Parallel Plate Electrostatic Actuation for High-Resolution Deformable Mirrors

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CfAO TMT MEMS DM WS

Outline

Electrostatic MEMS DM architectures

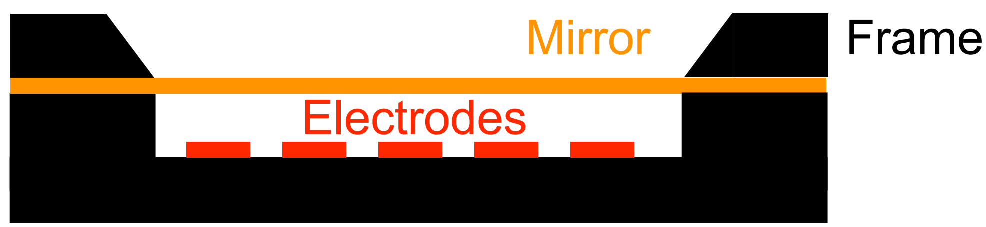
Electrostatics and mechanics of actuators

Scaling rules and real-world limits

Case study: Extending stroke

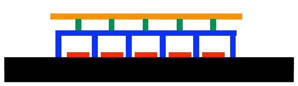
Electrostatic MEMS DM architectures

Edge-supported membranes

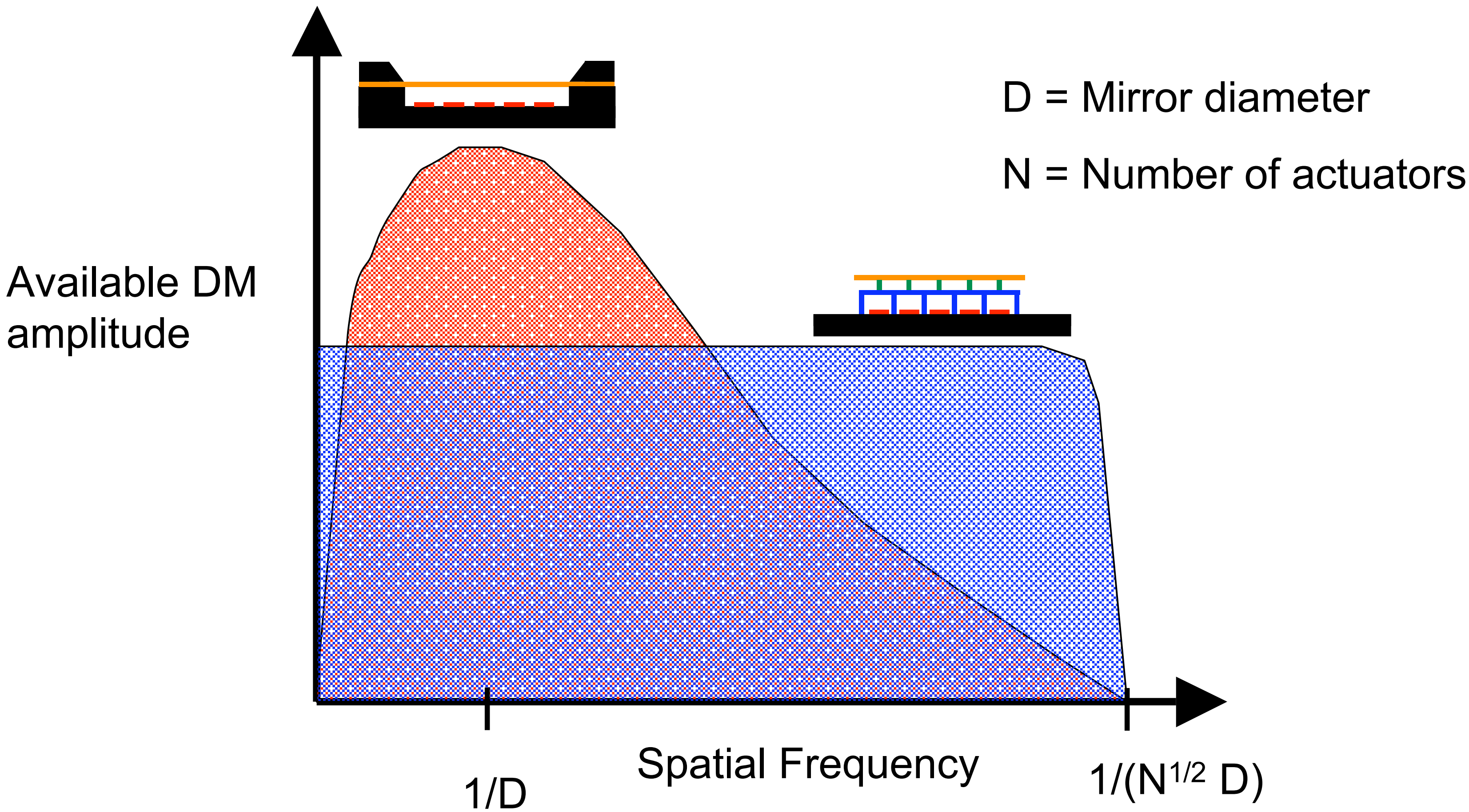


Post-supported membranes

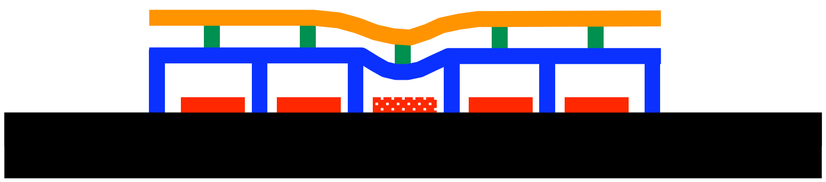
Advantages and disadvantages

	+	-
	Economical to develop Large stroke @ low order Customizable	Sensitive to sound Frame-induced warp Low stroke @ high order
	Scalable to many actuators High natural frequency Batch producible	Expensive to develop Fabrication induced stress Limited coating options

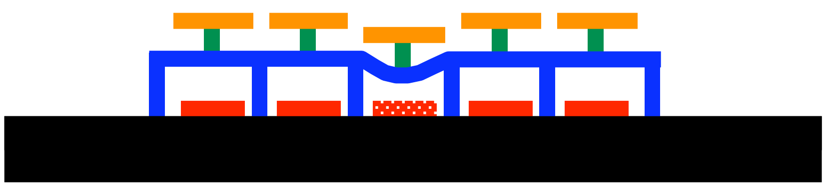
Controllable spatial frequency comparison



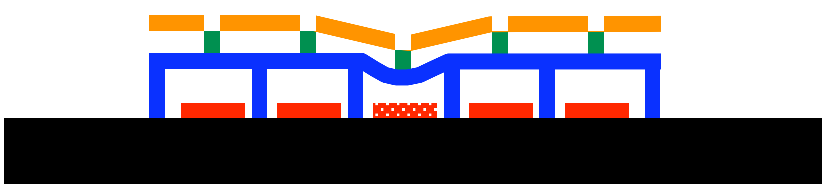
Boston University & Boston Micromachines Corporation Design



Continuous



Piston



Tip-Tilt

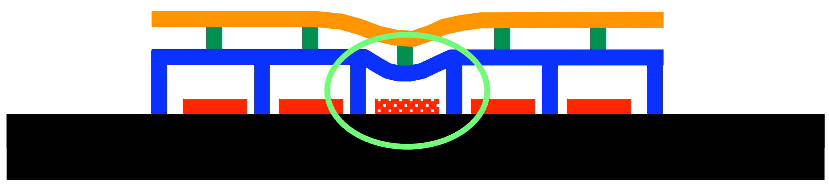
To get the same AO fitting error (Kolmogorov turbulence)

$N_{piston}/N_{continuous} = 6.2$

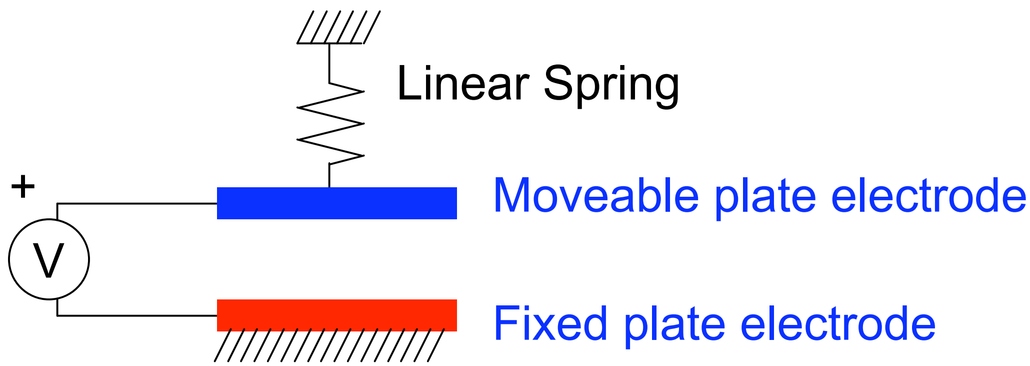
$N_{tip\text{-}tilt}/N_{continuous} = 1.8$

(C. Max, CfAO website)

Electrostatic actuators

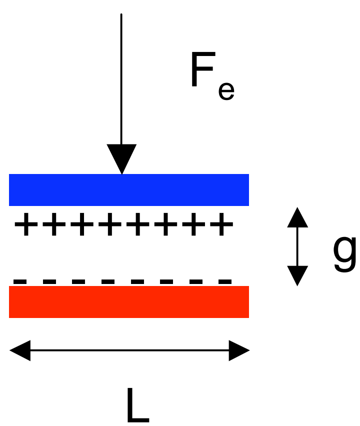


Simplified actuator model:



Electrostatic attraction force

Parallel plates form a capacitor



$$C = \frac{\varepsilon_o \varepsilon_r L w}{g}$$

ε_o = permittivity of free space ($8.8e^{-12}$ F/m)

ε_r = medium dielectric constant (1 for air)

L = plate length (m)

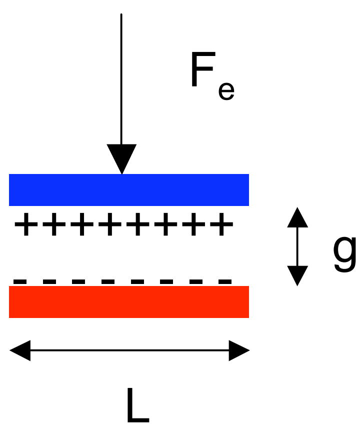
w = plate width (m)

g = gap (m)

Electrostatic attraction force

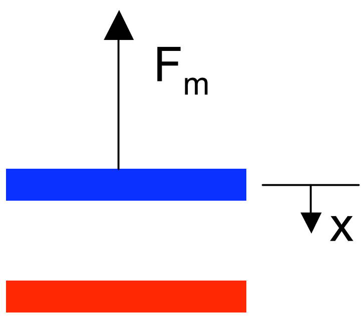
Potential energy: $$U = \frac{1}{2}CV^2 = \frac{\varepsilon_o \varepsilon_r L w V^2}{2g}$$

V = applied voltage (V)



Electrostatic force: $$F_e = \frac{dU}{dg} = \frac{\varepsilon_o \varepsilon_r L w V^2}{2g^2}$$

Mechanical restoring force



$$F_m = kx$$

$$x = g_o - g$$

x = displacement

g_o = initial gap

Static equilibrium: Σ F=0

$$F_e = F_m$$

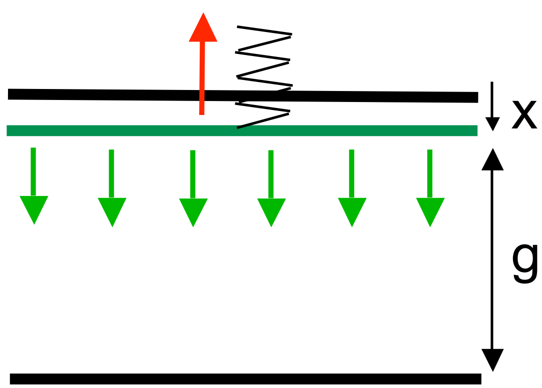
$$\frac{\varepsilon_o \varepsilon_r L w V^2}{2(g_o - x)^2} = kx$$

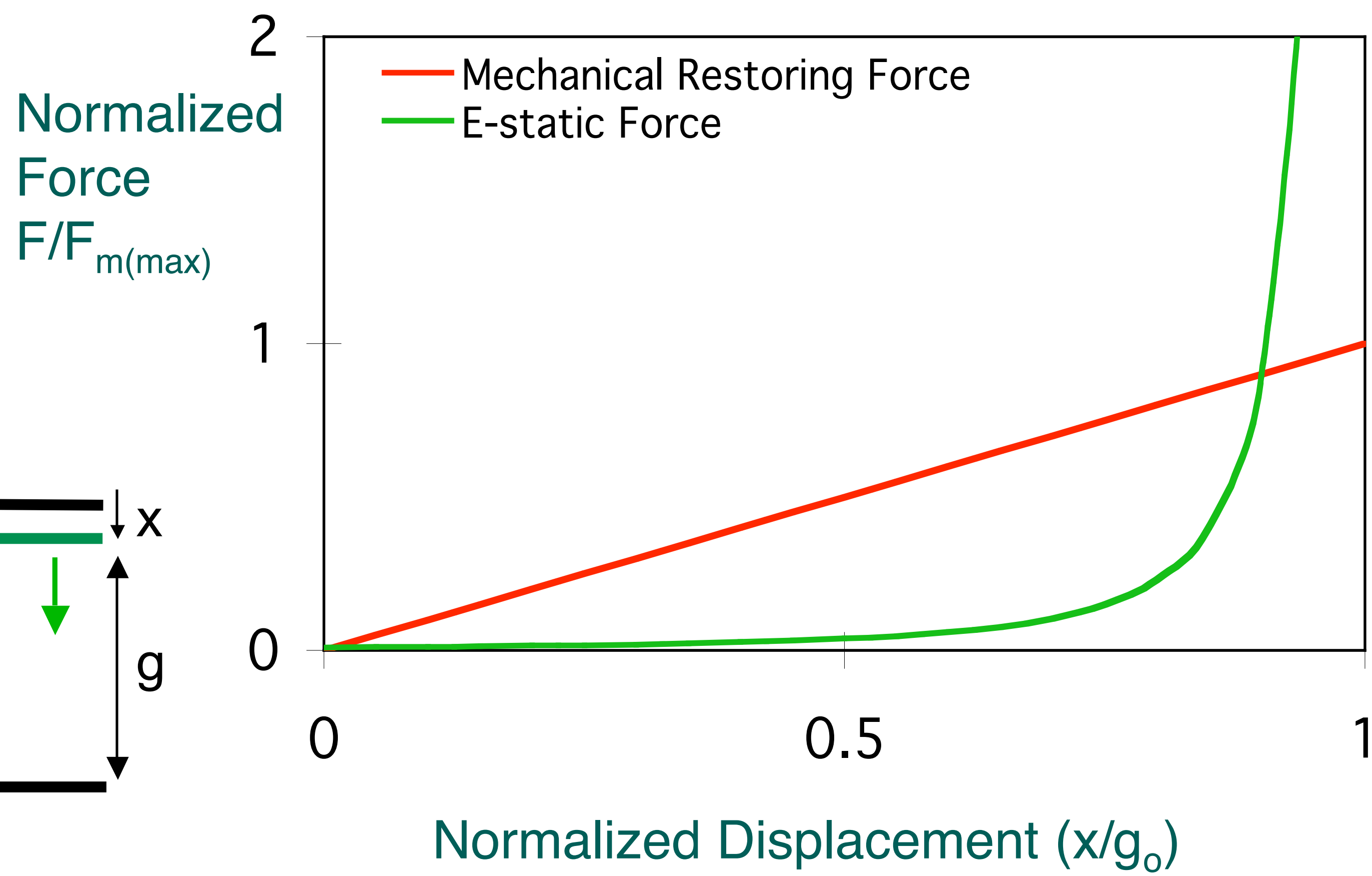
Cubic equation for x as a function of V^2

Graphical representation of equilibrium

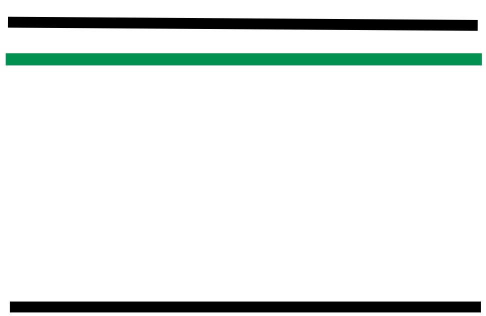
$$F_m = kx$$

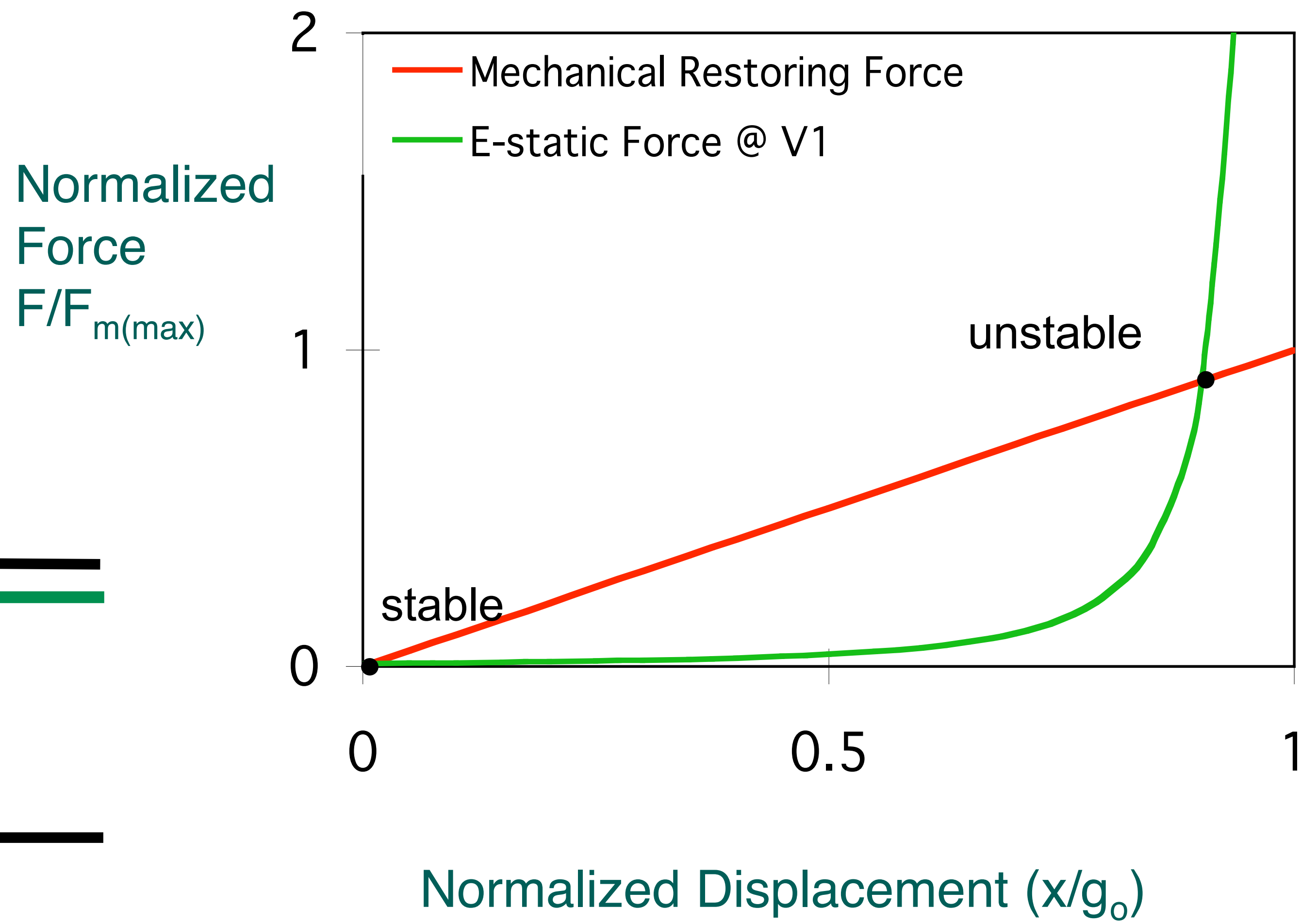
$$F_E = \frac{\varepsilon_o \varepsilon_r L w V^2}{2(g_o - x)^2}$$





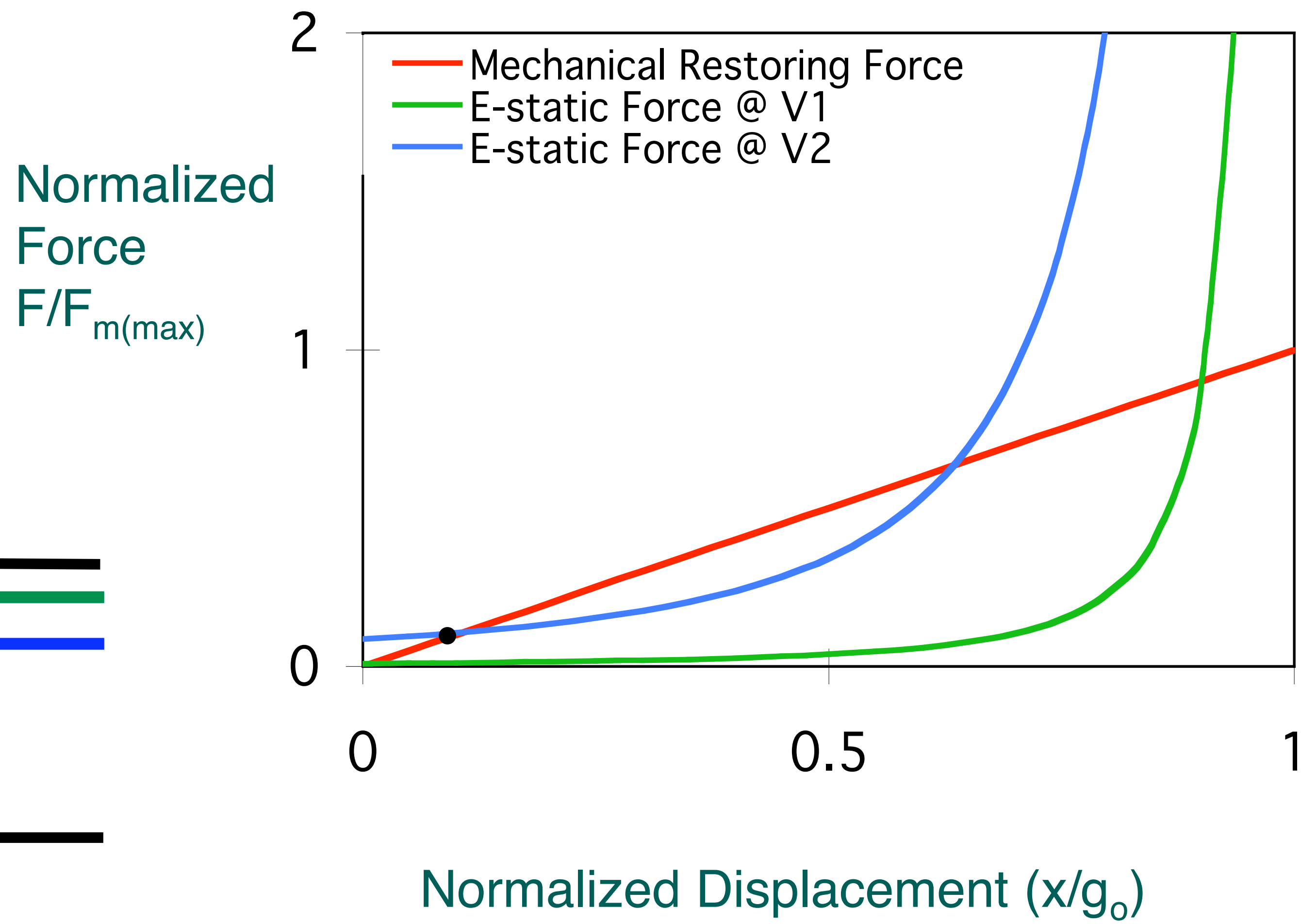
Graphical representation of equilibrium



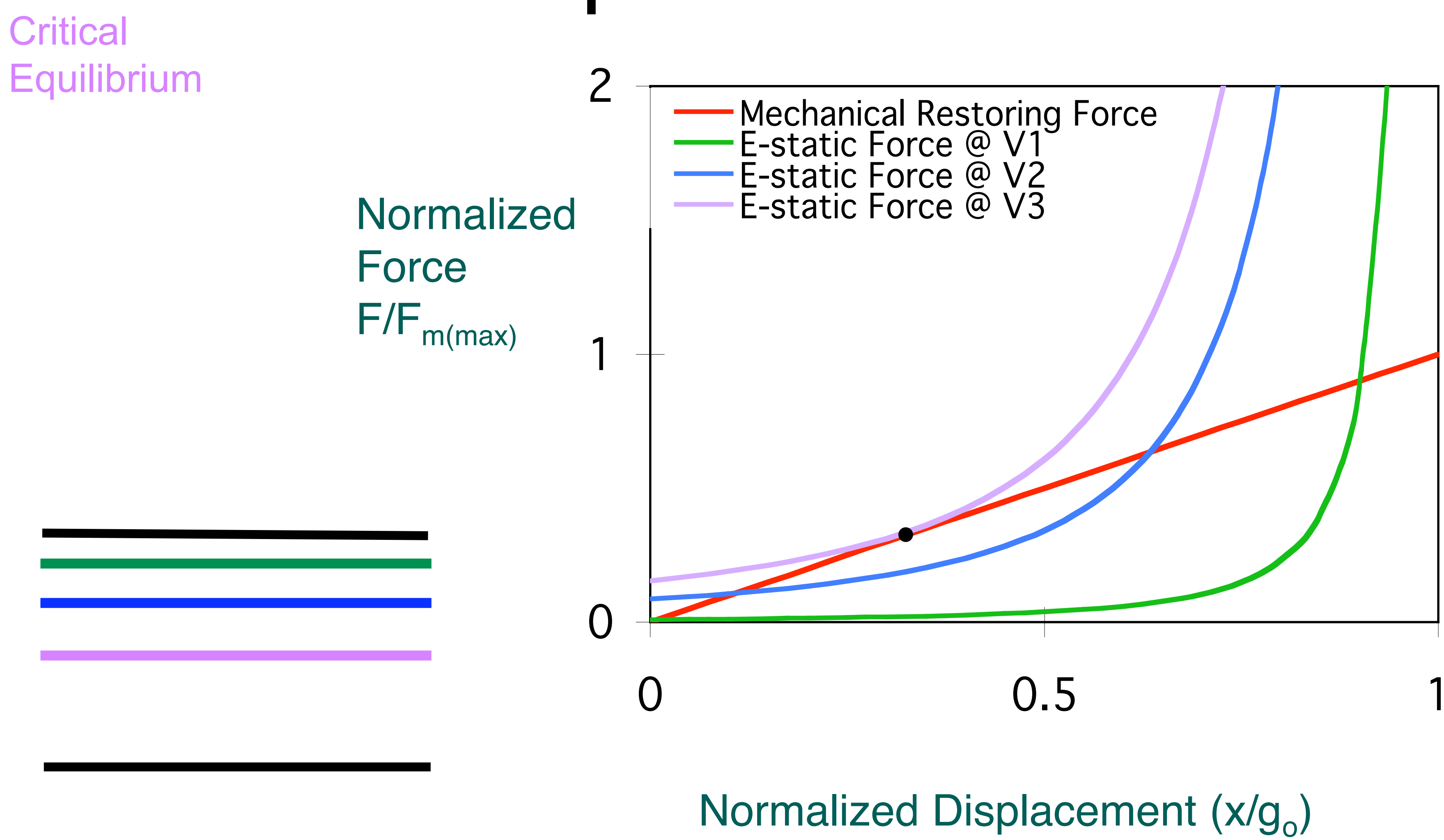


Graphical representation of equilibrium

Increasing V



Graphical representation of equilibrium

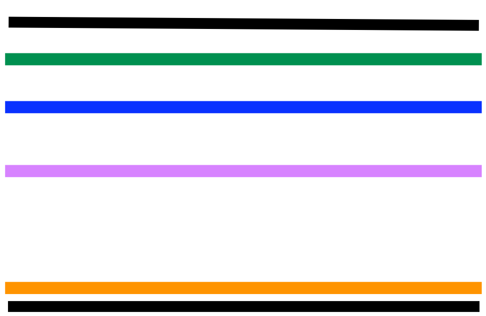


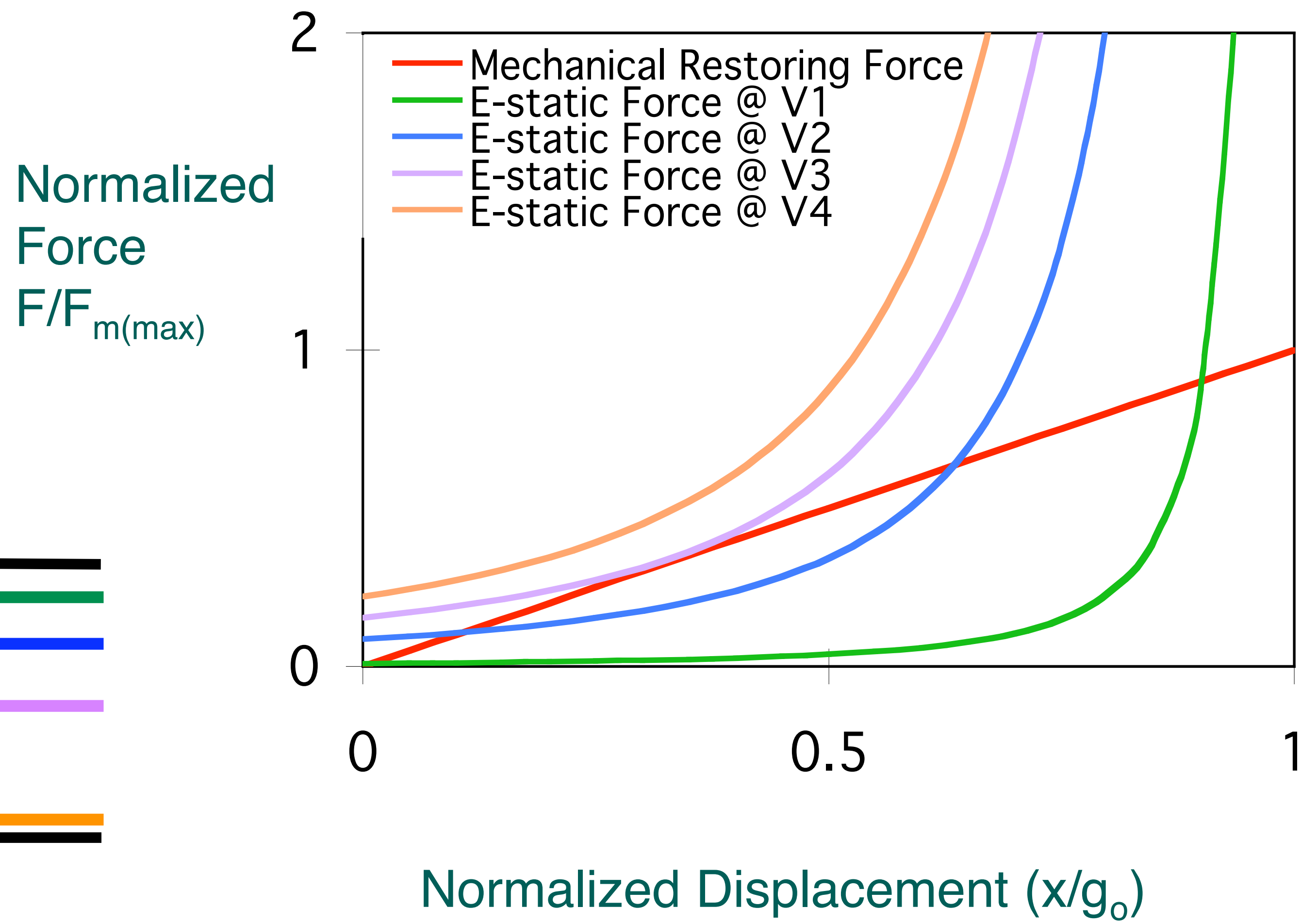
Graphical representation of equilibrium

Unstable

$F_e > F_m$

(Newton's second law: F=ma)





At critical equilibrium

$$F_e = F_m \qquad \frac{\varepsilon_o \varepsilon_r L w V^2}{2(g_o - x)^2} = kx$$

$$\left.\frac{dF_e}{dx}\right|_{x_c} = \left.\frac{dF_m}{dx}\right|_{x_c}$$

Curves are tangent

$$\frac{\varepsilon_o \varepsilon_r L w V_c^2}{(g_o - x_c)^3} = k$$

Substitute into equilibrium eqn:

$$\frac{\varepsilon_o \varepsilon_r L w V_c^2}{(g_o - x_c)^3} x_c = \frac{\varepsilon_o \varepsilon_r L w V_c^2}{2(g_o - x_c)^2}$$

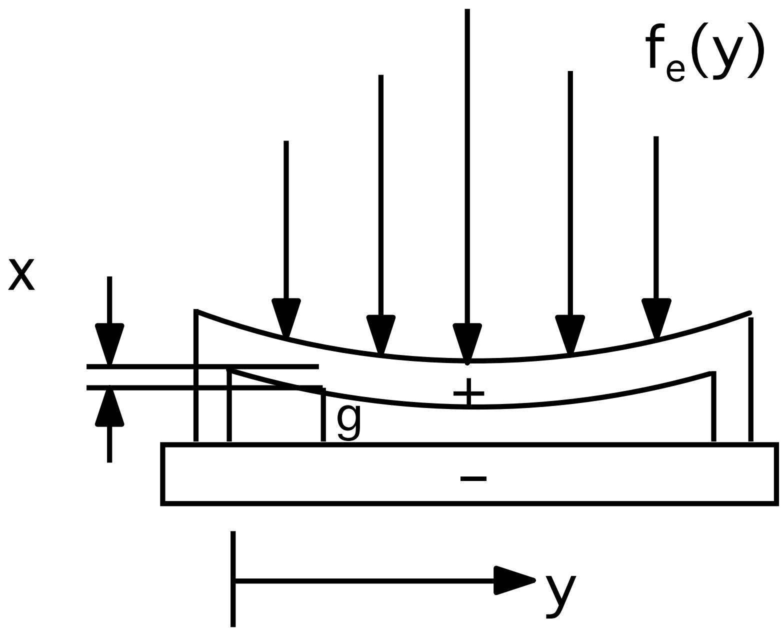
$$x_c = \frac{g_o}{3}$$

Independent of actuator stiffness

Critical voltage is maximum required to drive actuator

$$V_c = \sqrt{\frac{8kg_o^3}{27\varepsilon_o\varepsilon_r Lw}}$$

Real actuator is not a parallel plate, but a bending fixed-fixed beam



$$k \sim \frac{192EI}{L^3} = \frac{16Etw}{L^3}$$

E = Elastic modulus

I = Moment of inertia

t = Actuator thickness

$$V_c \sim \sqrt{\frac{5Et^3g_o^3}{\varepsilon_o \varepsilon_r L^4}}$$

BMC µDM140:

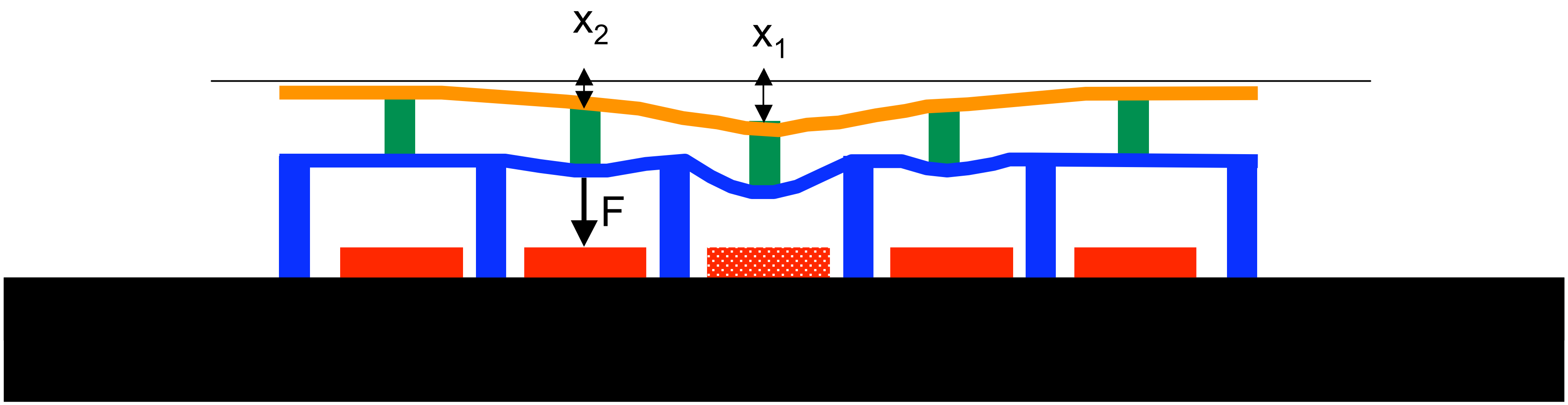
$$V_c = \sqrt{\frac{5 * 170e^9 * (3e^{-6})^3 * (5e^{-6})^3}{8.8e^{-12} * 1 * (3e^{-4})^4}} \sim 200V$$

Real actuator is not a parallel plate, but a bending fixed-fixed beam

Good news: fixed fixed beam improves stroke:

$$x_c \sim 0.4 g_o$$

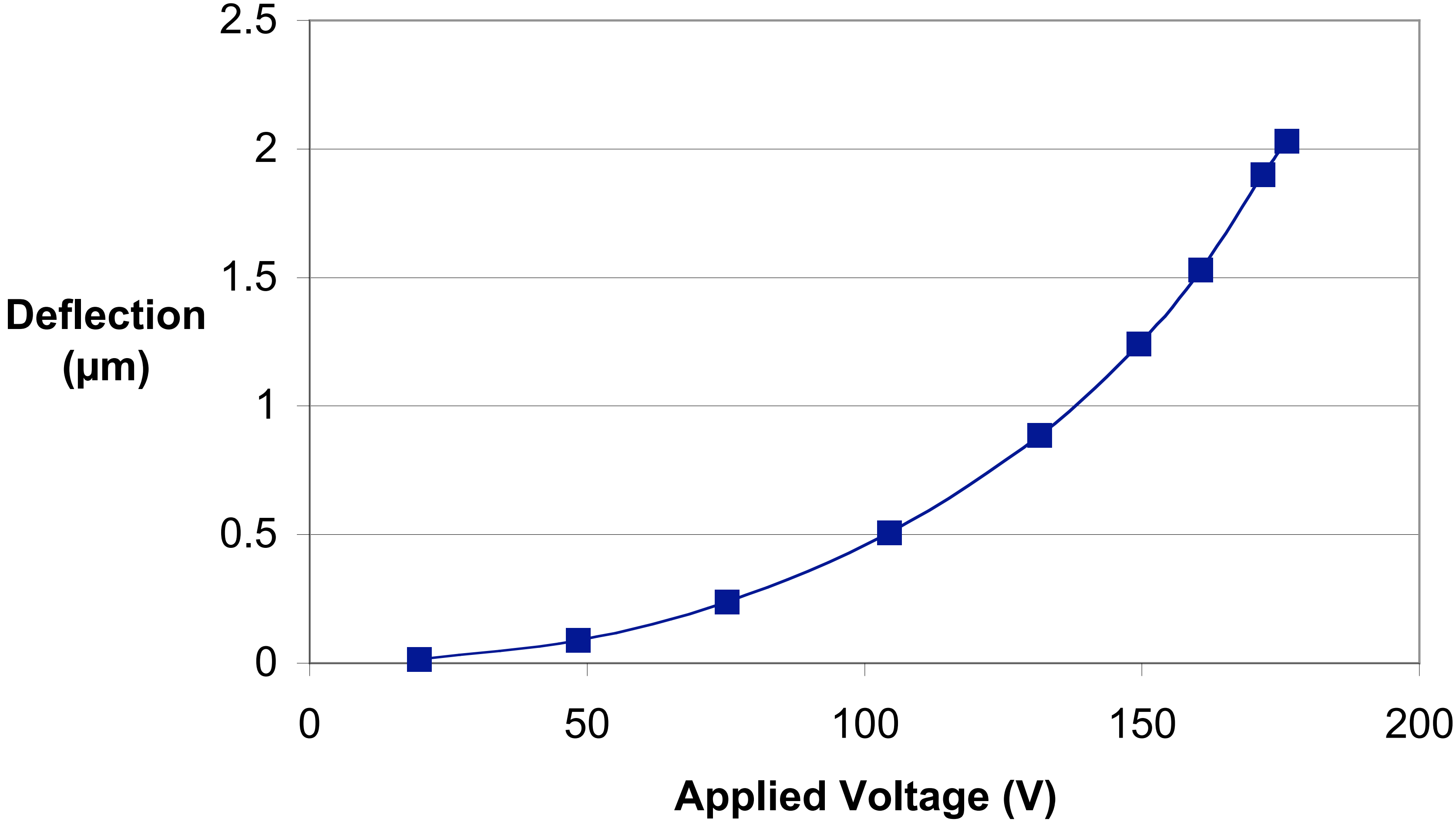
The mirror adds an additional mechanical force



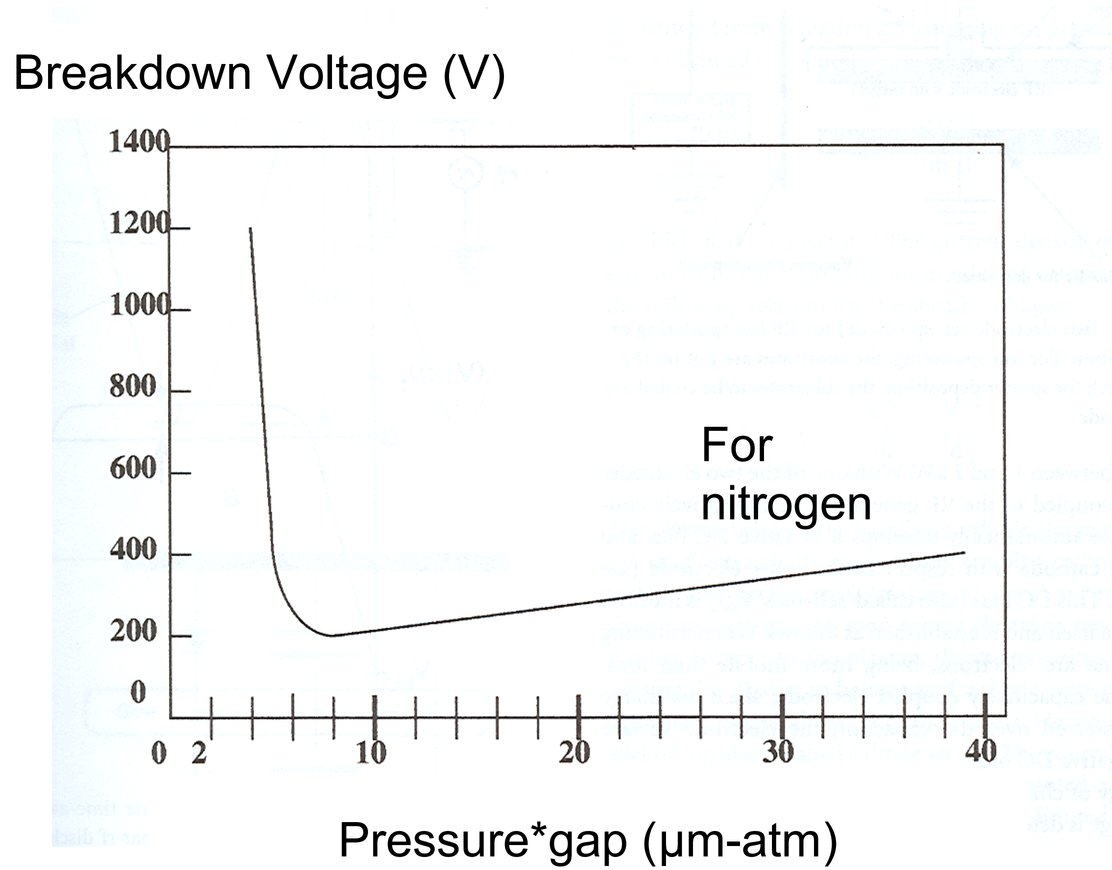
Energized central actuator exerts a force on its unenergized neighbors

Influence: x_2 / x_1 is determined by the relative stiffness of mirror and actuator. For different BMC designs, influence ranges from 0.00 to 0.25

Voltage versus deflection is nonlinear



There is a voltage limitation for parallel plate actuation



Minimum breakdown voltage as a function of gas

Gas	Vs min (V)	pd at Vs min (torr cm)	Gap at minimum (press. = 1 atm.)
Air	327	0.567	8
Ar	137	0.9	12
H_2	273	1.15	15
He	156	4.0	53
CO_2	420	0.51	7
N_2	251	0.67	9
N_2O	418	0.5	7
O_2	450	0.7	9
SO_2	457	0.33	4
H_2S	414	0.6	8

Naidu, M.S. and Kamaraju, V., High Voltage Engineering, 2nd ed., McGraw Hill, 1995, ISBN 0-07-462286-2

Additional factors in design and performance

Film stresses (usually ~10MPa compressive)

Cause actuator buckling, leading to smaller initial gap

- Buckling amplitude increases with L
- Process control can help

Cause mirror nonplanarity

- 30nm RMS typical, 10nm RMS achievable
- 1nm will require thicker mirror or different material

Spring nonlinearity (strain stiffening)

As actuator deflects, the membrane lengthens

- 50MPa change in stress with 5μm deflection
- This helps linearize voltage versus deflection curve!

Scaling the technology

More stroke: increase gap g_o or critical deflection ratio (x_c/g_o)

4.5μm is current maximum

10μm is possible with current processes

More actuators: increase array size up to wafer scale (140mm)

~150,000 actuators

requires through-wafer via connections to integrated driver electronics

Drivers wanted.

Resolution

Electrostatic actuation exhibits no hysteresis
Operation requires infinitesimal power (100fF capacitor)
13pm repeatability measured on actuator at JPL (2nm at BU)

*Current driver has 8-bit voltage resolution, and offers resolution of about 1% of FS deflection.

Design modification case study: Double stroke

A CfAO sponsored effort

Recall that :

$$V_c \propto g_o^{3/2}, L^2, k^{1/2}$$

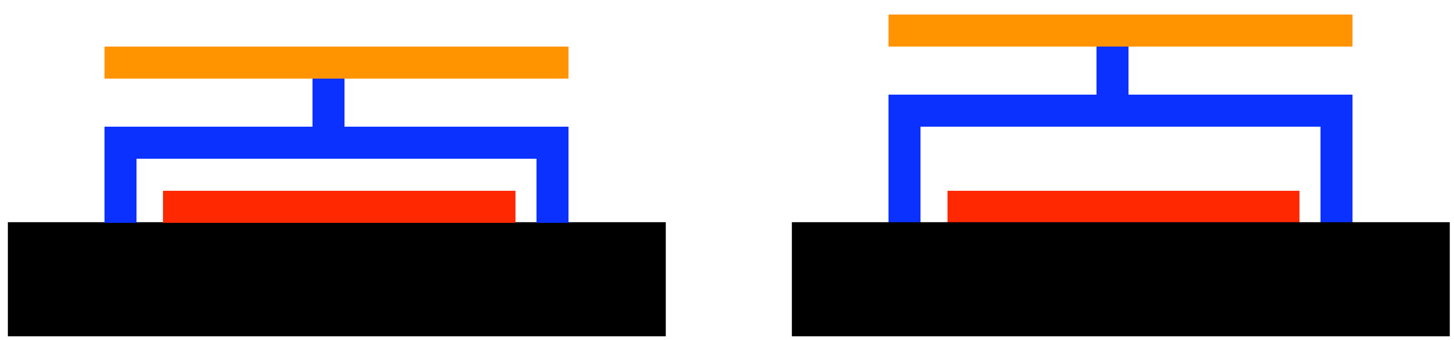
Initial device design

gap	5µm
V_c	150V
stroke	2µm
x_c/g_o	0.4
L	300µm

Design modification case study: Double stroke

Step 1: Increase gap, by thickening actuator sacrificial layer

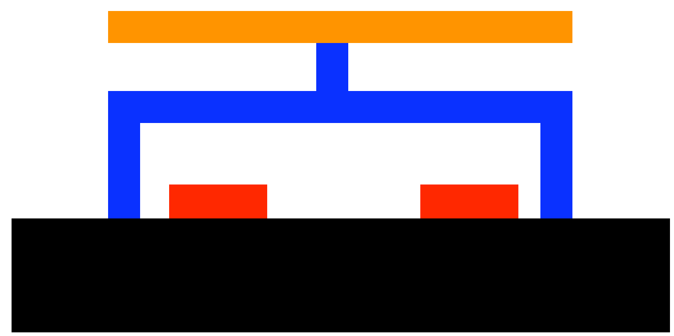
$$\frac{g_o^*}{g_o} = 1.5 \qquad \therefore \qquad \frac{V_c^*}{V_c} = 3.7 \qquad \frac{x_c^*}{x_c} = 1.5$$



Design modification case study: Double stroke

Step 2: Increase stability over a larger gap fraction, by splitting electrodes (can get 60% of gap)

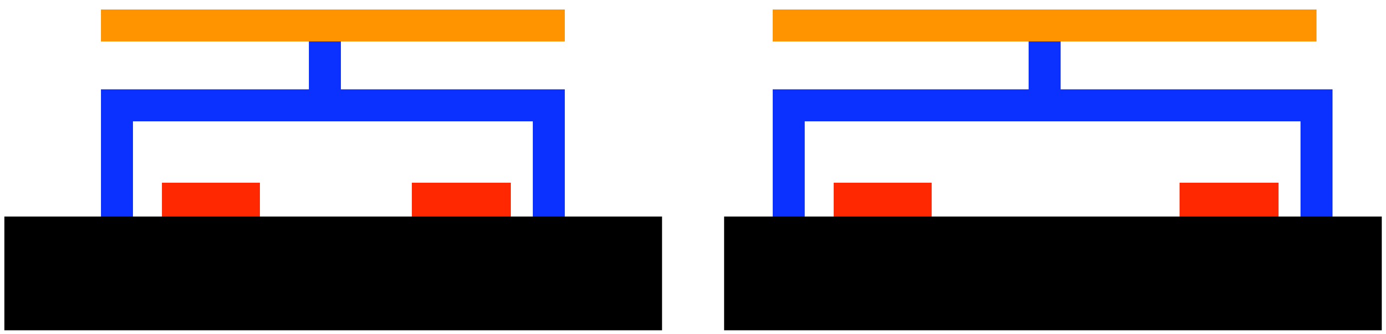
$$\frac{\left(x_c / g_o\right)^*}{x_c / g_o} = 1.5 \qquad \therefore \qquad \frac{V_c^*}{V_c} \sim 2 \qquad \frac{x_c^*}{x_c} = 1.5$$



Design modification case study: Double stroke

Step 3: Increase actuator length, by altering mask layout

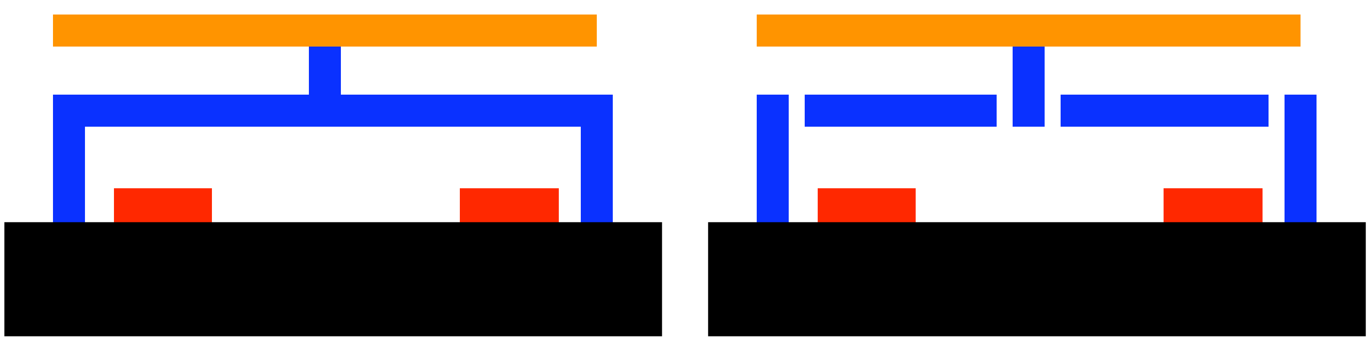
$$\frac{L^*}{L} = 1.3 \qquad \therefore \qquad \frac{V_c^*}{V_c} \sim 0.6 \qquad \frac{x_c^*}{x_c} = 1$$



Design modification case study: Double stroke

Step 4: Decrease actuator stiffness, by perforating membrane

$$\frac{k^*}{k} \sim 0.25 \qquad \therefore \qquad \frac{V_c^*}{V_c} \sim 0.5 \qquad \frac{x_c^*}{x_c} = 1$$

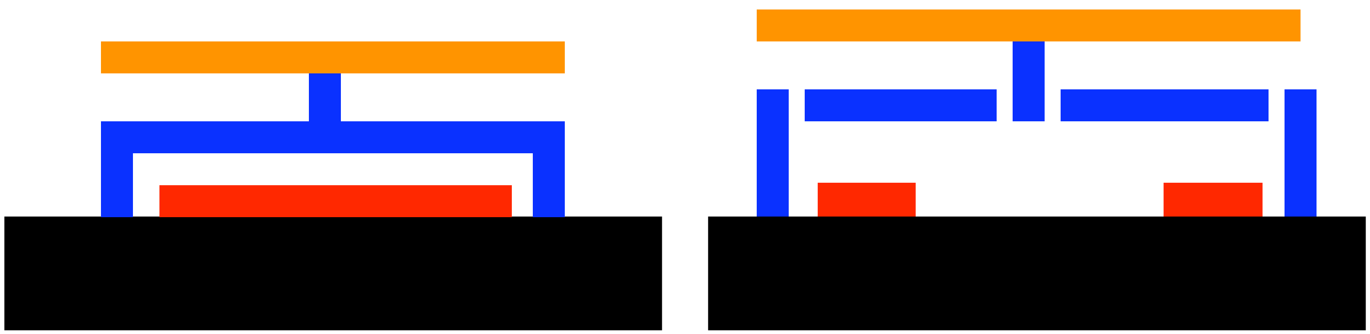


Design modification case study: Double stroke

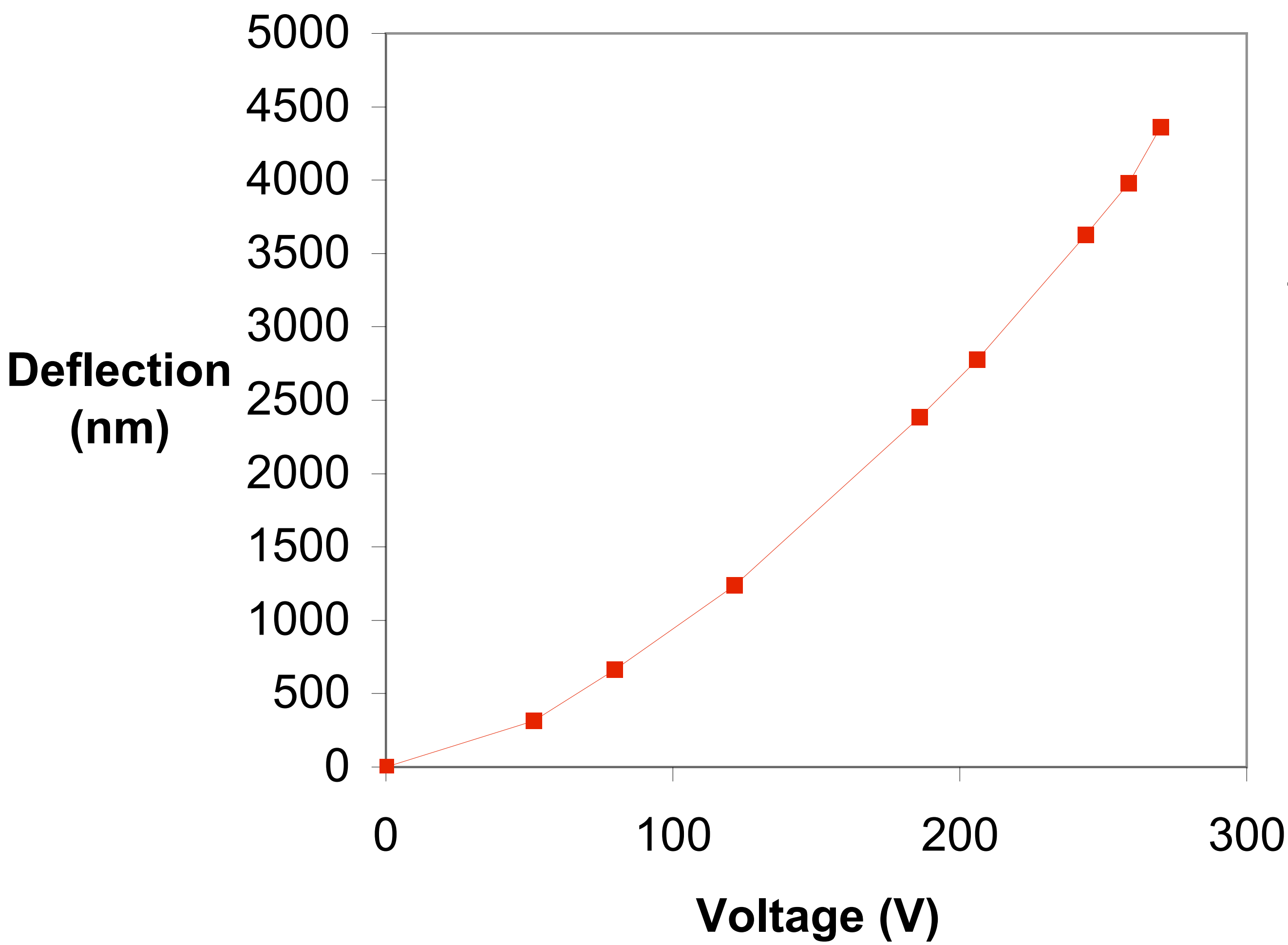
Net result:

$$\frac{V_c^*}{V_c} \sim 3.7 * 2 * 0.6 * 0.5 \sim 2.2$$

$$\frac{x_c^*}{x_c} \sim 1.5 * 1.5 * 1 * 1 \sim 2.2$$



Design modification case study: Double stroke



Unexpected benefit: Split electrodes prevent failure due to overvoltage instability

Unexpected liability: RMS figure of mirror increased due to actuator compliance

Conclusions

Parallel plate actuation is a robust, reliable approach to MEMS DM development. Its simplicity allows deterministic design. It provides a proven platform for future high-resolution DMs.