2. Consider \( n \) PPA's configured in parallel

\[
F_{el} = \frac{n \varepsilon_0 \varepsilon_r AV^2}{2} \left[ \frac{1}{(d_1-x)^2} - \frac{1}{(d_2+x)^2} \right]
\]

ignoring fringing

For \( d_2 > d_1 \rightarrow \) stable range of motion \( \approx \frac{1}{3} d_1 \)

As \( d_2 \) approaches \( d_1 \): the stable range of motion decreases

Called a Gap Closing Actuator (GCA)

Often GCA's are used as binary or 2-state actuators: off and snapped (a mech stop prevents electrode contact) and shorting.
3. Consider this structure

\[ b: \text{tooth height into the page} \]

\[ \text{motion is constrained to } x \text{ direction} \]

Electrostatic actuators: \( F_{el} \) tries to increase capacitance.

- Motion is tangential: \( \rightarrow \) Increases overlap electrode area

\[ F_T = \frac{\varepsilon_0 \varepsilon_R b V^2}{d} \rightarrow F_T \propto V^2, \quad F_T \neq f(L) \]

n tangential actuators can be configured in parallel, as two comb-like structures \( \rightarrow \) called a Comb Drive Actuator (CDA)

\[ F_{el} = n \beta b \varepsilon_0 \varepsilon_r V^2 \]

\( n \) = \# movable teeth

\( \beta = \) fringing effect correction factor
0 Comb drive actuator continued

\[ F = \pi B_0 e \tau b V_0^2 \Rightarrow F \propto V_0^2 \rightarrow \text{nonlinear} \]

How to linearize \( F \)?

1 Analog square root function

2 Digital square root function

3 Consider this
\[ F_1 = \frac{n_0 b E_0 \varepsilon_{er} (V_a + V_b)^2}{d} = \frac{n_0 b E_0 \varepsilon_{er}}{d} (V_a^2 + 2V_a V_b + V_b^2) \]
\[ F_2 = \frac{n_0 b E_0 \varepsilon_{er} (V_a - V_b)^2}{d} = \frac{n_0 b E_0 \varepsilon_{er}}{d} (V_a^2 - 2V_a V_b + V_b^2) \]

net force on \( \tau \) = \( F_1 - F_2 \)
\[
= \frac{n_0 b E_0 \varepsilon_{er}}{d} (4V_a V_b)
\]

where \( V_a \) is a constant voltage

now \( F_1 \propto V_b \)

penalty \( \Rightarrow \) higher voltage required to achieve same force as when \( F_2 = 0 \)