Audio and Strain Sensors

Speakers:

If you apply an AC voltage to a speaker, it produces sound. From duality, if you apply sound to a speaker, it produces voltage. It won't be large, but it's there. Amplify the bejeebers out of the signal and you can pick up audio signals.

Microphones:

There are many types of microphones.

- Some are essentially speakers. From duality, they also produce voltage is you hit them with sound.

- Some are piezo crystals. When you apply a voltage to a piece of quartz, it gets slightly larger. From duality, if you squeeze a piece of quartz (say, with a sound wave), it produces a voltage.

- Some are stain gages on a membrane. As sound waves hit the membrane, it moves, producing stress and strain on the membrane. A strain gage converts this to a resistance.

Most of the microphones in lab are Electret Condenser Microphones similar to the following:

To wire up this microphone, a pull-up resistor is used as per the data sheets:
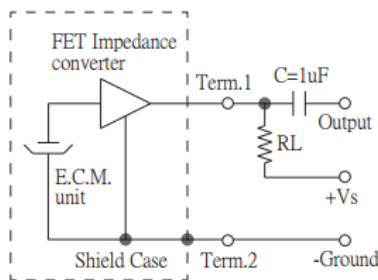
The output signal will be a small (10mV?) audio signal on top of a large DC offset. To amplify the signal,

- A DC block is used,
- Along with an amplifier:
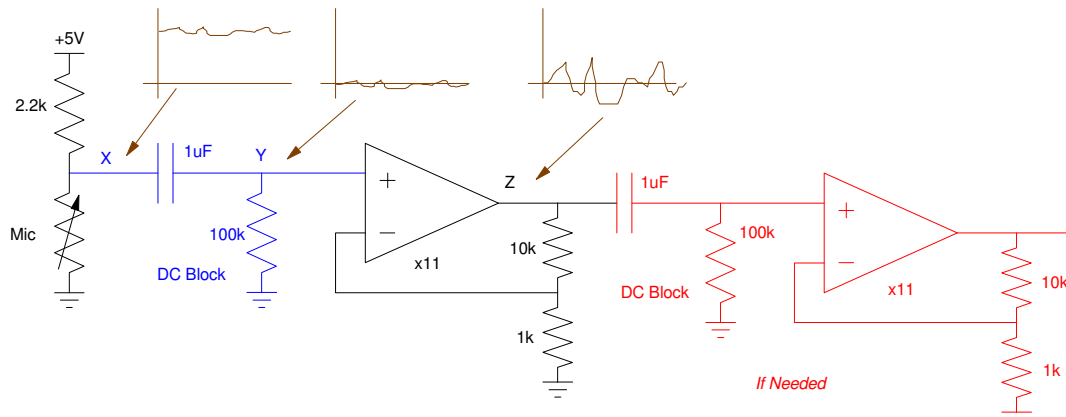
The DC block has a transfer function of

$$Y = \left(\frac{RCs}{RCs+1} \right) X$$

Picking a 1uF capacitor and 100k resistor results in a corner at 16Hz (passes 20Hz on up).   The op-amp then provides a gain of 11x.

If the signal at Z is large enough, you're done. If not,

- Block the DC offset (each op-amp adds a slight DC offset, which causes a problem if amplified), and
- Amplify again (shown in red).

Eventually, you have a signal which is large enough.

Sound on a Light Beam

Once amplified, you can transmit the sound on a light beam.

Step 1: Bias and LED so that there is some current (10mA here) when there is no sound. Assuming a red LED and a 5V supply

$$R_d = \left(\frac{5V - 1.9V}{10mA} \right) = 310\Omega$$

Step 2: Inject an AC signal on top of the 10mA (DC) signal from step 1. Assuming a 1Vpp sine wave at 1kHz, and you want to inject a 1mApp AC signal on top of the DC current to the LED

$$R = \left(\frac{1V_{pp}}{1mA_{pp}} \right) = 1k\Omega$$
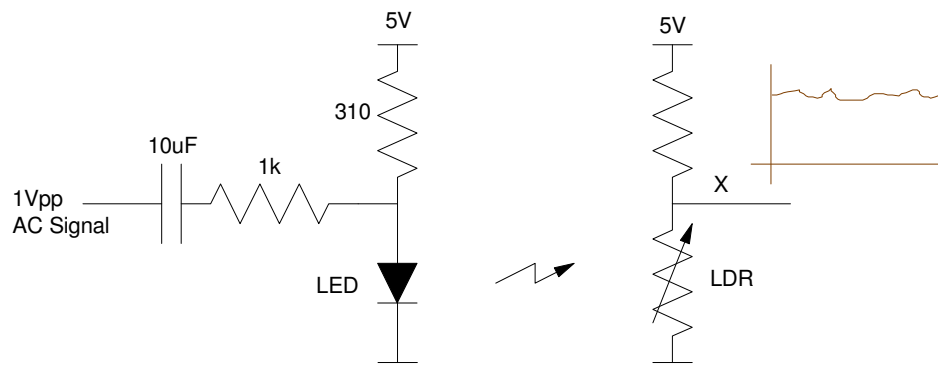
So that you don't change the DC operating current (10mA), add a DC blocking capacitor

$$\frac{1}{RC} = 20Hz$$

$$C = 7.9\mu F$$

Round up to 10uF (making the corner 100 rad/sec = 16Hz).

Step 3: Detect the light beam using a light sensor (LDR). Convert the resistance to a voltage using a voltage divider.

Once you have a signal at X, block the DC signal and amplify as before.

Envelope Detectors

1/2 Wave Rectifier: A diode can be used for a 1/2 wave rectifier, but you lose 0.7V across the diode. With an op-amp, you can remove that 0.7V drop:
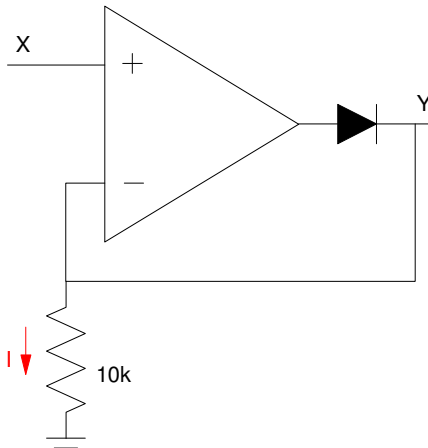
If X > 0

- V+ = V-
- I > 0
- The diode turns on

If X < 0

- The op-amp tries to make V+ = V-
- Which results in I < 0
- Which turns off the diode.

With the diode off, Y = 0
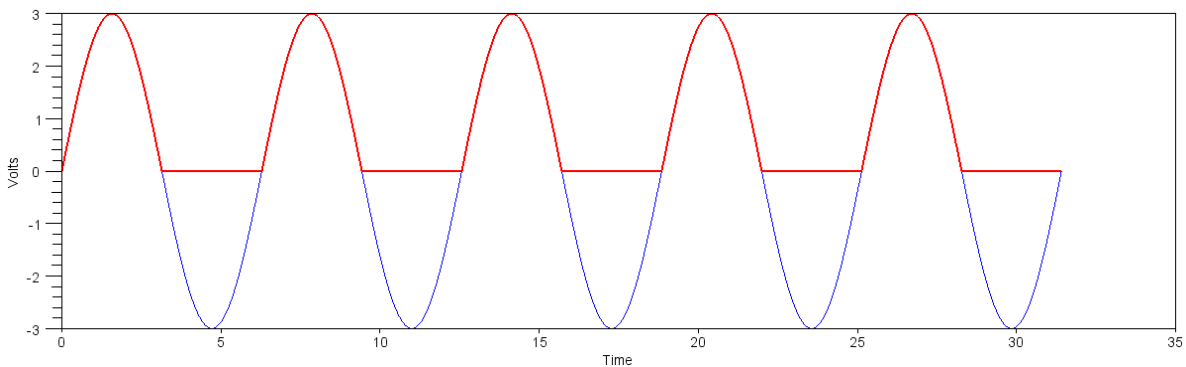
Input (blue) and output (red) for a 1/2 wave rectifier

Envelope Detector: If you add a capacitor across the 10k resistor

- When X > Y, the diode turns on, current flows, and the op-amp forces V+ to equal V- (Y=X)
- When X < Y, the diode turns off and the output floats. Y is then the voltage across C, slowly discharging.
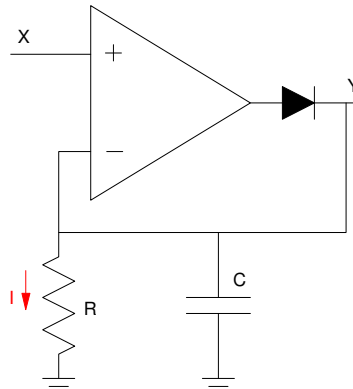
The RC time constant tells you how long you hold the voltage at Y:

$$V_y = \alpha \cdot \exp\left(\frac{-t}{RC}\right)$$
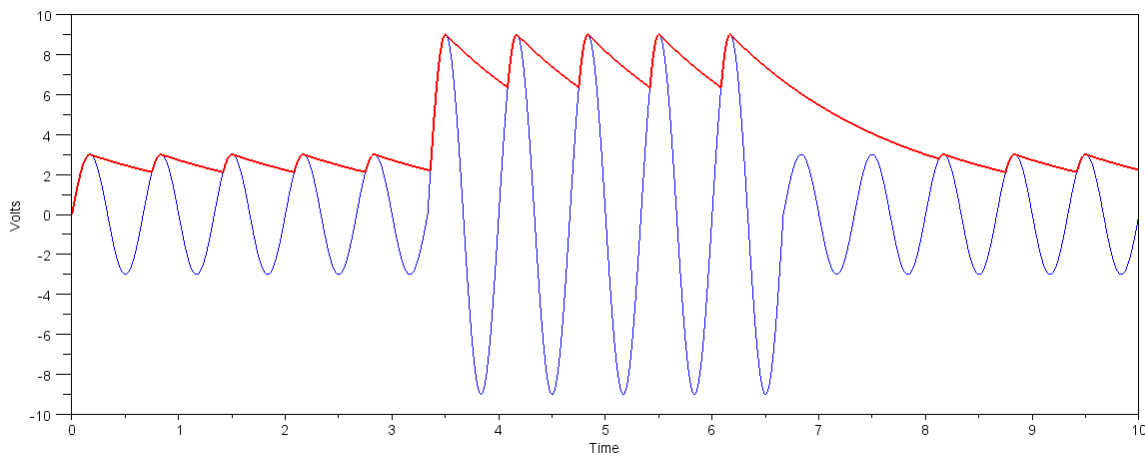
Envelope Detector: The output (red) tracks the amplitude of the input (blue)

Single-Sided Power Supplies

Active Filters with 0V and +5V Operation:

For amplifying AC signals with an op-amp, it would be convenient if you had +/- 2.5V rather than the single +5V power supply on your PIC boards. If you *did* have a +/- 2.5V power supply available, you could build the circuit on the left below. (We'll discuss this more later. For now, suffice it to say you could build it if you had +2.5V and -2.5V available).

If instead you only had 0V and +5V available, you could still use the circuit to the left if you treat +2.5V as circuit ground. If you *did* treat +2.5V as circuit ground, then

- +5V behaves as +2.5V relative to circuit ground
- +2.5V behaves as +0V (circuit ground)
- +0V behaves as -2.5V relative to circuit ground.

If you treat +2.5V as circuit ground, you suddenly have +2.5V and -2.5V available.

If you build the circuit to the right, you can amplify AC signals just like you can with the circuit to the left. In both cases, the AC signal is riding on circuit ground. For the circuit to the left, the AC signal is centered at 0V. For the circuit on the right, the AC signal is centered at +2.5V.

Likewise, if you want to build the circuits on the following pages with your PIC board (which only has 0V and +5V available), treat +2.5V as circuit ground. Wherever you see a ground symbol, use +2.5V (circuit ground) instead.

0V behaves as circuit ground

+2.5V behaves as circuit ground
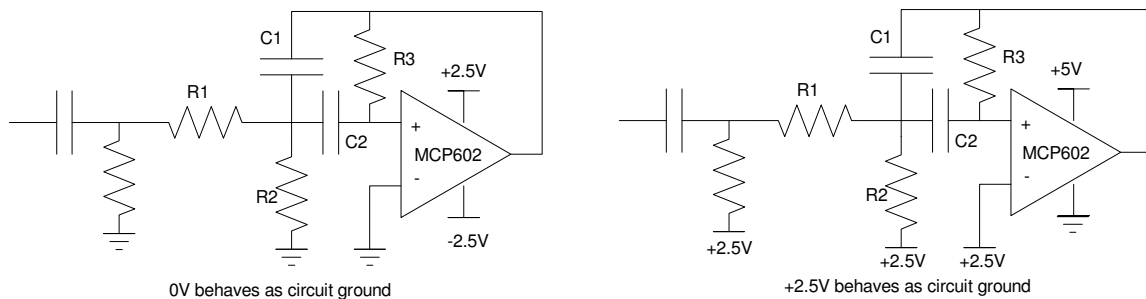
Strain Gages

When you bend a piece of metal, the metal stretches (stress) or compresses (strain). A strain gage measures this change.

Definitions:

Approximate Elastic Constants (from University Physics, Sears Zemansky, and Young, Reading, MA, 1979			
Material	Young's Modulus, (E) 10^{11}N/m^2	Shear Modulus, (S) 10^{11}N/m^2	Bulk Modulus, (B) 10^{11}N/m^2	Poisson's Ratio
Aluminum	0.7	0.3	0.7	0.16
Brass	0.91	0.36	0.61	0.26
Copper	1.1	0.42	1.4	0.32
Glass	0.55	0.23	0.37	0.19
Iron	1.9	0.7	1	0.27
Lead	0.16	0.06	0.08	0.43
Ni	2.1	0.77	2.6	0.36
Steel	2	0.84	1.6	0.19
Tungsten	3.6	1.5	2	0.2

$$Y = \text{Young's Modulus} = \frac{\text{stress}}{\text{strain}} = \frac{F/A}{dL/L} = \frac{\text{force}}{\text{unit change in length}}$$

$$S = \text{Shear Modulus} = \frac{F_{\text{parallel}}/A}{x/h}$$

$$B = \text{Bulk Modulus} = -\frac{dP}{dV/V} = \frac{\text{change in pressure}}{\text{unit change in volume}}$$

$$\text{Poisson's Ratio} = -\left(\frac{dw}{w}\right)\left(\frac{L}{dL}\right) = \frac{\text{unit change in width}}{\text{unit change in length}}$$

Thin Walled Cylinders

$$\text{Hoop Stress: } \sigma_t = \frac{pD}{2t} = \left(\frac{(\text{pressure})(\text{diameter})}{2(\text{thickness})}\right)$$

$$\text{Longitudinal Stress in a Closed Cylinder: } \sigma_l = \frac{pD}{2t}$$

Theory:

The resistance of a long thin wire is

$$R = \frac{\rho L}{A} = \frac{\text{(resistovity)(length)}}{\text{(area)}}$$

If you apply a force stretching the wire, the length changes proportional to the length of the wire and the force applied

$$\delta L = F \cdot L$$

The change in length per unit length is defined as the strain

$$\frac{dL}{L} = F = \varepsilon$$

For a given material, the force per unit area is equal to the Young's modulus of the material times the strain applied

$$\frac{F}{A} = E\varepsilon$$

where E is Young's modulus - which is a constant for each material. Solving for the change in length,

$$dL = \frac{F \cdot L}{A \cdot E}$$

Hence, the change in length is proportional to the force applied.

Also, assuming the density of the material remains constant, the volume must remain unchanged. Hence

$$L \cdot A = \text{constant}$$

Differentiating

$$dL \cdot A + L \cdot dA = 0$$

$$dA = -\left(\frac{A}{L}\right) \cdot dL$$

The change in resistance is then

$$dR = d\rho\left(\frac{L}{A}\right) + dL\left(\frac{\rho}{A}\right) + dA\left(-\frac{\rho L}{A^2}\right)$$

$$= 0 + \left(\frac{F \cdot L}{A \cdot E}\right)\left(\frac{\rho}{A}\right) + \left(-\frac{A}{L}\right)\left(\frac{F \cdot L}{A \cdot E}\right)dA\left(-\frac{\rho L}{A^2}\right)$$

$$= \left(\frac{2\rho L}{A^2 E}\right)F$$

The change in resistance is proportional to the force applied.

Example: Find the change in resistance as you apply a force to a steel wire with

- Length = 1m
- Area = 1mm2
- Force = 0N to 10N

For steel

$$\rho \approx 9.71 \mu\Omega \cdot cm \qquad \text{resistivity of steel}$$

$$E \approx 2 \cdot 10^{11} \, \frac{N}{m^2} \qquad \text{Young's modulus}$$

$$dL = \frac{FL}{AE} = \frac{(10N)(1m)}{\left(10^{-6}m^2\right)\left(2 \cdot 10^{11} N/m^2\right)} = 50 \mu m$$

The wire stretches 50um with a 10N load. The resistance becomes:

$$R = \frac{\rho L}{A} = \frac{\left(9.71 \cdot 10^{-4} \, \Omega m\right)(1m)}{10^{-6} \, m^2} = 971\Omega$$

$$dR = \left(\frac{2\rho L}{A^2 E}\right) F = \frac{(2)\left(9.71 \cdot 10^{-4} \, \Omega m\right)(1m)}{\left(10^{-6}m^2\right)^2 \left(2 \cdot 10^{11} N/m^2\right)} = 0.00974\Omega$$

R changes from 971 to 971.00974 Ohms.

Design of Strain Gages

To increase the sensitivity, a long wire is required. In order to reduce the size of the strain gage and make it capable of measuring strain over a smaller area, the wire is placed in a zig-zag pattern:

Direction of Maximum Sensitivity
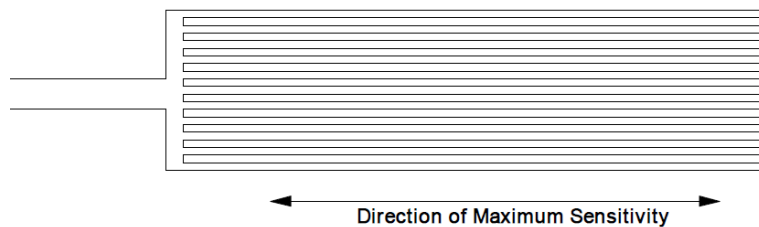
This results in a strain gage which is slightly influenced by strain perpendicular to the placement of the strain gage. Typically, the sensitivity of strain gages perpendicular to the main axis is on the order of 1% or so.

To increase the strength of the wire and electrically insulate it, it is placed on a plastic medium. This plastic must be slued to the material being measured (strain gage bonding material is often provided with the strain gages. Super glue also works.) The main requirements for the glue are that

- It is thin, so that deformation in the material is transferred to the strain gage, and
- It is bonded to the strain gage and the material, for the same reason.

Note that with this design, the average strain over the region is measured. Part of the reason for wrapping the wires back and forth is to minimize the size of the strain gage so that the strain over a smaller region can be measured. Even so, most strain gages are on the order of 2-10 mm is length rather than being a point.
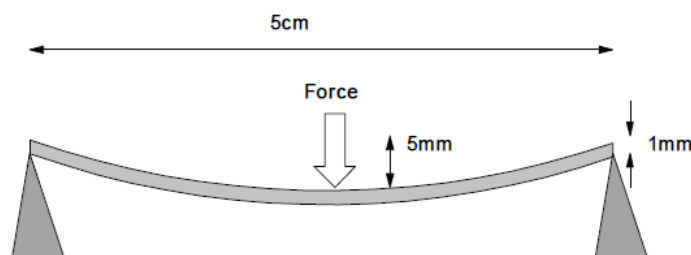
Use of a Strain Gage

To use a strain gage,

- Place it on a smooth material (to maximize the contact with the mylar coating of the strain gage)
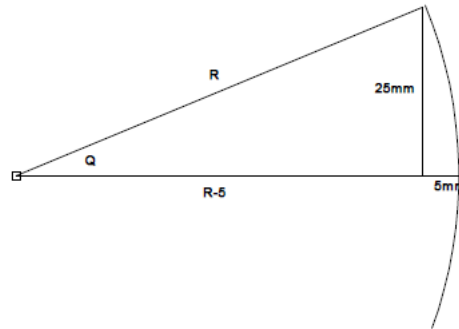- Place the wires so that they point in the direction of the strain, as follows
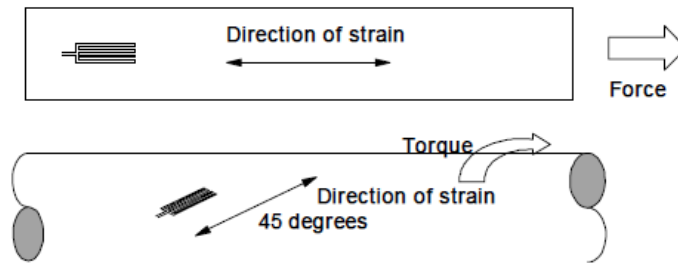
- Amplify the bejeebers out of the signal

Example: Find the strain on a piece of metal, 1mm thick, 5cm long, which bows 5mm under pressure.

Solution: First, find the radius of curvature of the beam.

$$R^2 = (R - 5)^2 + 25^2$$

$$R = 65mm$$

The strain is proportional to the change in the radius from the center line. The output edge will have a radious that is 0.5mm more, meaning

$$\varepsilon = \left(\frac{65.5mm - 65mm}{65mm} \right) = +0.007692 \qquad \text{(tension)}$$

The inner edge will be

$$\varepsilon = \left(\frac{64.5mm - 65mm}{65mm} \right) = -0.007692 \qquad \text{(compression)}$$

Example: Design a circuit to output 0V at 0 strain and +5V at 7700me. Use a strain gage with a nominal resistance of 120 Ohms and a gage factor of 2.14.

Solution: The resistance you're trying to measure is

$$R = 120(1 + 2.14\varepsilon)$$

$$R(0) = 120\Omega$$

$$R(0.0077) = 121.977\Omega$$

Using a Whetstone bridge, this is a voltage of

$$V(0) = 2.500 \text{ V}$$

$$V(0.0077) = 2.5204V$$

A gain of 244.74 is then required.

$$gain = \left(\frac{5V - 0V}{2.5404V - 2.5V} \right) = 244.74$$

So that the output is 0V at zeros strain, a 2.5V reference voltage is used. The following circuit then can be used. (note: This assumes the strain gage is placed on the inside surface do R decreases with strain. Switch the + and - inputs to the instrumentation amplifier if it is placed on the outside surface.)
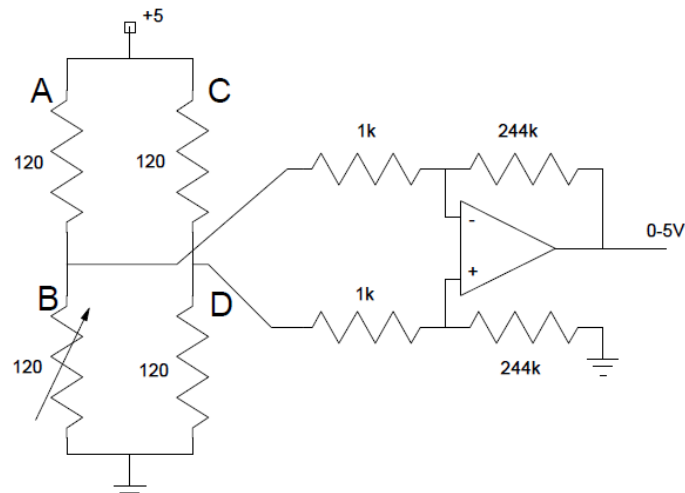

Variations:

Temperature Compensation: Since resistance also changes with temperature, the output will also change with temperature. To prevent this, replace resistor A with a second strain gage placed on the metal, perpendicular to the direction of strain.

Temperature Compensation with Double the Sensitivity: Replace resistor A with a strain gage placed on the other side of the bar. When one strain gage is under compression, the other is under tension, doubling the voltage change in the voltage divider.

Temperature Compensation with 4x the Sensitivity: Use four strain gages. B and C are placed on the inside surface, A and D are placed on the outside surface.

Uses of Strain Gages

1) Force Sensor: Design a mechanical system where strain is proportional to force. This is commonly used in electronic bathroom scales.
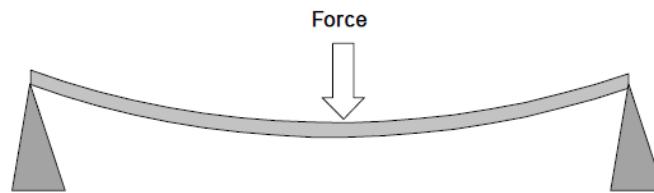
2) Pressure Sensor: Allow the force to be applied over a fixed area. The result measures force per unit area, or pressure.

3) Differential Pressure Sensor: Design a mechanical device where the strain is proportional to the difference in pressure: P1-P0
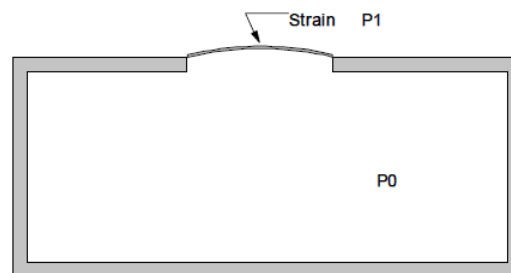
4) Accelerometer: Design a system where strain is related to acceleration.