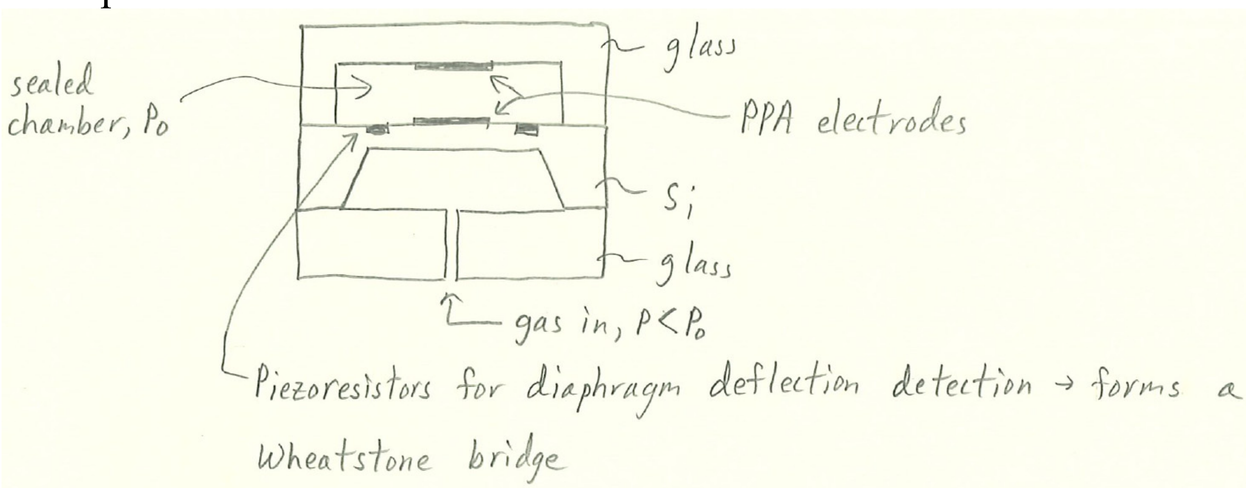
Lecture 10/24/24

Pressure Sensors (Continued)

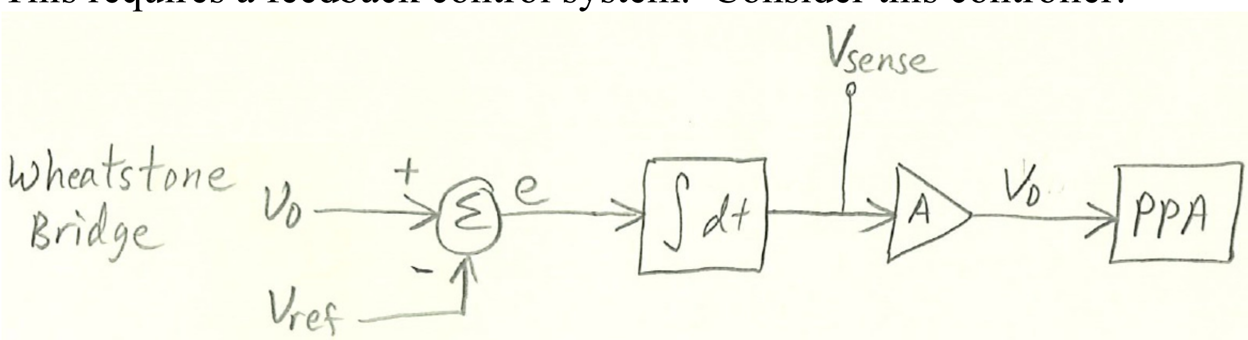
1) Force feedback pressure sensors

Detect diaphragm deflection, and then use feedback with a PPA to return the diaphragm to its original position.

Example:



This requires a feedback control system. Consider this controller:



V_o is the output voltage from the Wheatstone bridge.

V_{ref} equals V_o when the diaphragm is in the rest position.

e is an error signal that is non-zero when the diaphragm is not in its rest position.

V_{sense}, the control loop control voltage, is a DC signal generated by integrating e that is amplified and applied to the PPA as V_D to produce an electrostatic force to return the diaphragm to its rest position in response to the applied P.

V_{sense} is a function of P and is therefore the output signal of the sensor.

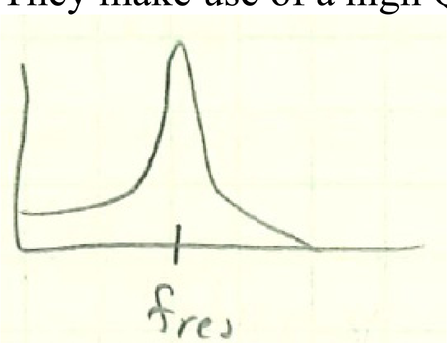
Although in this simplistic implementation, $(V_{sense})^2 \propto P$, this architecture illustrates these benefits:

(1) Nonlinearities due to diaphragm deflection are avoided since the diaphragm stays in its rest position.
(2) Issues with P_o changing due to the volume of the sealed chamber changing when the diaphragm deflects are avoided.
(3) A greater range of pressure can be measured since the diaphragm remains in its rest position.
(4) Built-In-Self-Test (BIST) features can be added by using the PPA to deflect the diaphragm and measure its deflection with the PRs.

An analog squaring circuit can be used to produce $V_{out} = (V_{sense})^2 \propto P$

2) Resonant pressure sensors

They make use of a high Q resonant microstructure (i.e. a resonator):



The proof mass is forced to oscillate at its resonant frequency, where:

$$\omega_{res} = 2\pi f_{res} = \sqrt{\frac{k}{m}}$$

Straining the spring structure of the resonant microstructure changes the system spring constant, k, which changes the oscillation frequency.

Therefore: $f_{res} = f(\varepsilon)$

To measure pressure, you fabricate the resonant microstructure (or at least the spring structure of it) on the diaphragm so that the diaphragm's deflection strains the resonator's springs.

Then: $f_{res} = f(P)$.

3) Mass-loading pressure sensor

If the proof mass of a resonator has a relatively large area in its direction of motion, it will push the gas around it as it moves. This process appears to increase the proof mass and thereby lower f_{res}.

Particularly in low pressure environments, this type of resonator can be used to measure ambient pressure.

4) MEMS microphones

Since sound travels through air as pressure waves, a microphone is a pressure sensor.

For a MEMS microphone, which is used in cell phones, a sensitive diaphragm or membrane with a fast response time is desired.

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See the following data on sound level:

Source of sound	Sound pressure	Sound pressure level
	Pascal	**dB SPL**
Theoretical limit for a sound wave at 1 atmosphere environmental pressure	101,325 Pa	194 dB
Krakatoa explosion at 100 miles (160 km) in air	20,000 Pa	180 dB
Simple open-ended thermoacoustic device [5]	12,000 Pa	176 dB
M1 Garand being fired at 1 m	5,000 Pa	168 dB
Jet engine at 30 m	630 Pa	150 dB
Rifle being fired at 1 m	200 Pa	140 dB
Threshold of pain	100 Pa	130 dB
Hearing damagc (duc to short-term exposure)	20 Pa	approx. 120 dB
Jet at 100 m	6 – 200 Pa	110 – 140 dB
Jack hammer at 1 m	2 Pa	approx. 100 dB
Hearing damage (due to long-term exposure)	6×10^{-1} Pa	approx. 85 dB
Major road at 10 m	$2\times10^{-1} – 6\times10^{-1}$ Pa	80 – 90 dB
Passenger car at 10 m	$2\times10^{-2} – 2\times10^{-1}$ Pa	60 – 80 dB
TV (set at home level) at 1 m	2×10^{-2} Pa	approx. 60 dB
Normal talking at 1 m	$2\times10^{-3} – 2\times10^{-2}$ Pa	40 – 60 dB
Very calm room	$2\times10^{-4} – 6\times10^{-4}$ Pa	20 – 30 dB
Leaves rustling, calm breathing	6×10^{-5} Pa	10 dB
Auditory threshold at 2 kHz	2×10^{-5} Pa	0 dB

Decibel Exposure Time Guidelines

Accepted standards for recommended permissible exposure time for continuous time weighted average noise, according to NIOSH and CDC, 2002. For every 3 dBs over 85dB, the permissible exposure time before possible damage can occur is cut in half.

Continuous dB	Permissible Exposure Time
85 db	8 hours
88 dB	4 hours
91 db	2 hours
94 db	1 hour
97 db	30 minutes
100 db	15 minutes
103 db	7.5 minutes
106 dB	3.75 min (< 4min)
109 dB	1.875 min (< 2min)
112 dB	.9375 min (~1 min)
115 dB	.46875 min (~30 sec)

Inertial Sensors

Chapter 8 in the textbook

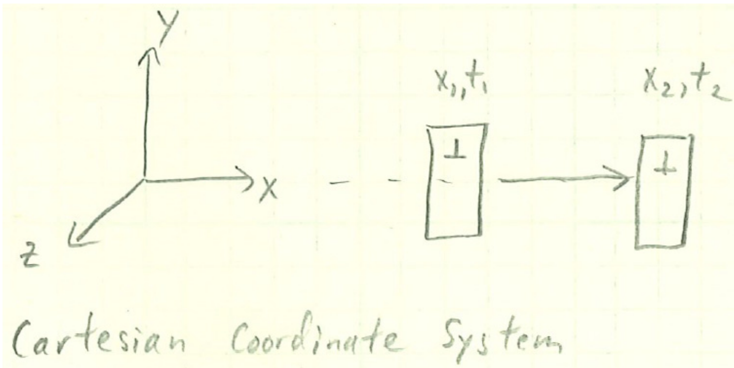
Inertial sensors: accelerometers and gyroscopes:

Accelerometers: measure linear or translational acceleration

Gyroscopes: measure angular or rotational motion: angular rate or angular position

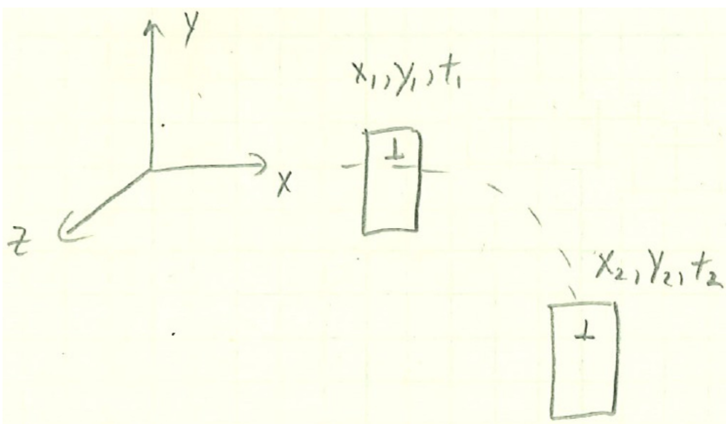
1) 1, 2, or 3 axis inertial measurement

Consider this case:



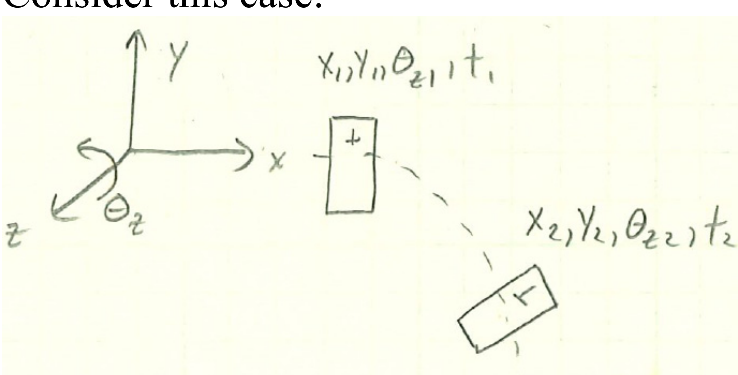
This is 1 axis translational motion with no rotation. 1 accelerometer (for the x-axis) is needed for this case.

Consider this case:



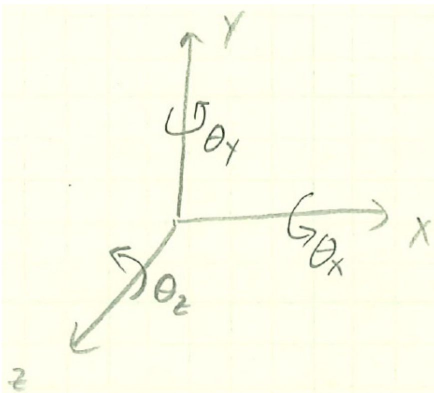
This is 2-axis translational motion with no rotation. 2 orthogonally mounted accelerometers (for the x and y axes) are needed for this case.

Consider this case:



This is 2-axis translational motion with 1-axis rotational motion. 2 orthogonally mounted accelerometers (for the x and y axes) and 1 gyroscope (about the z-axis to measure θ_z or $\dot{\theta}_z$) are needed for this case.

2) Inertial measurement for full 3D motion



3 axis translational motion and 3 axis rotational motion: 6 degrees of freedom (6DOF)

This case requires 3 orthogonally mounted accelerometers (x, y, and z) and 3 orthogonally mounted gyroscopes (x, y, and z).

The complete unit of these 6 sensors is called an Inertial Measurement Unit (IMU), and a system with this kind of motion is a 6DOF system.

3) Sinusoidal acceleration

Consider a single axis sinusoidal acceleration:

$$x = X_o \sin(\omega t)\text{: displacement}$$
$$\dot{x} = \frac{dx}{dt} = X_o \omega \cos(\omega t)\text{: velocity}$$
$$\ddot{x} = \frac{d^2x}{dt^2} = -X_o \omega^2 \sin(\omega t)\text{: acceleration}$$

Therefore, maximum acceleration magnitude = $X_o \omega^2$

For a constant amplitude sinusoidal displacement, the acceleration increases by ω^2 as the frequency increases.

Consider mechanical vibrations: low amplitude, high frequency sinusoidal motions can have very high accelerations:

Example: 1 mm amplitude at 1 kHz:

$$|a_{max}| = X_o\omega^2 = 1\text{x}10^{-3}(2\pi 1000)^2 = 39{,}478.35 \text{ m/s}^2$$

$$1 \text{ G} = 9.8 \text{ m/s}^2\text{: } a_{max} = 4028.4 \text{ G's}$$

4) Mechanical shock

Mechanical shock is a very fast change in acceleration.

Examples: 2 objects colliding, or 1 object falling onto a hard surface

Example: an item falling 1 m onto a hard surface:

$a = G = 9.8 \text{ m/s}^2$
velocity: PE = KE

$$mgh = \frac{1}{2}mv^2$$

Reduces to $v = \sqrt{2gh} = \sqrt{2(9.8)(1)} = 4.427m/s$

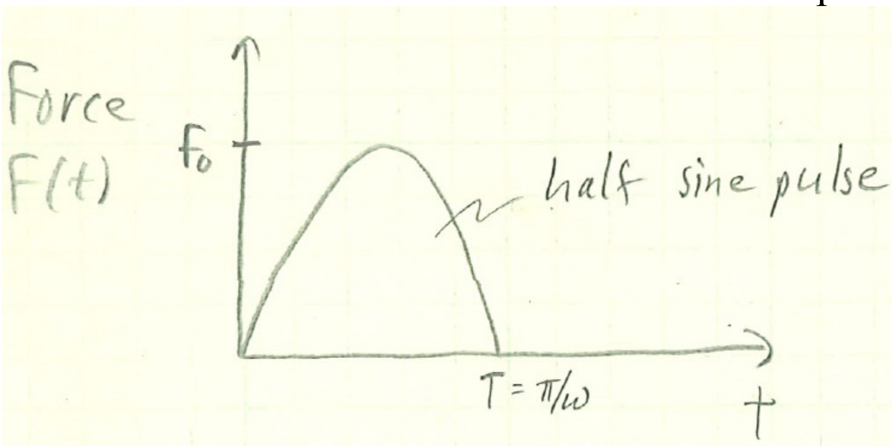
This is the velocity at impact. It takes some amount of time for the object to stop once impact occurs. For example, let t_{stop} = 1 ms here.

Therefore $a = \frac{dv}{dt} \approx \frac{\Delta v}{\Delta t} = \frac{4.427-0}{0-1\times10^{-3}} = -4427m/s^2 \approx -452G's$

Usually, we are just interested in |a| = 452G's: an approximation for |a|.

5) A better model for shock events

A better model for shock events is the half sine pulse:



where the force resulting from the shock event has a half sine pulse versus time profile. The maximum force (acceleration) occurs at T/2. As a result, shock events produce very large accelerations:

Table 8.1 Typical Applications for Micromachined Accelerometers

Application	*Bandwidth*	*Resolution*	*Dynamic Range*
Automotive			
Airbag release	0–0.5 kHz	<500 mG	±100G
Stability and active	0–0.5 kHz	<10 mG	±2G
control systems	dc–1 kHz	<10 mG	100G
Active suspension			
Inertial navigation	0–100 Hz	<5 μG	±1G
Seismic activity			
Shipping of fragile goods	0–1 kHz	<100 mG	±1 kG
Space microgravity measurements	0–10 Hz	<1 μG	±1 G
Medical applications (patient monitoring)	0–100 Hz	<10 mG	±100G
Vibration monitoring	1–100 kHz	<100 mG	±10 kG
Virtual reality (head-mounted displays and data gloves)	0–100 Hz	<1 mG	±10G
Smart ammunition	10 Hz to 100 kHz	1 G	±100 kG

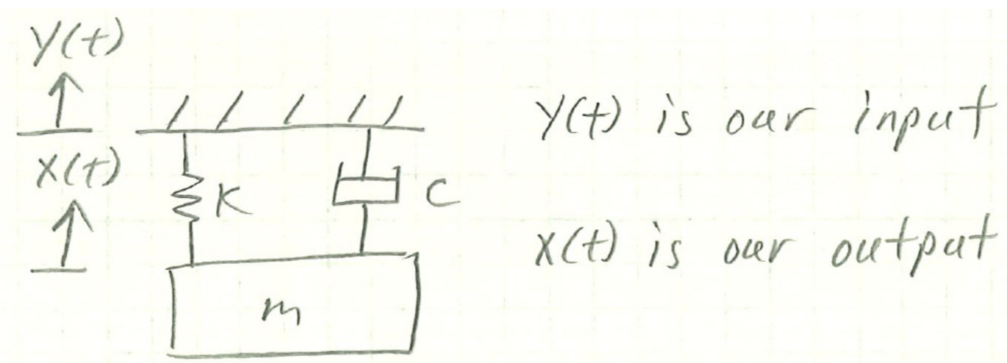
One application for shock sensors (a type of accelerometer) is asset health monitoring, where the shock level that a stored or shipped asset is exposed to is monitored and later examined before the asset is used, to verify that the asset has not been damaged during shipping or storage. Often, either low-power or no-power shock sensors are used for this application.

A no-power shock sensor can be made with MEMS technology using a micromachined SMD with a locking mechanism that gets tripped if the proof mass reaches a certain level of displacement (due to an external shock event), which completes an otherwise open electrical circuit.

Inertial Sensors (Accelerometers)

1) Accelerometer Sensitivity

Consider this model for a MEMS accelerometer:



For a constant acceleration, a, when the accelerometer has reached steady state ($\ddot{x} = \ddot{y}$ and $\dot{x} = \dot{y}$):

$$F_{inertial} = F_{spring}$$

$m\ddot{x} = kd$, where d is the proof mass displacement

$$\therefore d = a\frac{m}{k} = \frac{a}{\omega_n^2}, \text{ since } \omega_n = \sqrt{\frac{k}{m}}$$

Let's define Sensitivity ≡ S, where $S = \frac{m}{k} = \frac{1}{\omega_n^2}$, $[S] = s^2$
Now, d = aS

So, given an accelerometer's sensitivity, S, an acceleration, a, will result in a proof mass displacement of d = aS, once steady state is reached.

S illustrates a tradeoff in accelerometers:

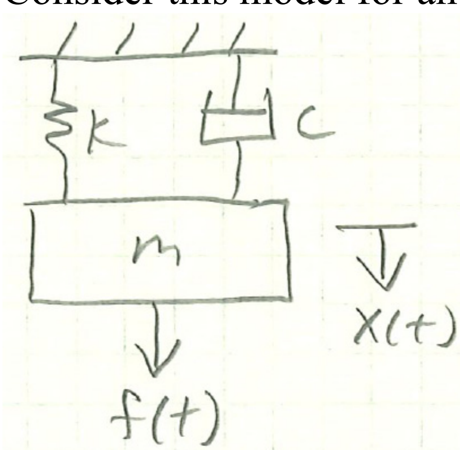
Wide bandwidth sensor: large ω_n → low sensitivity

High sensitivity sensor: large S → low bandwidth

Therefore, it is difficult to make a simple SMD accelerometer for measuring small amplitude, high frequency mechanical vibrations.

2) Damping ratio for an accelerometer

Consider this model for an accelerometer:



f(t) = inertial force = ma(t)

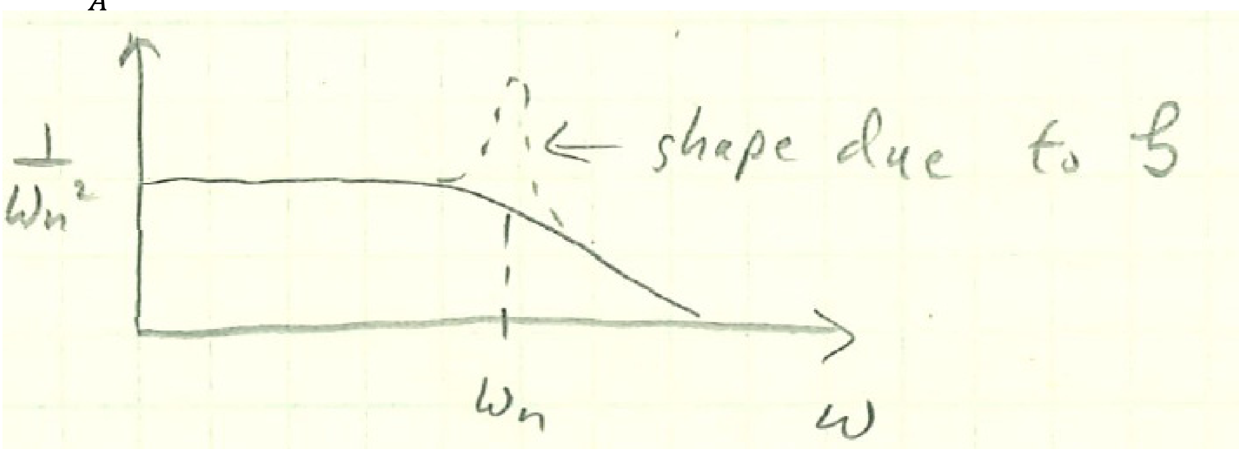
From our system's dynamics: $m\ddot{x} + c\dot{x} + kx = f(t) = ma(t)$

Taking the Laplace transform: $X(s)s^2 + X(s)s\frac{c}{m} + X(s)\frac{k}{m} = A(s)$

Rearranging: $\frac{X}{A}(s) = \frac{1}{s^2+\frac{c}{m}s+\frac{k}{m}} = \frac{1}{s^2+2\zeta\omega_n s+\omega_n^2}$

Consider a plot of $|\frac{X}{A}(j\omega)|$ versus ω:

$|\frac{X}{A}(j\omega)|$



The overshoot in the frequency and time domains is due to the value for ζ. A value of ζ = 1 (critically damped) results in a fast response time with no overshoot (or oscillation) in the time response.

Remember that most MEMS devices are high Q (low ζ). So how do we increase damping to achieve ζ = 1 (Q = 0.5)? One way is to package the MEMS SMD in a hermetically sealed package with an inert gas to add sufficient fluidic damping. However, damping will change with temperature, and all hermetic packages leak over time.