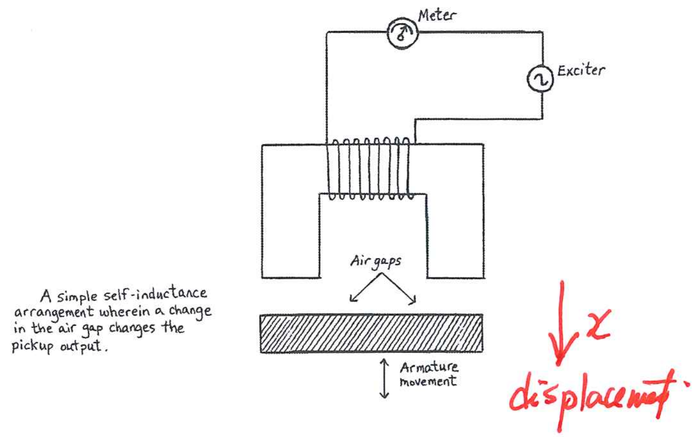
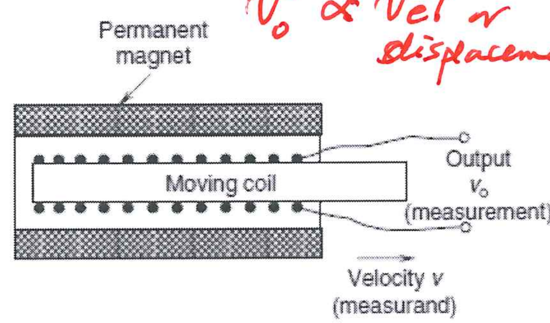
Self-Induction Transducers:



- Unlike mutual-induction transducers, only a single coil is employed.
- This coil is activated by an ac supply voltage V_{ref} of sufficiently high frequency.
- The current produces a magnetic flux, which is linked back with the coil.
- The level of flux linkage (or self-inductance) can be varied by moving a ferromagnetic object within the magnetic field.
- This movement changes the reluctance of the flux linkage path and also the inductance in the coil.
- The change in self-inductance, which can be measured using an inductance-measuring circuit represents the measurand (displacement of the object).
- Note that self-induction transducers are usually variable-reluctance devices as well.

Permanent-Magnet Transducers:

$V_o \propto Vel$ or displacement.

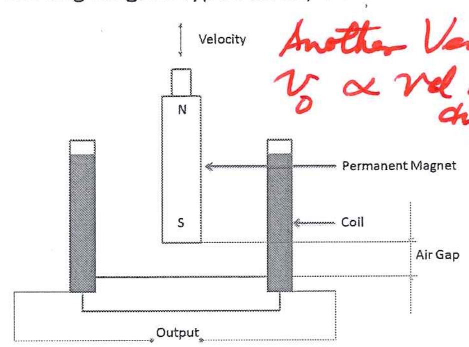


A distinctive feature of permanent magnet transducers is that they have a permanent magnet to generate a uniform and steady magnetic field.

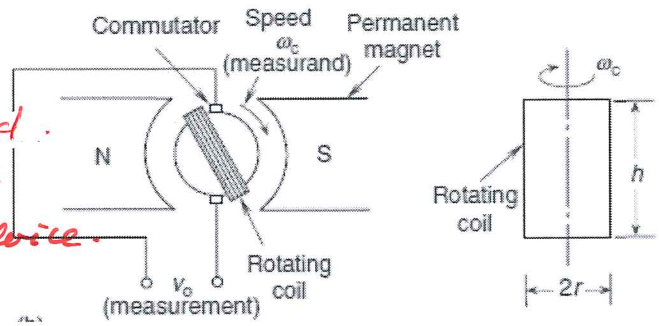
- A relative motion between the magnetic field and an electrical conductor induces a voltage, which is proportional to the speed at which the conductor crosses the magnetic field (i.e., the rate of change of flux linkage).
- In some designs, a unidirectional magnetic field generated by a dc supply (i.e., an electromagnet) is used in place of a permanent magnet.
- Permanent-magnet transducers are not variable-reluctance devices in general.

Moving Magnet Type velocity Transducer

Another Version $V_o \propto Vel$ or displacement



DC Tachometer



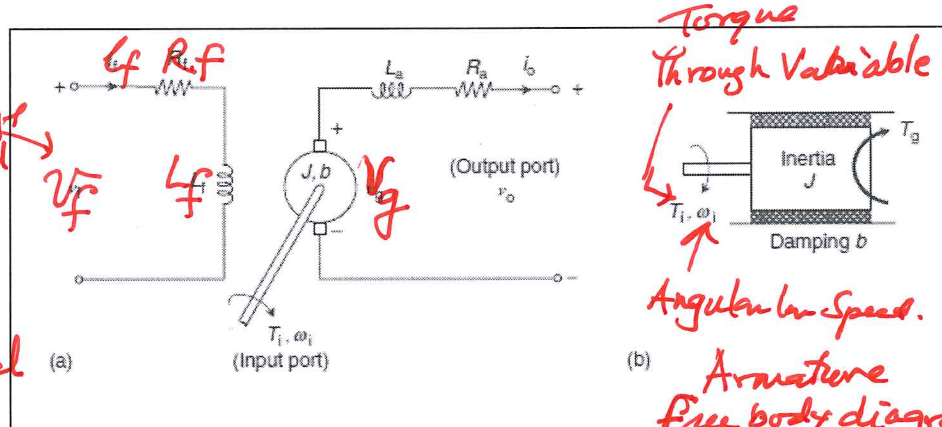
- Measures Angular Velocities
- output signal that is induced in rotating coil is picked up as DC voltage V_o using a Commutator device.

$$V_o = (2nhr\beta)\omega_c = k\omega_c$$

Coil turns, Coil height, Coil width (2r), flux density, Angular Speed, Back emf constant.

Modeling and Design Example:

field windings powered by.



(1) Find Transfer function

(2) Assumptions required to decouple this result into practical input/output model for a tachometer.

(3) Significance of Mechanical and Electrical Time Constant.

gen. voltage, constant field current

$$v_g = K\omega_i i_f = k\omega_i \Rightarrow \boxed{v_g = k\omega_i} \quad (1)$$

$$T_g = k' i_f i_o = K i_o \quad (2)$$

Armature Resistance, Leakage Inductance

$$v_o = v_g - R_a i_o - L_a \frac{di_o}{dt} \quad (3)$$

Armature Inertia

using Newton's Second Law: F=ma.

$$J\frac{d\omega_i}{dt} = T_i - T_g - b\omega_i \quad (4)$$

damping Constant

Equation (1) substituted into (3) to eliminate V_g, (2) into (4) ~~to~~ eliminate T_g

Result

$$v_o = k\omega_i - (R_a + sL_a) i_o \quad (5)$$

$$(b+sJ)\omega_i = T_i - K i_o \quad (6)$$

Note: Laplace Transforms.

i_o in (5) can be eliminate using equation (6)

Finally, i_0 in Equation (5) is eliminated using Equation (6). This gives the matrix transfer function relation:

$$\begin{bmatrix} v_o \\ i_o \end{bmatrix} = \begin{bmatrix} K + (R_a + sL_a)(b + sJ)/K & -(R_a + sL_a)/K \\ -(b + sJ)/K & 1/K \end{bmatrix} \begin{pmatrix} \omega_i \\ T_i \end{pmatrix}.$$

decoupling

$$v_o = K + \frac{(R_a + sL_a)(b + sJ)}{K} \omega_i - \underbrace{\frac{(R_a + sL_a)}{K} T_i}$$

* to minimize this K should be Large

⇒ increase # of turns

* Also system will become stable

Electrical terms: $\frac{L_a}{R_a}$

Mechanical terms: $\frac{J}{b}$

In practical sense $\frac{L_a}{R_a} << \frac{J_a}{b}$

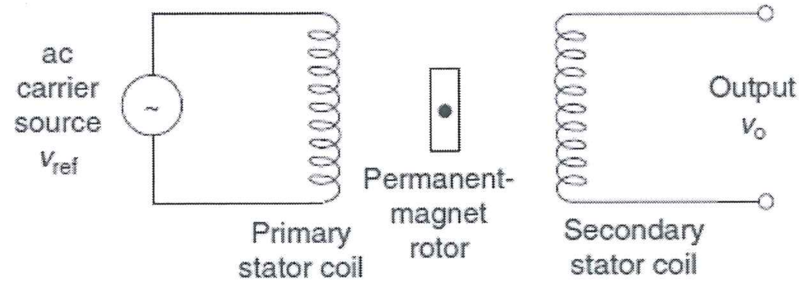
Electrical Time constant: $\frac{L_a}{R_a} = \tau_e$

Mechanical Time constant: $\frac{J}{b} = \tau_m$

+ * To Reduce τ_m: Decrease Inertia, increase Rotor damping
− * Rotor Inertia ∝ dimensions which determine gain K − Face ↓K
− * Increase b ⇒ Large τ_i for Tachometer, could create Loading.
+ * Low K: Reduction of coupling & Reduction of freq. dep. on system..

Permanent-Magnet AC Tachometer:

- When the rotor is stationary or moving in a quasi-static manner, the output voltage is a constant amplitude signal much like the reference voltage, as in an electrical transformer.



(a)

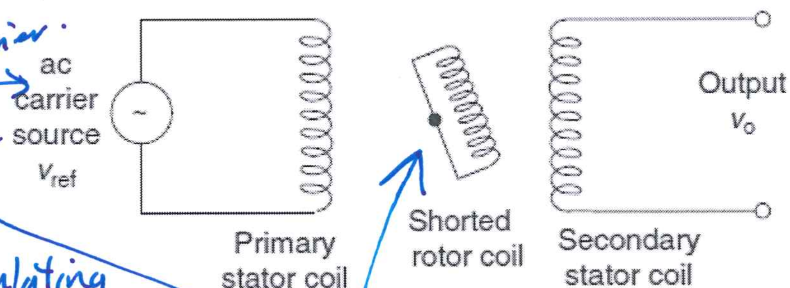
- As the rotor moves at a finite speed, an additional induced voltage, which is proportional to the rotor speed, is generated in the secondary coil.

- This is due to the rate of change of flux linkage into the secondary coil as a result of the rotating magnet. The overall output from the secondary coil is an amplitude-modulated signal whose amplitude is proportional to the rotor speed.

- For transient velocities, it becomes necessary to demodulate this signal in order to extract the transient velocity signal (i.e., the modulating signal) from the overall (modulated) output.

- The direction of velocity is determined from the phase angle of the modulated signal with respect to the carrier signal.

AC Induction Tachometer:



Carrier:

- Primary stator Coil induces a voltage in Rotor coil. Modulated Signal
- Rotor spin provides modulating signal
- which is $\propto$ spin (speed of Rotation
- Non-Energized stator: Secondary coil provides o/p of Tachometer.
  $V_o \propto$ stator field & speed of Rotor. Coil
- Demodulation required to extract component $\propto$ angular speed of Rotor.
- No sliprings, no brushes, (No voltage ripple as in DC + Brush Noise.)

Variable-Capacitance Transducers:

$j\omega L$ $\quad$ $1/j\omega C$

Variable-inductance devices and variable-capacitance devices are variable-reactance devices.

$L\dfrac{di}{dt} = v$ and $C\dfrac{dv}{dt} = i$

Capacitance $= K\dfrac{A}{x}$; x : gap between plates
K = dielectric constant $= \epsilon = \epsilon_r \cdot \epsilon_0$ (in Vacuum)
A : overlapping Area of Two plates (Fixed & Rotating)
Results in varying ϵ.?

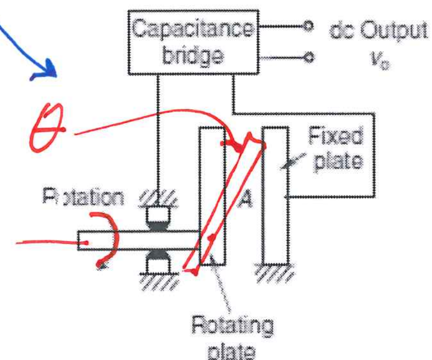
Capacitive Rotation Sensor: (fig a)

1-stationary plate + 1-Rotating plate
$A \propto \theta$; K: Sensor-Constant

$C = K\theta$

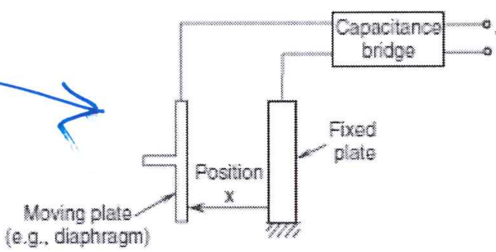
Sensitivity of this angular displacement sensor is:

$$S = \frac{\partial C}{\partial \theta} = K$$



(a)

Capacitive Displacement Sensor: (fig b)



(b)

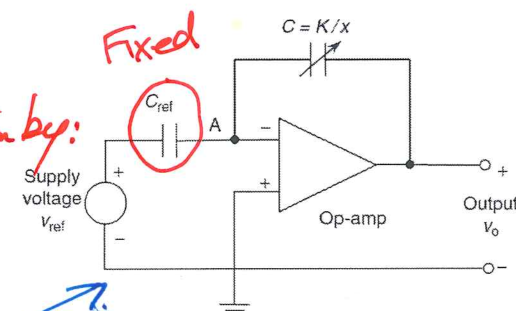
- Sensor for Measuring transverse displacements and Proximities
- Cap. Plate attached to Moving plate

Sensor Relation is $C = \dfrac{K}{x}$

- Corresponding Sensor Sensitivity is given by:

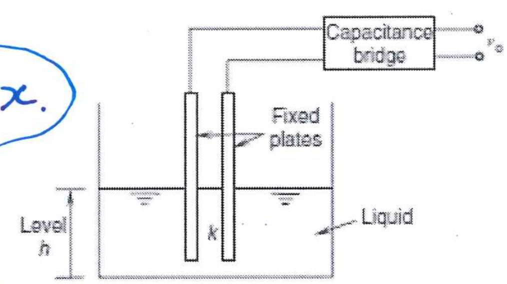
$$S = \frac{\partial C}{\partial x} = -\frac{K}{x^2} \quad \leftarrow \text{NON LINEAR}$$

- To Linearize; use inverting Amp.



Node-A: $v_{ref}\, C_{ref} + v_o\, C = 0$

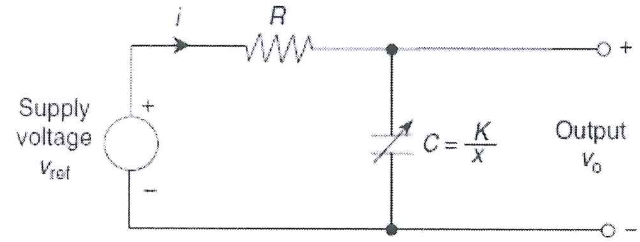
$\because C = K/x \;\therefore\; v_o = -\dfrac{v_{ref} \cdot C_{ref}}{K}\, x.$



- Solid Di-Electric element, free to Move in Longitudal direction of Capacitor plates
- Di-Electric Const. changes due to Motion $\therefore$ Level detection.

Example:

Consider the circuit shown, examine how this arrangement could be used to measure displacements.



Solution:

- Assuming high Z used to measure v_o
- i in C is same as in R

$$i = C\frac{dv_o}{dt} = \frac{v_{ref} - v_o}{R}$$

Sensor Relationship is $C = \frac{K}{x}$

$$\therefore \frac{K}{x}\frac{d}{dt}v_o = \frac{v_{ref} - v_o}{R}$$

$$\frac{RKv_o}{x} = \int_{t=0}^{t} v_{ref} - v_o \, dt$$

$$\therefore x = \frac{RKv_o}{\int_{t=0}^{t}(v_{ref} - v_o)\,dt}$$

Integration ⇒ Accumulation → delay → operating speed limit → frequency Range.

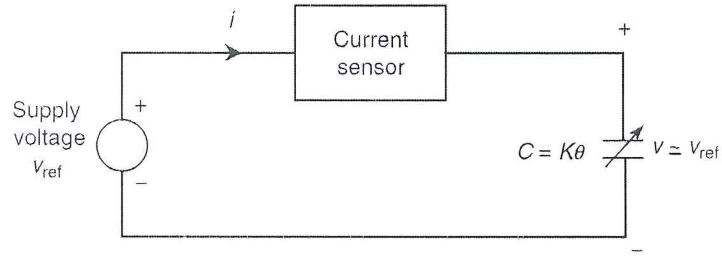
Frequency Domain transfer function. v_o/v_{ref} ?

$$\frac{v_o}{v_{ref}} = \frac{1}{[1 + RKj\omega/x]}$$

Measuring Magnitude for $x = \frac{RK\omega}{\sqrt{1/M^2 - 1}}$

phase lag $\phi = \frac{RK\omega}{\tan\phi}$

Capacitive Angular Velocity Sensor:



- uses Rotating-plate Capacitor
- Current Sensor has negl. Res.
- $V_{capacitor} = V \simeq V_{ref}$

$$i = \frac{d}{dt}(C\, V_{ref}) = V_{ref}\frac{dC}{dt}$$; For Rotating Plate : $C = K\theta$.

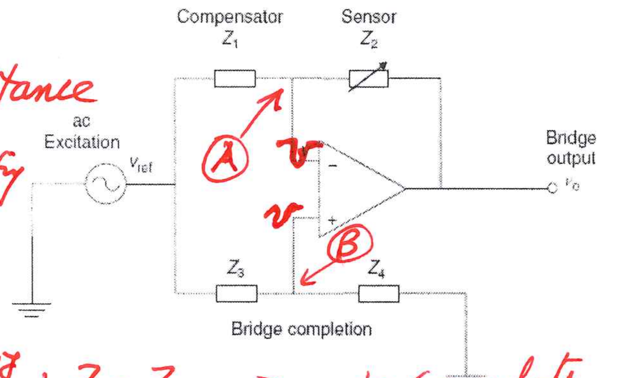
$$\therefore\ i = V_{ref}\frac{dK\theta}{dt} = V_{ref}\cdot K\cdot\frac{d\theta}{dt} \quad \therefore \boxed{\frac{d\theta}{dt} = \frac{i}{K\,V_{ref}}}$$

angular Velocity $\propto i$

- Some loading due to moving plate, frictional forces?
- Temp, Humidity, Pressure Can also introduce errors.
over come by

1Pf/1mm

Capacitive-Bridge Circuit:



- Sensors depend on change of Capacitance
- Change due to Temp/press/humidity resulting in Capacitance change should be Compensated !!

$Z_2 = \frac{1}{j\omega C_2}$; $Z_1 = \frac{1}{j\omega C_1}$ ← Compensating Cap. ; Z_3, Z_4 : Imp. to Complete Bridge.

C_2 ← Sensing Cap.

$V_{ref} = V_a \sin\omega t$ (excitation ac 'v') ; $V_o = V_b \sin(\omega t - \phi)$ ϕ - Lag.

(A) $$\frac{V_{ref} - V}{Z_1} + \frac{V_o - V}{Z_2} = 0$$; (B) $$\frac{V_{ref} - V}{Z_3} + \frac{0 - V}{Z_4} = 0$$

Eliminating 'v' ; $$V_o = \left(\frac{\frac{Z_4}{Z_3} - \frac{Z_2}{Z_1}}{1 + \frac{Z_4}{Z_3}}\right) V_{ref}$$, $V_o = 0$ if $\frac{Z_2}{Z_1} = \frac{Z_4}{Z_3}$

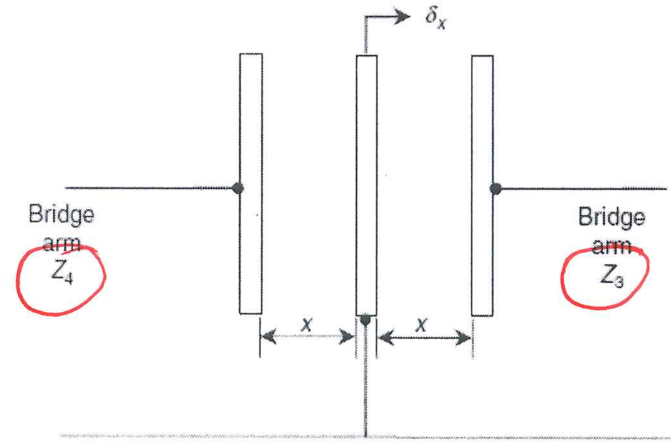
⇒ Balanced Bridge.

Note: All Caps changed equally so Ambient Effects are taken Care of !!

Change in $Z_2 \rightarrow Z_2 + \delta Z$

$$\delta V_o = -\frac{\delta Z}{Z_1(1 + Z_4/Z_3)} V_{ref}$$; Z_1, Z_4, Z_3 Known.

Differential (Push–Pull) Displacement Sensor:



- Two end plates are fixed
- Middle plate attached to a moving object whose displacement (Linear) δx needs to be measured.
- plates connected to bridge circuit (Last Page) forming $Z_3 + Z_4$. (displacement x to be observed)
- Initially Middle plate is placed at an equal separation of x from either plate.
- Then moved by δx

$$Z_3 = \frac{1}{j\omega C_3} = \frac{x - \delta x}{j\omega K}$$
$$Z_4 = \frac{1}{j\omega C_4} = \frac{x + \delta x}{j\omega K}$$

Note that $C = \frac{K}{x}$

$$v_0 = \frac{\frac{Z_4}{Z_3} - \frac{Z_2}{Z_1}}{1 + \frac{Z_4}{Z_3}} V_{ref}$$

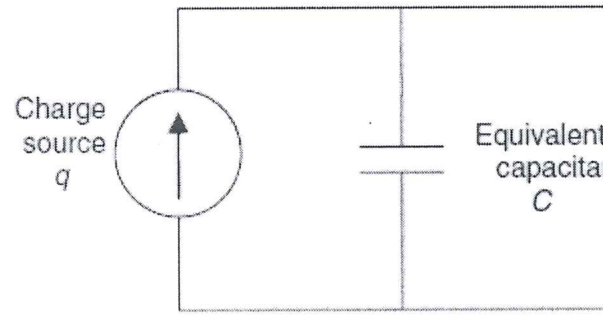
Z_1, Z_2 make the bridge & EQUAL.

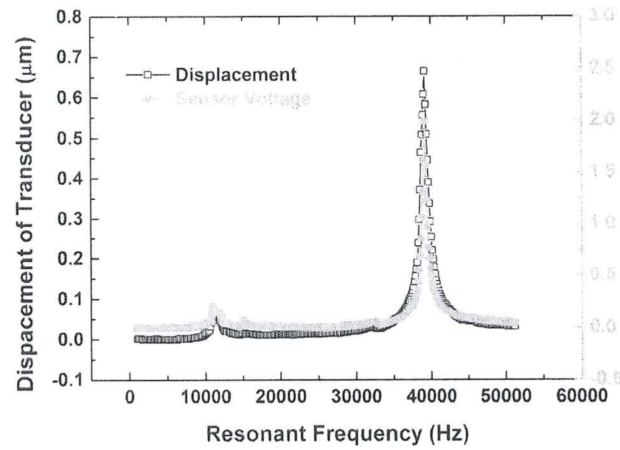
$$\therefore v_0 = \frac{\frac{Z_4}{Z_3} - 1}{1 + \frac{Z_4}{Z_3}} V_{ref} = \left(\frac{Z_4 - Z_3}{Z_3 + Z_4}\right) V_{ref} \quad ; \quad Z_1 = Z_2$$

Then.
$$v_0 = \frac{\frac{x+\delta x}{j\omega K} - \frac{x - \delta x}{j\omega K}}{\frac{x+\delta x}{j\omega K} + \frac{x - \delta x}{j\omega K}} V_{ref} = \frac{\frac{\cancel{x} + \delta x - \cancel{x} + \delta x}{\cancel{j\omega K}}}{\frac{x + \cancel{\delta x} + x - \cancel{\delta x}}{\cancel{j\omega K}}} V_{ref} = \frac{2\delta x}{2x} = \frac{\delta x}{x} V_{ref}$$

$$\therefore v_0 = \frac{\delta x}{x} v_{ref}$$ } Linear and measures the incremental displacement.

Piezoelectric Sensors:
Some substances, such as barium titanate, single-crystal quartz, and lead zirconatetitanate (PZT) ***can generate an electrical charge and an associated potential difference when they are subjected to mechanical stress or strain***. This piezoelectric effect is used in piezoelectric transducers.





- $Z = \frac{1}{j\omega C} \Rightarrow Z \uparrow$ especially at Low 'f'
- e.g. Quartz Signal at 100 Hz
  Z is several Mega ohms
- Limitation on useful Low 'f' area
- Charge leakage $\propto$ Insulation Resistance.

Sensitivity:

- Sensitivity of Piezoelectric Xtal may be represented by charge sensitivity OR voltage sensitivity
- Charge Sensitivity: $S_q = \frac{\partial q}{\partial F}$ — charge — Applied force

Given Surface Area 'A'

$$S_q = \frac{1}{A}\frac{\partial q}{\partial P} \leftarrow \text{stress/Pressure}$$

- Voltage Sensitivity $S_v = \frac{1}{d}\frac{\partial v}{\partial P}$ ← change in v ← unit change in Press. ~~or~~ STRESS.

  change in V due to a unit ↑ in press. per unit thickness

  ↑ xtal thickness

But $\delta q = C\,\delta V$

$$S_q = k\,S_v.$$

Relation between Two Sensitivities.