain relationship becomes relatively simple, and is given by



$$\varepsilon = \frac{r}{2GJ}T,$$

where T is the torque transmitted through the member, « is the principal strain (which isa t 45 degrees to shaft axis) at radius r within the member, J is the polar moment of area of crosssection of the member, and G is the shear modulus of the material.

Moreover, the shear stress t at a radius r of the shaft is given by

$$\tau = \frac{Tr}{J}$$

Using the general bridge equation, we can obtain torque T from bridge output

$$T = \frac{8GJ}{kS_s r}\frac{\delta v_o}{v_{\text{ref}}}$$

Ss is the gage factor (or sensitivity) of the strain gages. The bridge constant k depends on the number of active strain-gages used. Strain gages are assumed to be mounted along a principal direction

Force And Torque Sensing

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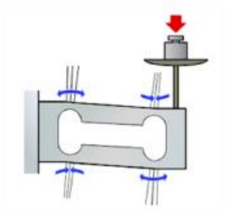
Strain gauge load cell

A load cell is a transducer that is used to convert a force into electrical signal



The strain-gage sensor is one of the most widely used means of load, weight, and force detection.

The most common type is a strain gauge load cell.

As the force is applied, the support column experiences elastic deformation and changes the electrical resistance of each strain gage.

By the use of a Wheatstone bridge, the value of the load can be measured. Load cells are popular weighing elements for tanks and silos and have proven accurate in many other weighing applications.

Shear

Canister

S Type

Beam

Button