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<u>Introduction to MEMS Actuators</u>

Why cover actuators in a sensors class?

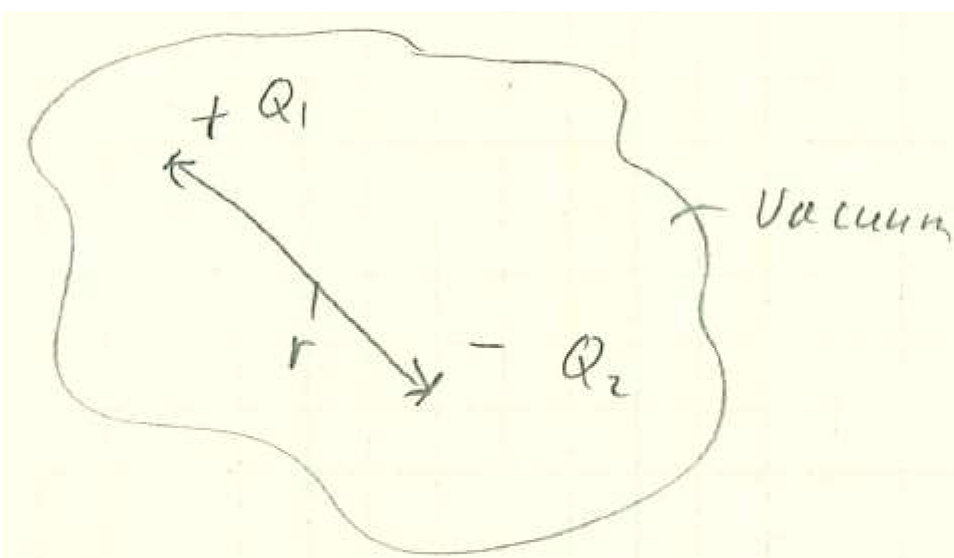
Answer: some of the most advanced sensors use actuators for tuning and/or operation.

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}:

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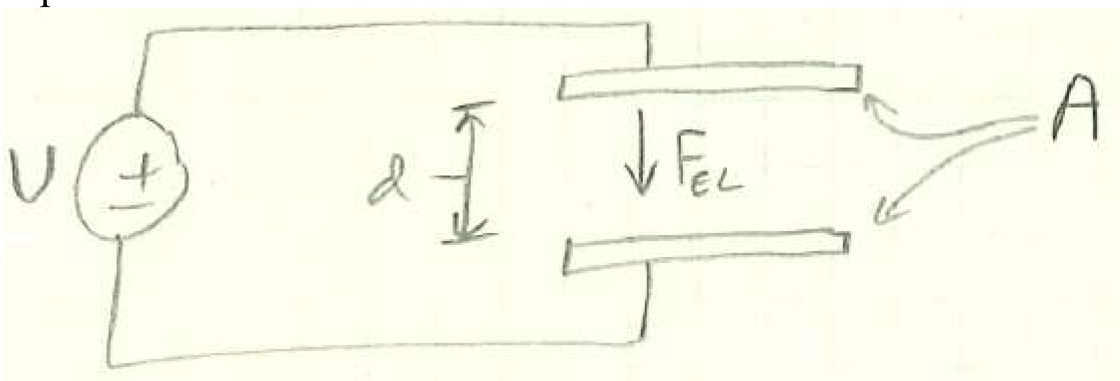
$|F_{EL}| = \frac{kQ_1Q_2}{r^2}$, where $k = \frac{1}{4\pi\varepsilon_o}$

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:

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

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.

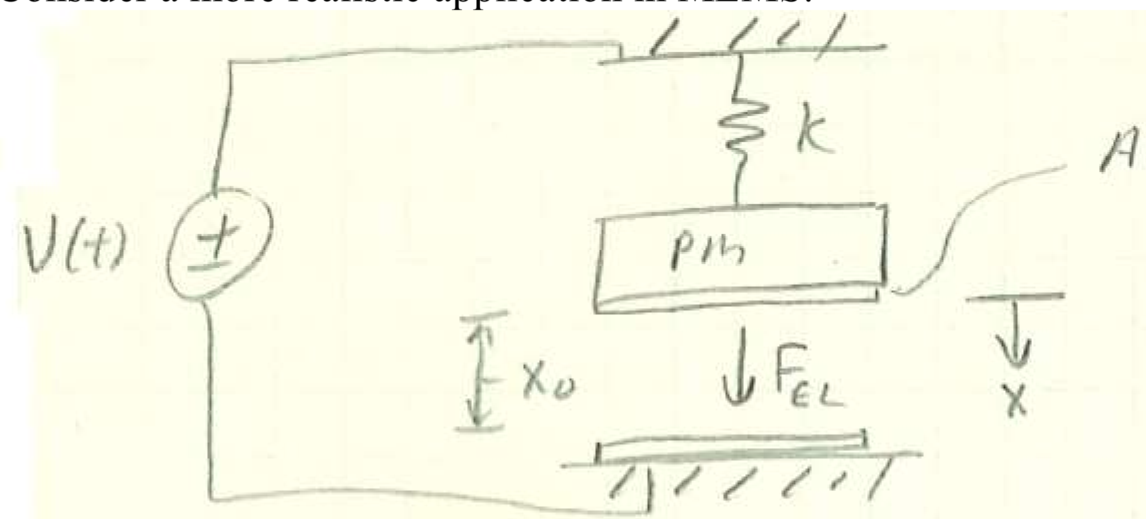
Also observe that since F_{EL} is proportional to V^2, the electrostatic actuator is a <u>square law device</u> with a couple of interesting characteristics:

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

This type of actuator is called a Parallel Plate Actuator or PPA for short.

Note: 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 $\omega >> \omega_n$, 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).

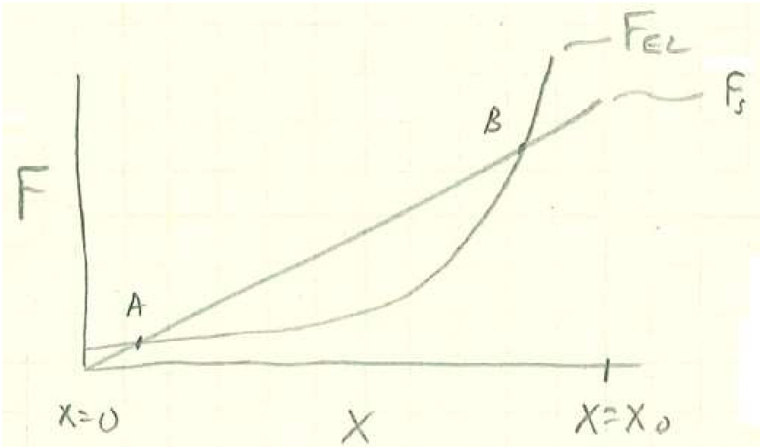
Back to the system differential equation: $m\ddot{x} + c\dot{x} + kx = \frac{\varepsilon_o \varepsilon_r A V^2}{2(x_o - x)^2}$.

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 Pull-in Voltage, 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 snap-in or pull-in.

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.

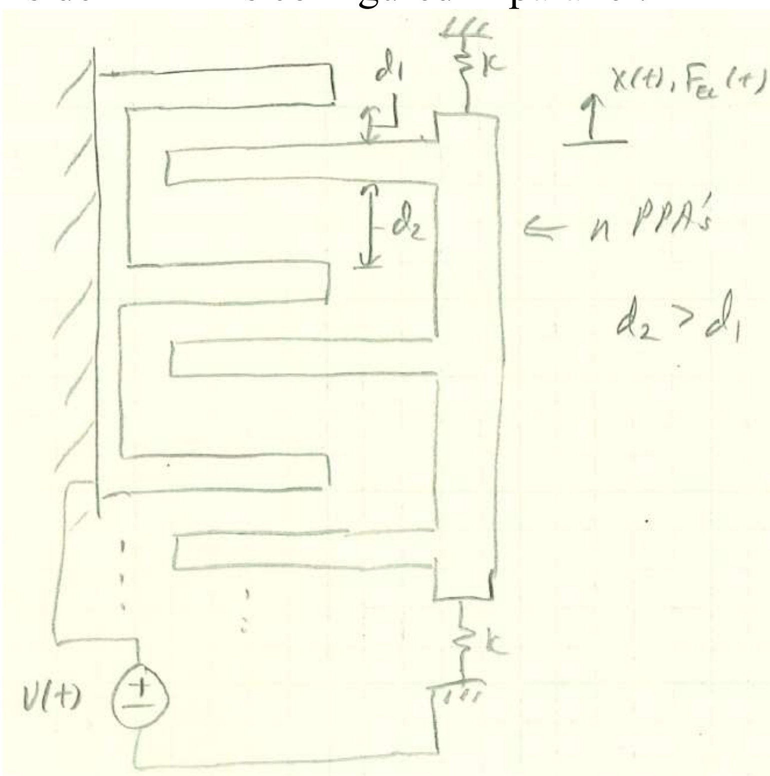
Since a PPA is a capacitor, driving it with a DC voltage uses very little power. However, driving it with an AC voltage can use considerable power.

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.

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).

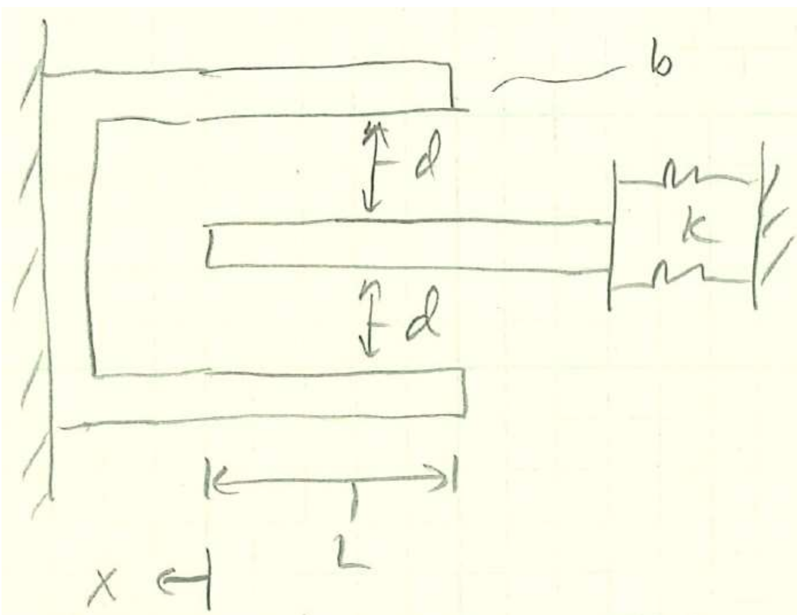
If $d_2 >> d_1$, then the stable (open loop voltage controllable) range of motion is almost: $0 \le x < \frac{1}{3}d_1$, like a PPA.

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.

3) Electrostatic Comb Drive Actuator (CDA)

Consider this MEMS structure:



"b" is the tooth height into the page.

Motion is constrained by the suspension system to the x-direction, so that the movable tooth on the right moves deeper into or out from between the two fixed teeth on the left.

Applying a voltage, V, between the left and right teeth results in an electrostatic force that attempts to pull the movable tooth deeper between the two fixed teeth, which increases the capacitance between the teeth. Note: **Electrostatic force always attempts to increase capacitance**.

Here, the motion of the movable tooth is tangential in regard to the two fixed teeth: the movable tooth stays exactly between the two fixed teeth as it moves to the left, but overlap electrode area increases.
Define the resulting net tangential electrostatic force at F_T:

$$F_T = \frac{\varepsilon_o \varepsilon_r b V^2}{d}$$

Observe that F_T is proportional to V^2, but it is NOT a function of displacement! This removes one nonlinearity from the system.

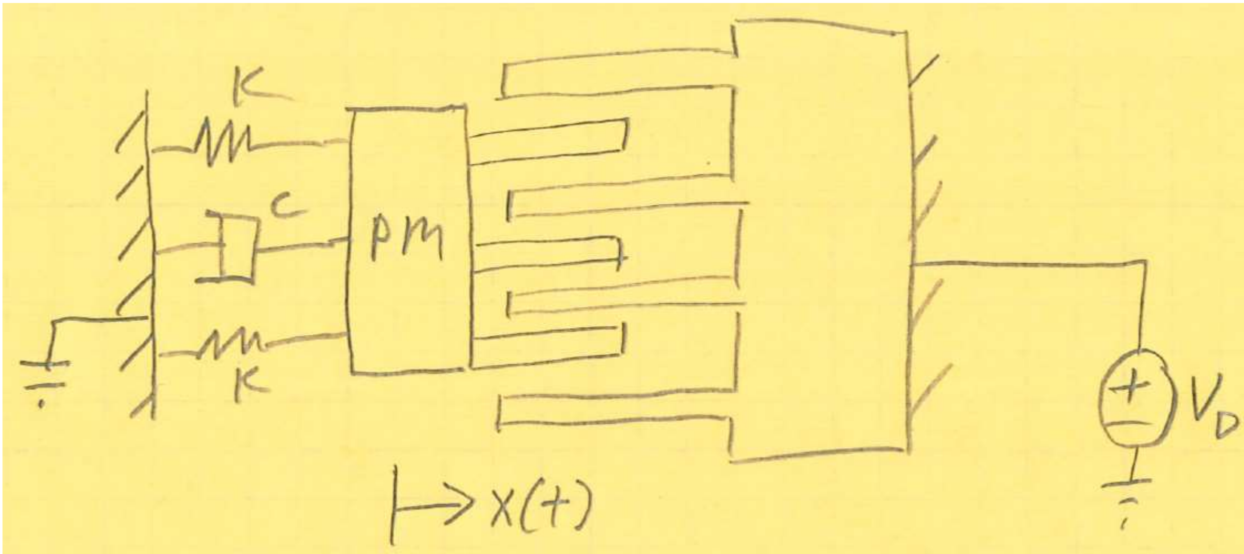
Now, let's connect n of the electrode units above so that all the movable teeth are electrically connected and move together into the fixed teeth, which are also electrically connected. The structure appears as two interdigitated combs. Hence, this actuator is called a <u>Comb Drive Actuator</u> or CDA.

The resulting electrostatic force is:

$$F_{EL} = \frac{n \beta b \varepsilon_o \varepsilon_r V^2}{d}$$

where n is the number of movable teeth, and β is a fringing effect correction factor ($\beta \geq 1$).

Consider this CDA implementation with a SMD:

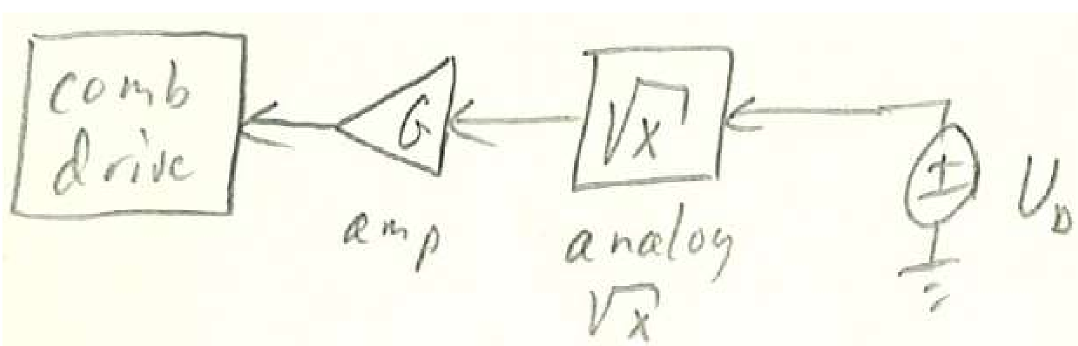


NOTE: k is the system spring constant and V(t) = V_D. Our system differential equation becomes:

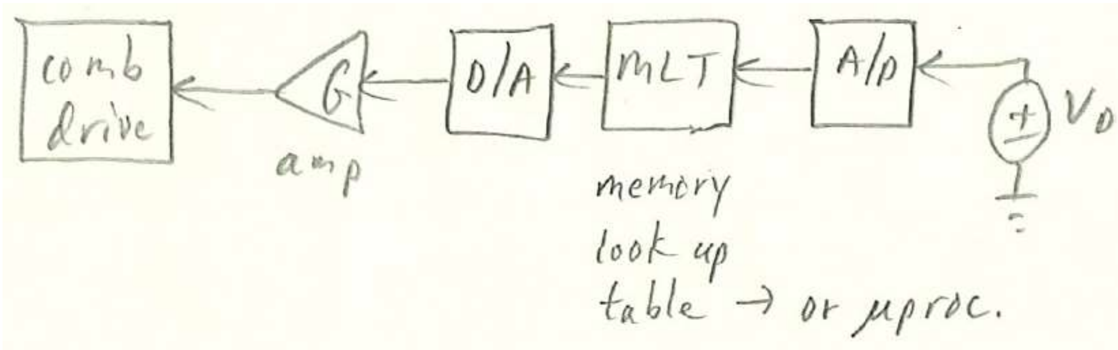
$$m\ddot{x} + c\dot{x} + kx = \frac{n\beta b\varepsilon_o\varepsilon_r V^2}{d}$$

If V is constant, the system is linear. However, it would be nice to remove the nonlinearity of V^2 for any V(t) input. There are some ways to do that:

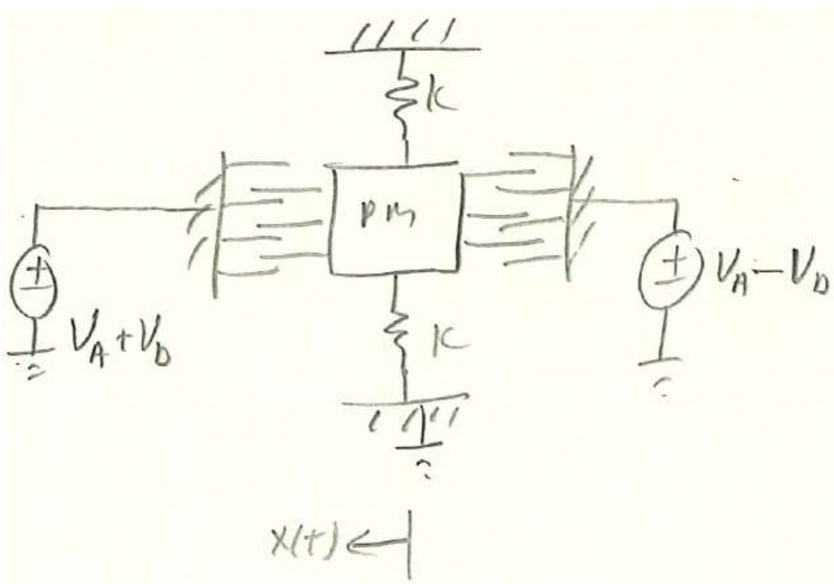
1) Analog square root function



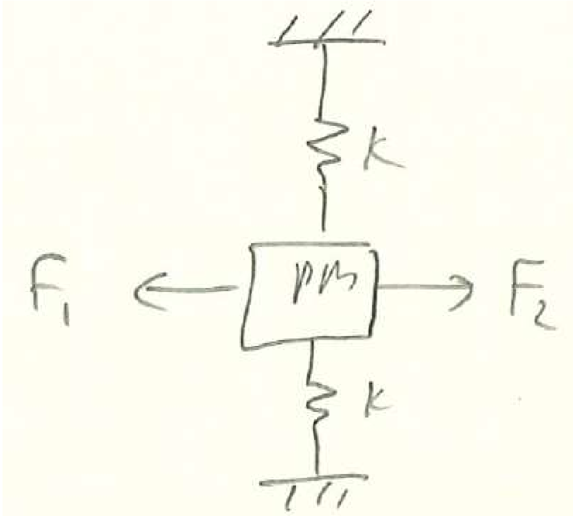
2) Digital square root function



3) Multiple power supplies



The proof mass has two opposing CDA's attached to it. Let's model it as:



Equations for the two opposing forces:

$$F_1 = \frac{n\beta b\varepsilon_o\varepsilon_r}{d}(V_A + V_D)^2 = \frac{n\beta b\varepsilon_o\varepsilon_r}{d}(V_A^2 + 2V_AV_D + V_D^2)$$

$$F_2 = \frac{n\beta b\varepsilon_o\varepsilon_r}{d}(V_A - V_D)^2 = \frac{n\beta b\varepsilon_o\varepsilon_r}{d}(V_A^2 - 2V_AV_D + V_D^2)$$

The net force on the PM is F_N:

$$F_N = F_1 - F_2 = \frac{n\beta b\varepsilon_o\varepsilon_r}{d}(4V_AV_D) = KV$$

where V = V(t) = V_D.

Also, V_A is a constant voltage, and K is a constant: $K = \frac{4n\beta b\varepsilon_o\varepsilon_r V_A}{d}$.

Now, the net electrostatic force on the PM is a linear function of V, and the system in linear:

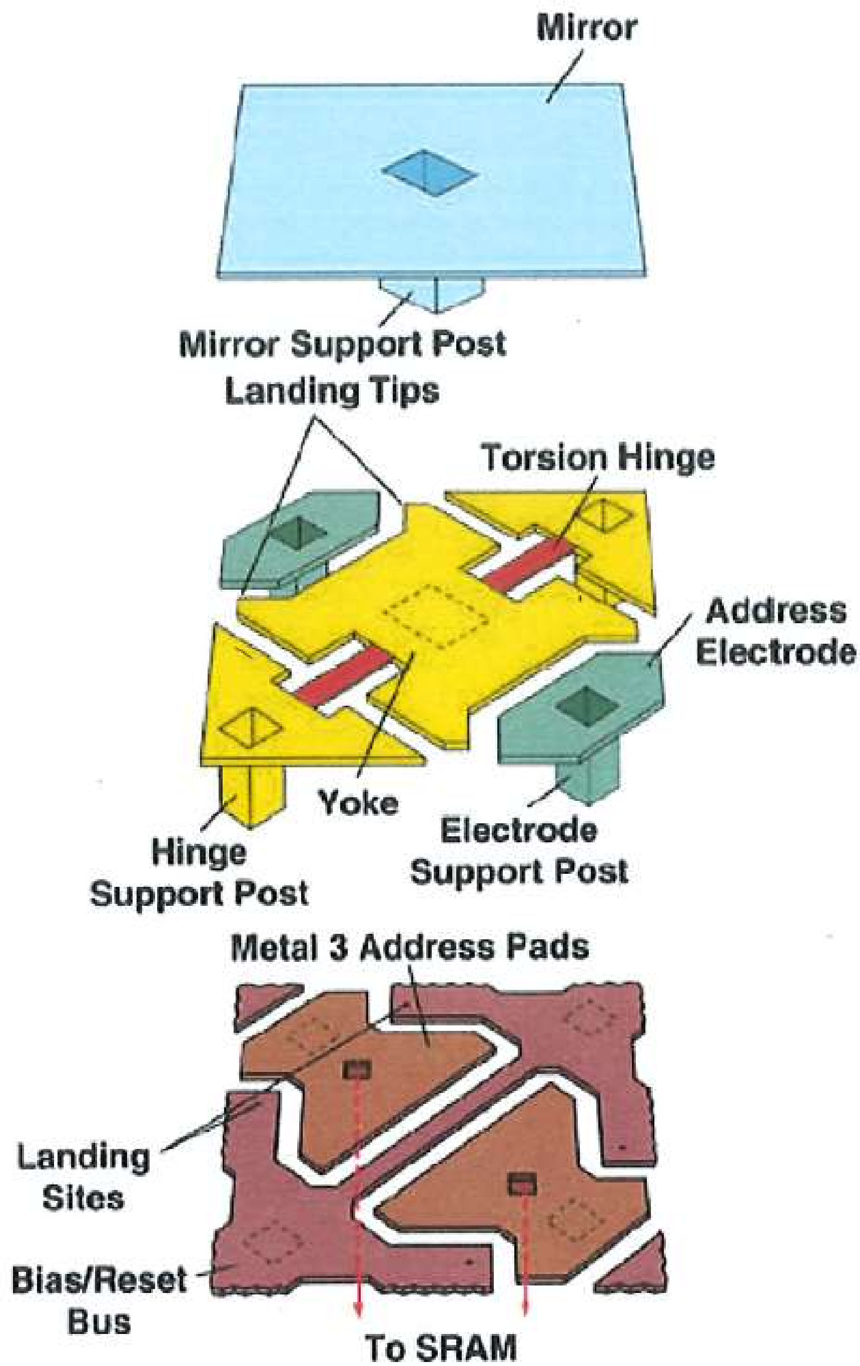
$$m\ddot{x} + c\dot{x} + kx = KV$$

This solution does come with a penalty: a higher voltage is required to achieve the same force on the PM because of the voltage terms that cancel.

We have three electrostatic actuators: PPA, GCA, and CDA.

Some example electrostatic actuators are shown below.

Drawing of the TI DLP



Photographs of Comb Drive Actuators (Courtesy Sandia National Labs)