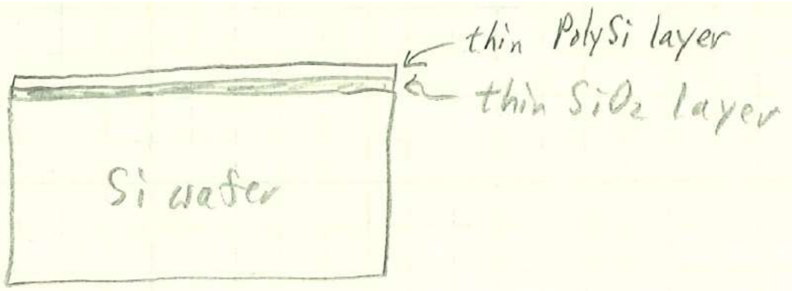
Lecture 10/28/22

Inertial Sensors (MEMS Accelerometer Architectures) Continued

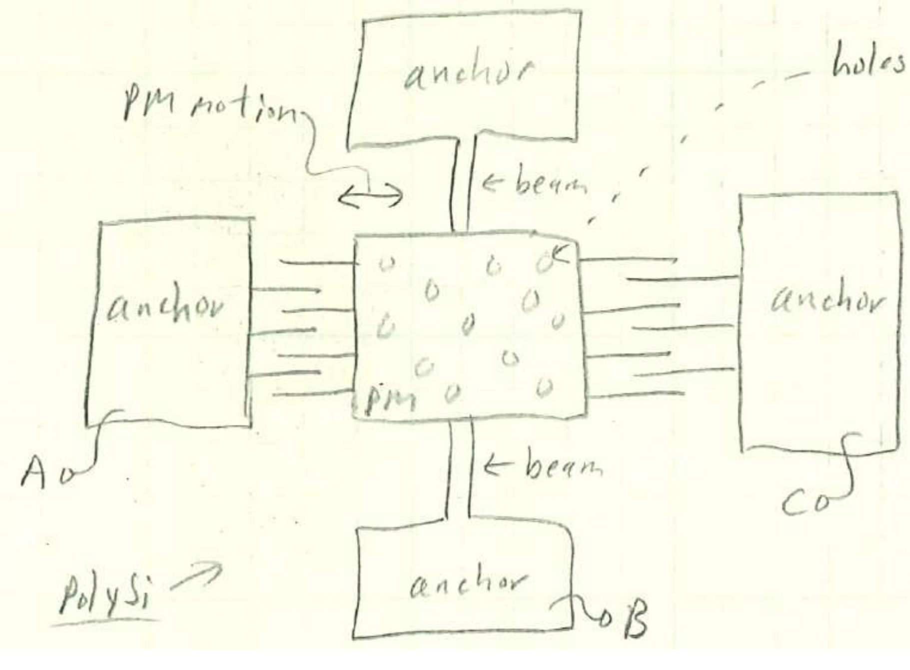
1) Surface micromachined accelerometer designs

We can build the frame, the suspension system, and the proof mass in a deposited layer of polysilicon on top of a deposited layer of silicon dioxide (sacrificial layer). This initial structure is similar to an SOI wafer, except the polysilicon layer is usually much thinner than an SOI wafer's Device Layer.

Start with:



Often, with this fabrication process, the accelerometer is designed so that the proof mass moves laterally, using interdigitated capacitive sensing to measure proof mass motion.



The holes in the proof mass (PM) allow the SiO_2 layer under the proof mass to be etched away to release the proof mass.

There are two complementary IDE capacitors: C_1 between points A and B, and C_2 between points B and C. Together, they realize a differential capacitive sensing structure, suitable for use as an AC voltage divider.

A similar lateral proof mass motion accelerometer could also be fabricated using an SOI wafer.

2) Force feedback accelerometers

All the previously discussed accelerometer architectures have been open loop. Next, we will discuss some closed loop (or force feedback) accelerometer architectures.

a. Limitations of open loop accelerometers

In the open-loop designs, the output signal = f(proof mass displacement). This results in some limitations:

1. For clamped multi-beam suspensions systems designs: the proof mass displacement is a nonlinear function of the applied acceleration, especially for large displacements.

2. Fluidic damping around the suspension system and proof mass adds additional nonlinear effects as the proof mass displaces.

3. With accelerometer sensitivity, S, high sensitivity = low bandwidth.

b. Closed loop accelerometers

A closed loop feedback controller is used to keep the proof mass in the same position over the measurable range of acceleration.

Any proof mass displacement is detected with piezoresistors or capacitively, and reduced to zero using one of more MEMS actuators (PPA, CDA, etc.).
Closed loop accelerometers have several advantages:

1. They avoid clamped beam and fluidic induced nonlinearities.

2. The sensitivity is set by the control loop and not by the mechanical bandwidth.

3. Additional features are possible, such as BIST, and temperature compensation.

4. They can have improved performance, such as a wider acceleration measurement range.

Closed loop accelerometers do have some disadvantages too:

1. Increased complexity (more things that can go wrong).

2. Added cost (more components, lower yield).

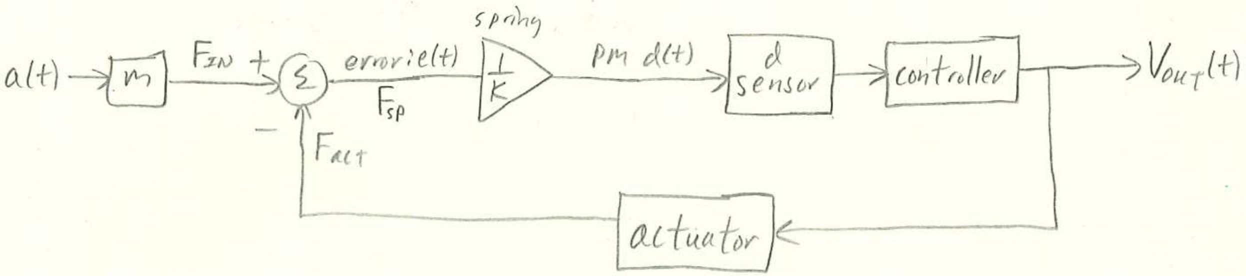
3) Analog closed-loop accelerometers

Similar to force feedback pressure sensors, we will use an actuator to produce a force equal in magnitude but opposite in direction to the inertial force affecting the proof mass. In the force feedback pressure sensor, it was a difference in pressure affecting the diaphragm that the actuator corrected for.

So to make this work, we need several components:

(1) Sensor(s) to detect proof mass motion
(2) Actuator(s) to move the proof mass back to its rest position
(3) A closed loop controller (feedback network) to process the output of the sensor(s) and generate an appropriate drive signal to the actuator(s).

Consider this controller block diagram:



F_{IN} is the inertial force: $F_{IN} = ma$

F_{SP} is the spring force: $F_{SP} = kd$

F_{act} is the force produced by the actuator

F_{sp} is also the error signal, e(t), which the controller attempts to make equal to zero.

The three boxes, d sensor, controller, and actuator, might be as simple as a gain, or as complex as a second order dynamic system.

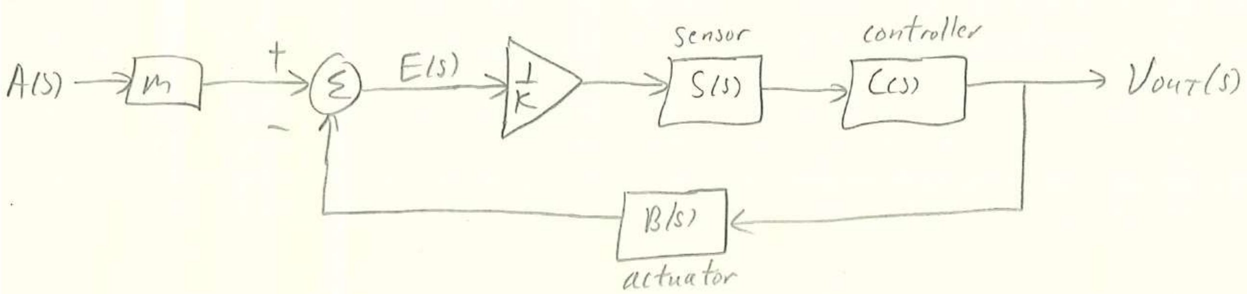
$V_{OUT}(t)$ is the drive signal for the actuator. It also contains all the information about a(t) and is therefore the output signal of the closed loop accelerometer.

Note: there might be an amplifier between V_{OUT} and the actuator. Since this can often be modelled as a simple gain, it could be included in the actuator block.

It is useful to find a transfer function relating $V_{OUT}(t)$ to a(t):

$$\frac{V_{OUT}}{A}(s) = G(s)$$

To do this, we will assume each block has a sufficiently accurate linear model so that we can take its Laplace Transform:



$$E(s) = A(s)m - V_{OUT}(s)B(s) \quad (1)$$

$$V_{OUT}(s) = E(s)\left(\frac{1}{k}\right)S(s)C(s) \quad (2)$$

Rewrite (2): $E(s) = \frac{V_{OUT}(s)k}{S(s)C(s)}$ (3)

Then (1) → (3): $\frac{V_{OUT}(s)k}{S(s)C(s)} = A(s)m - V_{OUT}(s)B(s)$

Or: $V_{OUT}(s)\left(\frac{k}{S(s)C(s)} + B(s)\right) = A(s)m$

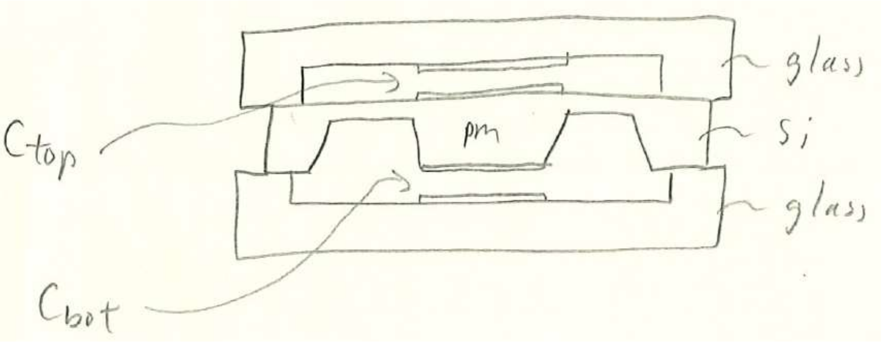
Then: $G(s) = \frac{V_{OUT}}{A}(s) = \frac{m}{\frac{k}{S(s)C(s)}+B(s)}$

Now: $V_{OUT}(s) = A(s)G(s)$

And $V_{OUT}(t) = L^{-1}[A(s)G(s)]$

a. Sensors and actuators

For a vertical motion proof mass architecture, a differential capacitor structure can be used for both sensing *and* actuation:



Let $\bar{V}_1$ be a high voltage, low frequency signal: for PPA actuation.

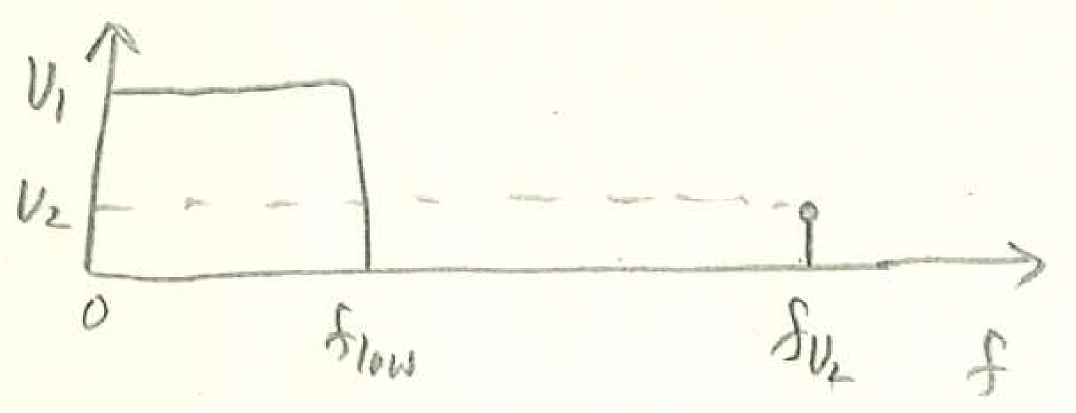
> Note: "high voltage" here could mean 100 V, and low frequency might be 1 kHz.

Let $\bar{V}_2$ be a low voltage, high frequency signal: for d(t) sensing.

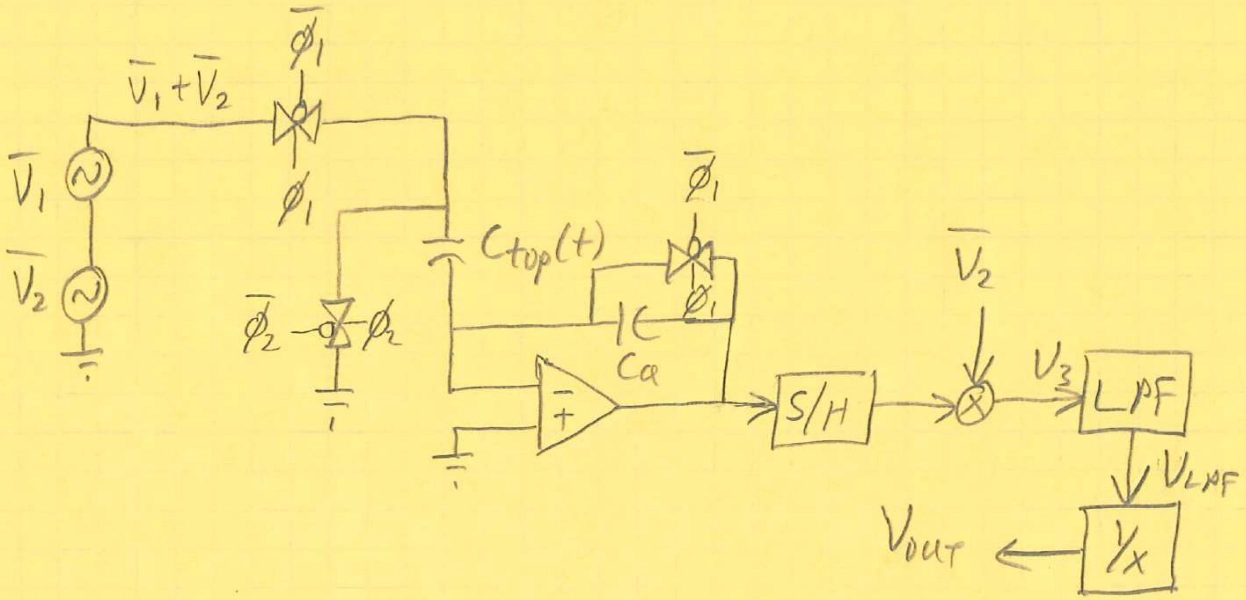
> Note: "low voltage" here could be 1 V, and high frequency might be 50 kHz.

$\bar{V}_1$ is typically over a small bandwidth, while $\bar{V}_2$ is a sinusoid.

$\bar{V}_1$ and $\bar{V}_2$ are added together to realize the following spectral content:



Consider this circuit:



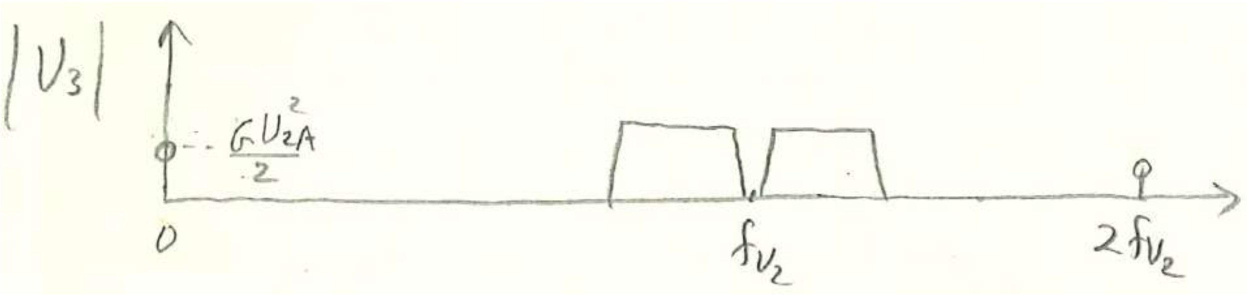
This interface / PPA drive circuit is for one side only. The other side (other PPA) would have a similar circuit. $C_{top}(t)$ and C_a, along with the AC analog switches (little triangles with the dot and the $\emptyset$ and $\bar{\emptyset}$ drive signals) form a charge amplifier with the input signals being ~AC. Actually, $\bar{V}_1$ is really time varying DC, while $\bar{V}_2$ is single frequency AC.

S/H is a sample and hold circuit so that the signal into the mixer is continuous.

The fundamental frequency of $\emptyset$ and $\bar{\emptyset}$ is much higher than the $\bar{V}_2$ frequency, maybe 200 kHz.

So, the input voltage to the mixer is approximately: $\frac{C_{top}(t)(\bar{V}_1+\bar{V}_2)}{C_a}$, with high frequency switching noise from $\emptyset$ and $\overline{\emptyset}$. This voltage is mixed with $\bar{V}_2$ to produce V_3, which is low pass filtered to produce V_{LPF}.

The spectral content of V_3 is approximately (ignoring $\emptyset$ and $\overline{\emptyset}$ components):



The DC term is recovered by the LPF, yielding:

$$V_{LPF}(t) \approx \frac{GV_{2A}^2}{2} = \frac{V_{2A}^2}{2}\frac{C_{top}(t)}{C_a} = \frac{V_{2A}^2}{2}\frac{\varepsilon_o\varepsilon_r A}{C_a d(t)},$$

where $\bar{V}_2 = V_{2A}\cos(\omega t)$.

Notice that $V_{LPF}(t) \propto \frac{1}{d(t)}$, which is not a linear function.

Therefore a 1/x analog circuit is used to produce V_{OUT}, so that:

$$V_{OUT}(t) = \frac{2C_a}{V_{2A}^2\varepsilon_o\varepsilon_r A}d(t) = k_1 d(t)$$

This d(t) sensor and interface circuit is compatible with Laplace transforms.

Since the PPA can only pull, not push, only the PPA needed to pull the proof mass would be actuated at any given time. Either or both PPA capacitors could be used to measure d(t) though.

Since there are a lot of different frequency components being input to the mixer, it should be a high-quality mixer with minimal intermodulation products (spurious frequency components generated when two or more signals pass through a non-linear device) so that these unwanted signals do not become part of the $V_{out}(t)$ signal.

The PPA is clearly not a linear device. In order to use Laplace Transforms, a linear model would be needed for it. This could be obtained with a Taylor series approximation for it. However, keep in mind that our linear control system model only approximates the actual nonlinear system…

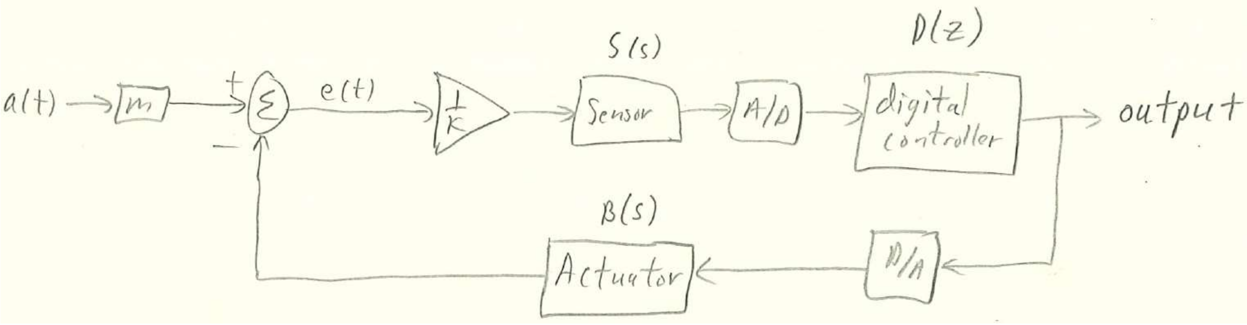
A similar approach would be taken with a lateral closed-loop accelerometer architecture.

4) Digital closed loop accelerometers

Portions of the analog feedback controller can be replaced with a digital controller, enabling some additional features.

a. Traditional digital implementation

Consider the block diagram of the controller shown below:



The digital controller can be implemented on a microcontroller in software or in programmable logic circuitry (FPGA, PLA, etc.). An advantage of this implementation is that the digital controller can easily be modified by changing the programming.

A/D and D/A converters are used to connect the digital controller to the rest of the analog system.

Also, instead of just Laplace transforms being used, z transforms are used in modeling the system.

b. Binary digital controller

This implementation uses a sigma-delta (ΣΔ) controller:

> Both PPA's are driven with high frequency voltage pulses, where $\omega_p >> \omega_n$. The SMD responds to the DC average of the force produced by the PPAs.
>
> At zero applied acceleration, both opposing PPA's receive the same number of voltage pulses per second. So, both PPA's produce the same force and the proof mass remains in its rest location.
>
> When an acceleration is applied, the proof mass displaces and the displacement is sensed. In response, the PPA whose electrodes are now closer together begins to receive less voltage pulses per second than the other PPA. At this point, the opposing PPA applies a net force on the proof mass to move it back to its rest location.
>
> This controller uses "pulse density modulation," which also contains the information about the acceleration. However, an internal signal that controls the generation of the pulses, rather than the pulses themselves, would be used for the output signal from the accelerometer.