MEMS Applications: Ref: Werner Karl Schomburg: ㊱ Date: 16/03/2015
Introduction to Microsystem Design

Applications based on MEMS are developed where miniaturization is beneficial like

- Consumer products
- Aerospace
- Automotive
- Biomedical
- Chemical
- Optical displays
- Wireless and Optical communications
- Fluidics

In the applications listed above, the MEMS device types can be classified under the following heads.

- Pressure sensors
- Inertial Sensors
- Chemical Sensors

} Sensors.

- Micromirrors
- Optical Scanners
- Gear Trains
- Miniature Robots
- Fluid pumps
- Microdroplet generators
- Neural & Surface probes
- Analyzers
- Imagers.

In ~~the following~~ today's class, we will discuss some of these devices.
We will start with MEMS Sensors.

MEMS Sensors:

Sensors are a major application for MEMS devices. Three primary MEMS sensors are

(1). Pressure sensors
(2). Chemical sensors
(3). inertial sensors.

MEMS sensors can also be used in combination with other sensors for multisensing applications. For example, a MEMS can be designed with sensors to measure the flow rate of a liquid sample and at the same time identify any contaminates within the sample.

Pressure Sensors:

- MEMS pressure sensor contain a membrane (diaphragm). deflected by the pressure difference to be measured.
- One side of the membrane is exposed to a sealed, reference pressure and the other side is open to external pressure
- The ~~d~~ membrane moves with a change in the external pressure.

For a circular membrane, the deflection of the membrane is a function of the pressure difference its can be calculated from

$$\Delta p = \frac{4 d_M w_0}{R_M^2}\left(\frac{4}{3}\frac{d_M^2}{R_M^2}\frac{Y_M}{1-\nu_M^2} + \sigma_0 + \frac{64}{105}\frac{w_0^2}{R_M^2}\frac{Y_M}{1-\nu_M^2}\right).$$

where Δp = pressure difference
d_M = thickness of membrane
w_0 = deflection of membrane due to Δp
Y_M = Young's modulus of the membrane
ν_M = Poisson's ratio
R_M = Radius of the membrane.

first term in the eqn represents the effect of bending moments

Second term " the effect of residual stress

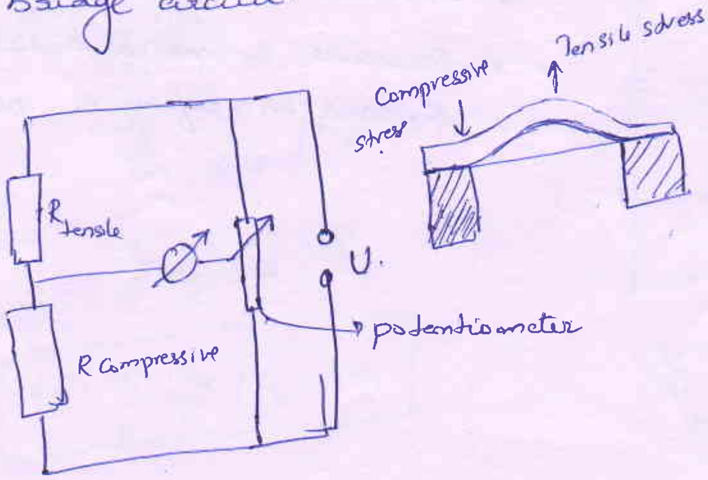
third term " the effect of stress due to straining.

It is important to note that the residual stress term is detrimental because the stress of a micromembrane is easily changed by outer forces acting on the sensor housing. Therefore, it is usual to mount the membrane at the free end of a tube where the stress of the housing is kept away from the sensing membrane.

The third term represents the stress change of the neutral fiber and the entire membrane due to the straining of the membrane generated by its deflection. This term is responsible for a non linear relationship between pressure difference and membrane deflection. Hence, for a linear relation between pressure difference and membrane deflection, the deflection ω_0 should be much less than its thickness d_m.

→ This implies the first term dominates.

The deflection of the membrane can be detected by strain gauges, as a capacity change, or the frequency change of a resonating micro-structure. When strain gauges are employed, it is necessary to compensate for changes of their electrical resistance as a function of temperature. This is done by using a bridge circuit.



The potentiometer is adjusted such that the output voltage U_m of the bridge is zero when the membrane is not deflected. Therefore, the output voltage is equal to the change in the voltage drop over one of the resistances

$$U_2 = \frac{R_2}{R_1+R_2} U_0$$

$$\frac{\partial u_2}{\partial R_1} = U_0 \cdot \frac{-R_2}{(R_1+R_2)^2} \Delta R$$

$$+ \; U_0 \cdot \frac{R_1}{(R_1+R_2)^2} \cdot \Delta R_2$$

$$\Rightarrow \quad U_m = \frac{\partial u_2}{\partial R_1} \Delta R_1 + \frac{\partial u_2}{\partial R_2} \Delta R_2$$

$$= U_0 \cdot \left[\frac{-R_2 \, \Delta R_1}{(R_1+R_2)^2} + \frac{R_1 \, \Delta R_2}{(R_1+R_2)^2} \right]$$

If $R_1 = R_2$,

$$U_m = \frac{U_0}{4R_{e1}} (\Delta R_2 - \Delta R_1)$$

Use of Pressure Sensor:

→ MEMS pressure sensors sense, monitor and transmit,

- Tire pressure
- Fuel pressure
- Oil pressure
- Air flow
- Absolute air pressure with in the intake manifold of the engine.

→ In Biomedical applications

- Blood pressure sensor
- Intracranial pressure sensor
- Pressure sensor in endoscopes
- Sensors in infusion pumps.

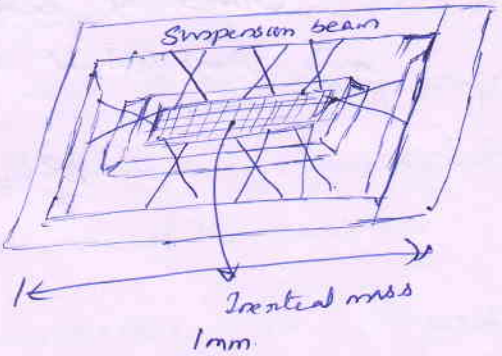
Inertial Sensors:

Newton's law: An object remains in its state of rest or of uniform motion unless acted upon by an external force.

MEMS inertial sensors are designed to sense a change in an object's inertia and then convert or transduce inertial force into a measurable signal. They measure changes in acceleration, vibration, orientation and inclination. This is done through the use of micro-sized devices called accelerometers and gyroscopes.

MEMS accelerometers:

Nearly, all acceleration sensors employ a seismic mass fixed to a beam. The mass deflected when accelerated and the deflection is measured.



If the deflection is measured with strain gauges on the surface of the beam, the strain ε_B can be calculated assuming that the force F_I acting at the end of the beam in the transversal direction is the mass multiplied by m_0 of the seismic mass the acceleration.

Now the deflection

$$\omega = \frac{F}{6YI_B} x^2(3L_B - x)$$

Now the strain can be calculated as

$$\varepsilon = -\frac{d_B}{2}\frac{\partial^2\omega}{\partial x^2}$$

$$= -\frac{d_B}{2} \cdot \frac{F}{6YI}\left(6L_B - 6x\right)$$

$$= \frac{d_B}{2} \cdot \frac{F}{YI}(L_B - x)$$

$$\boxed{\varepsilon_0 = \frac{d_B}{2}\frac{m_0}{YI}(L_B - x)a}$$

$$\frac{\partial\omega}{\partial x} = \frac{F}{6YI}\{2x(3$$

$$+ x^2 x - 1)$$

$$\frac{\partial^2\omega}{\partial x^2} = \frac{F}{6YI}\{2(3L_B$$

$$2x x - 1 -$$

$$+$$

$$3L_B - 2x - 2x - 2$$

$$\frac{F}{3YI}(3L_B \quad - 2x)$$

$$= \frac{F}{YI}[L_B$$

$$\omega = 3L_Bx^2 - x^3$$

$$\frac{\partial\omega}{\partial x} = 3L_B \times 2x - 3x^2$$

$$\frac{\partial^2\omega}{\partial x^2} = 6L_B - 6x.$$

If the beam is etched into a single crystalline silicon and longitudinal and transverse strain gauges are fabricated, the resistance change can be calculated as

$$\Delta R = R\,(\bar{\pi}_l \sigma_l + \bar{\pi}_b \sigma_b + \alpha_T \Delta T)$$

$\bar{\pi}_l$ - piezoresistive coefficient in longitudinal direc

$\bar{\pi}_b$ - " " transverse

σ_l - longitudinal stress

σ_b - transverse stress

α_T - thermo extension coefficient

ΔT - temp. gradient

Since the beam is fixed in the longitudinal direction, there is only longitudinal stress. which can be calculated from Hook's law.

$$\frac{\Delta R}{R} = \bar{\pi}_l Y_B \varepsilon_B + \alpha_T \Delta T$$

$$= \bar{\pi}_l . Y_B . \frac{d_B}{2} \frac{m_0}{YI} (l_B - x) a_0 + \alpha_T \Delta T$$

$$= \bar{\pi}_l . \frac{d_B}{2} \frac{m_0}{I} (l_B - x) a_0 + \alpha_T \Delta T$$

The output signal of the strain gauge is

$$U_m = \frac{U_0}{4R} (\Delta R_2 - \Delta R_1)$$

$$\boxed{U_m = \frac{U_0}{4R} \frac{d_B}{2} \frac{m_0}{I} \left[(l_B - x_l)\bar{\pi}_l - (l_B - x_t)\bar{\pi}_t \right] a_m.}$$

Important points :→

* In principle, it is possible to measure the deflection of a beam also with a strain gauges from metal on the surface of the beam. The disadvantage of this approach is that the beam needs to be small in order to be sensitive and economic. As a consequence, metal conductor paths cannot be very long. and therefore their resistance is small.

– Heating of the beam must be avoided since it changes Young's modulus and electrical resistance

- the supply voltage U_0 of the bridge circuit needs to be low and only very small output signals can be achieved.

* Acceleration sensors should be sensitive and show large resonance frequency to allow the measurement of quick acceleration changes. The resonance frequency of a beam clamped at one end is large, if its thickness is large, its length is short and the mass at the end of the beam is small.

$$\text{frequency} = \frac{1}{2\pi}\sqrt{\frac{3Y_B I}{L_B^3(m_0+0.24\,m_B)}}$$

Y_B = Young's modulus of beam

I : second moment of inertia

L_B : length of beam

m_0 : point mass at the end of beam

m_B : mass of beam.

This condition also implies that the sensitivity is small.

* For high sensitivity and quick reaction time a balanced acceleration sensor is used. In this sensor, the acceleration force is balanced by some force such that the seismic mass is not moving. If the mass always (nearly) stays in its idle position, the properties of the beam, Young's modulus, geometry and resonance frequency do not influence the performance of the sensor.

For e.g. the mass can be held by an electrostatic force, The position of the mass can be ~~but~~ measured by strain gauges on the beam or by a small a.c. voltage applied in the electrodes in series with another capacitor or resistance. The applied voltage (a.c) should not change the beam deflection much.

Inertial forces and electrostatic force are equal, if the beam is in its ideal position. Then the voltage U_m required to balance acceleration and electrostatic force can be calculated from

$$\frac{1}{2}\varepsilon_0\varepsilon_r\frac{A_c}{d_c^2}U_m^2 = a_m m_0$$

$$U_m = d_c\sqrt{\frac{2m_0 a_m}{\varepsilon_0\varepsilon_r A_c}}$$

A_c : area of the electrodes

d_c : distance ~~between the~~

Angular velocity sensor:

- employed mainly in automobiles for electronic stability control.
- based on Coriolis force/acceleration which appears to act on a moving body in a rotating system.
- In the figure shown in class, the dark parts are fixed to the substrate and the whole rest is movable and supported by the beams which act as springs. An alternating voltage applied to the actuator electrodes generates a primary oscillation of the entire structure. When the oscillating structure is rotating, a secondary oscillation is generated which is measured with the sensing electrodes.

The position x of the body moved by the primary oscillation as a function of time t is described by

$$x(t) = A_0 \sin(\omega t)$$

A_0: amplitude of primary oscillation

$$V(t) = \frac{\partial x}{\partial t} = A_0 \omega \cos(\omega t)$$

V: the velocity of the body due to primary oscillation

The Coriolis acceleration a_c is calculated from the cross product of the velocity vector V of the moving mass and the angular velocity Ω of the rotating system as

$$a_c = 2\,\vec{V} \times \vec{\Omega}$$

$$= 2V\Omega \sin(\alpha).$$

For the sensor shown in class, it measures the angular velocity around an axis perpendicular to the plane. Hence $\sin\alpha = 1$.

$$\Rightarrow a_c = 2V\Omega$$

$$= 2 A_0 \omega \cos(\omega t)\, \Omega$$

$$\boxed{a_c = 2 A_0 \omega \Omega \cos(\omega t)}$$

Large Coriolis acceleration can be achieved when amplitude and frequency of the primary oscillations are large → hence better to work at the resonance frequency.