Lecture 10/10/22

Introduction to MEMS Actuators

Why cover actuators in a sensors class?

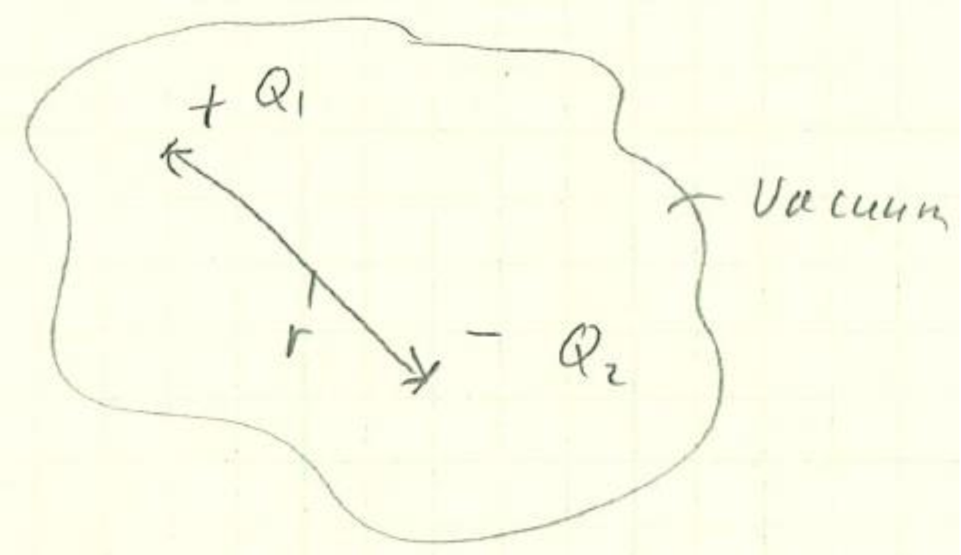
Answer: some of the most advanced sensors use actuators for tuning and/or operation.

Just as a sensor is an input transducer, an actuator is an output transducer. An actuator converts an electrical signal into a nonelectrical quantity, such as force.

There are several types of MEMS actuators, but electrostatic actuators are probably the most common.

1. Electrostatic Actuators: the Parallel Plate Actuator

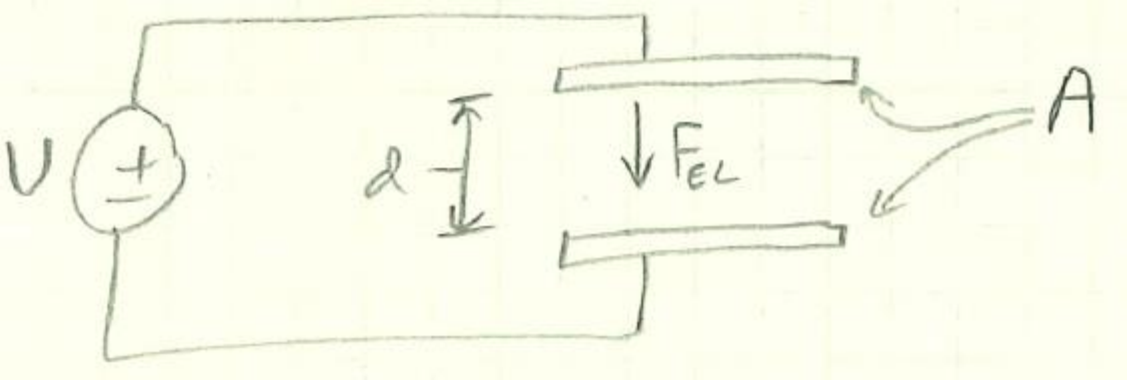
Consider two opposite charges, Q_1 and Q_2, in a vacuum separated by a distance r:



An attractive electrostatic force exists between Q_1 and Q_2 that attempts to bring the two charges into contact. Let that force be F_{EL}:

$|F_{EL}| = \frac{kQ_1Q_2}{r^2}$, where $k = \frac{1}{4\pi\varepsilon_o}$

This, however, is not particularly useful. So, consider a parallel plate capacitor:



where A is the electrode surface area, d is the electrode separation distance, and V is an applied DC voltage.

It has a capacitance: $C = \frac{\varepsilon_o\varepsilon_r A}{d}$, with charge stored in it of Q = CV.

The top electrode has a positive charge and the bottom electrode has a negative charge. Therefore, an attractive electrostatic force, F_{EL}, exists between the electrodes that attempts to pull them into contact:

$$|F_{EL}| = \frac{\varepsilon_o\varepsilon_r A V^2}{2d^2} = \frac{CV^2}{2d}$$

Observe that F_{EL} is proportional to C and to V^2, and inversely proportional to d^2: force can be increased by increasing capacitance or voltage, or by reducing the electrode separation distance.

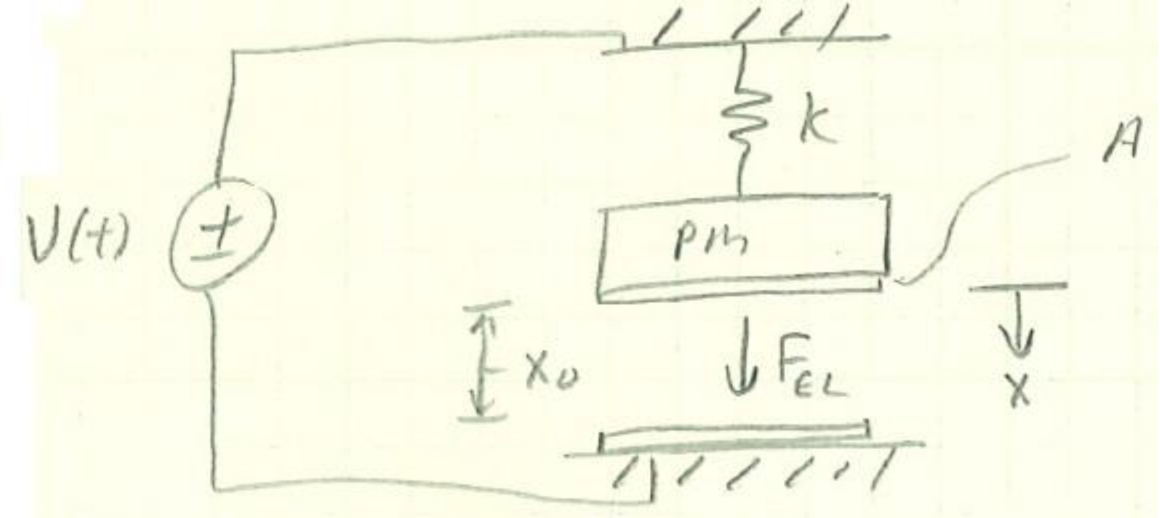
Also observe that since F_{EL} is proportional to V^2, the electrostatic actuator is a <u>square law device</u> with a couple of interesting characteristics:

1) Positive or negative voltage makes no difference
2) For an AC voltage, it responds to the RMS value when $\omega \gg \omega_n$.

This type of actuator is called a <u>Parallel Plate Actuator</u> or PPA for short.

<u>Note</u>: consider another square law device, the n-channel MOSFET in saturation: $i_D = 0.5k'_n(\frac{W}{L})(v_{GS} - V_{TN})^2$.

Consider a more realistic application in MEMS:



Here, the PPA has been integrated with a MEMS SMD where the proof mass is a movable electrode and the frame is a fixed electrode.

When x(t) = 0, x_o is the PPA rest distance.

Therefore: $F_{EL} = \frac{\varepsilon_o \varepsilon_r A (V(t))^2}{2(x_o - x(t))^2}$

And the system differential equation becomes:

$$m\ddot{x} + c\dot{x} + kx = F_{EL} = \frac{\varepsilon_o \varepsilon_r A V^2}{2(x_o - x)^2}$$

We know that the SMD is a mechanical LPF and does not respond to frequencies >> ω_n.

So, let $V(t) = V_A \cos(\omega t)$.

$\therefore (V(t))^2 = V_A^2[0.5 + 0.5\cos(2\omega t)]$.

If ω >> ω_n, then the SMD primarily just responds to a DC force from the $0.5V_A^2$ term.

Notice that for this case, and equivalent DC input voltage is: $V_{EQ} = \frac{V_A}{\sqrt{2}}$, which is the RMS value for V(t).

If $\omega = 0.5\omega_n$, then the SMD experiences the DC force and a force at ω_n.

Often, MEMS PPAs might require a relatively large voltage to achieve a sufficiently high F_{EL}, such as 100 V. How do you generate 100 V with modern devices like op amps?

1) You can design a circuit to increase a DC voltage to 100 V with diodes or transistors (possibly an on-chip solution).

2) You could possibly use a transformer with a reasonably low input AC voltage, such as 10 V, to easily step it up to the required voltage (likely not an on-chip solution).

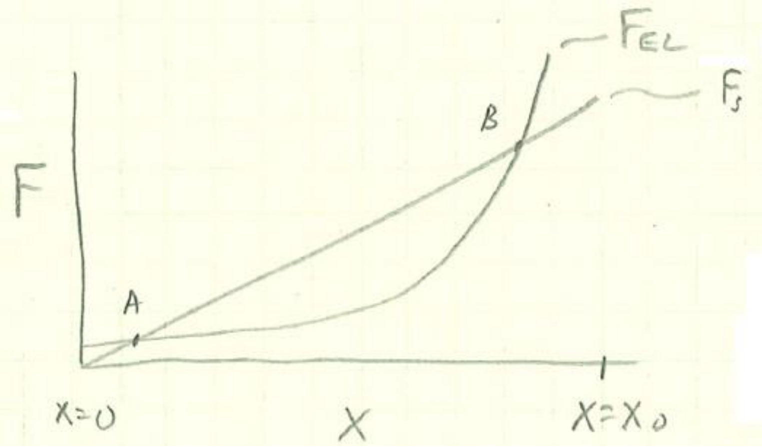
Back to the system differential equation: $m\ddot{x} + c\dot{x} + kx = \frac{\varepsilon_o \varepsilon_r A V^2}{2(x_o - x)^2}$.

Let's consider the case where V(t) is a DC voltage and we have reached steady state. At this point: $\dot{x} = \ddot{x} = 0$, and our system differential equation reduces to:

$kx = \frac{\varepsilon_o \varepsilon_r A V^2}{2(x_o - x)^2}$. To investigate a solution, let's graph both sides, where:

$F_s = kx$ and $F_{EL} = \frac{\varepsilon_o \varepsilon_r A V^2}{2(x_o - x)^2}$, and look for where the traces intersect (solutions) when V > 0 and small.

Also, $0 \leq x \leq x_o$.



Notice that there are two mathematical solutions, A and B, which are called equilibrium points.

A is a stable equilibrium point: if the proof mass is moved a small distance away from the x value corresponding to A and released, it will move back to that location.

B is an unstable equilibrium point: if the proof mass is moved a small distance away from the x value corresponding to B and released, it will either move to the x location for A (moved to the left of B), or else the movable electrode will slam into the fixed electrode (at $x = x_o$).

Now slowly increase V → The F_{EL} trace moves up, resulting in A and B moving closer together.

At an input voltage called the <u>Pull-in Voltage</u>, V_{PI}, A and B converge into one unstable equilibrium point:

$$V_{PI} = \sqrt{\frac{8kx_o^3}{27A\varepsilon_o\varepsilon_r}} \rightarrow \text{ corresponds to } x = \frac{1}{3}x_o.$$

For $V > V_{PI}$, no equilibrium point exists and the two electrodes snap into contact, a condition called <u>snap-in</u> or <u>pull-in</u>.

Therefore, for an open loop PPA where proof mass displacement is controlled by adjusting V, where $|V| < V_{PI}$, the PPA has a stable range of motion of $0 \leq x < \frac{1}{3}x_o$. Notice it is NOT stable at $x = \frac{1}{3}x_o$!

However, when $V < V_{PI}$, if an external disturbance or a transient from too quickly changing V causes the $x > x|_B$, the unstable condition will be reached and the two electrodes will snap into contact.

Typically, V_{PI} is between 10s V and 1000s of V.

Several closed-loop controllers have been developed to extend the PPA stable range of operation, but that is beyond the scope of this course.

Since a PPA is a capacitor, driving it with a DC voltage uses very little power. However, driving it with an AC voltage can use considerable power.

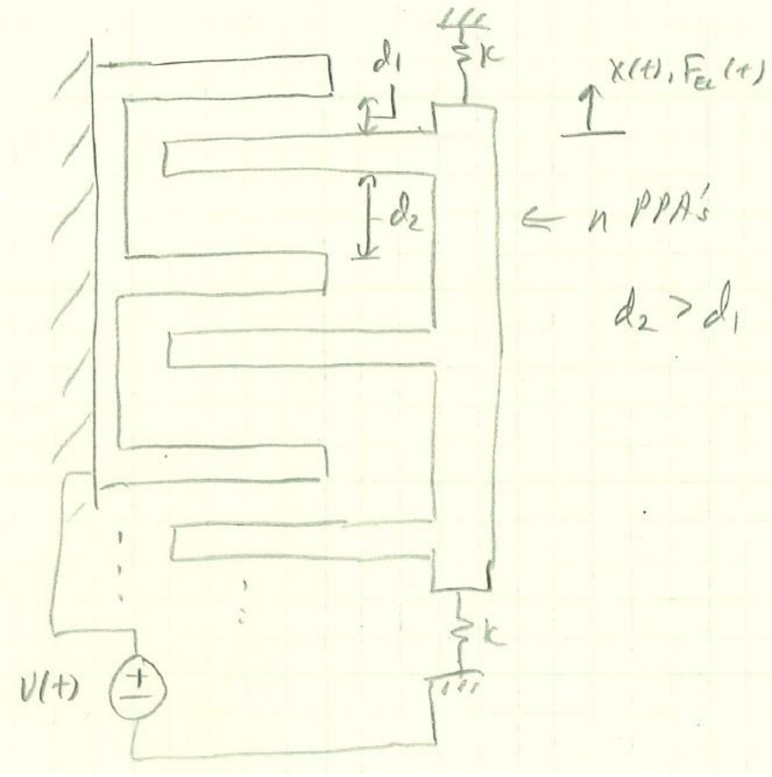
Adding a 1 kΩ to 10 kΩ resistor in series with the PPA and the power supply driving it (often an amplifier) can protect the PPA and the power supply in case the PPA electrodes short from a pull-in condition.

However, adding the series resistor results in a small proof mass oscillation due to the nonlinear system differential equation. The amplitude of oscillation increases as R increases, but is very small for R < 100 kΩ. With a really large R (typically R > 10 MΩ), this can be used to produce a sizable proof mass oscillation and a distorted AC voltage across the PPA. Notice that a DC voltage, a resistor, and the PPA are all that are needed to produce an oscillator, due to the inherent nonlinearity of the system.

Lecture 10/10/22

2. Electrostatic Gap Closing Actuator (GCA)

Consider n PPA's configured in parallel:



If we ignore fringing effects, then F_{EL} can be approximated by:

$$F_{EL} \cong \frac{n\varepsilon_o \varepsilon_r A V^2}{2}\left[\frac{1}{(d_1 - x)^2} - \frac{1}{(d_2 + x)^2}\right]$$

Since $d_2 > d_1$, there is a net force that attempts to move the proof mass to decrease d_1 and to increase d_2.

If this device was implemented in the Device Layer of an SOI wafer, then the motion would be lateral: in-plane with the surface of the wafer (die).

If $d_2 >> d_1$, then the stable (open loop voltage controllable) range of motion is almost: $0 \le x < \frac{1}{3} d_1$, like a PPA.

However, as d_2 approaches d_1 (but $d_2 > d_1$), the stable range of motion decreases, and snap-in occurs at a very low voltage compared to a PPA. Therefore, this actuator is called a Gap Closing Actuator (GCA).

Usually, GCA's are used as binary or 2-state actuators: off and snapped. A mechanical stop is added to prevent actual electrode contact from occurring once snap-in occurs, so that the electrodes do not electrically short.