5. Technical Review – Actuators

Actuators

- Actuators convert electrical (or other energy) into mechanical energy
- An ideal actuator would have low power consumption, high mechanical efficiency, robustness to mechanical/environmental conditions, fast response and linear proportionality between force/torque/speed and control signal.

Type of Motor	Torque/Mass (N•m/kg)	Power/Mass (W/kg)
Sarcos Dextrous Arm (electrohydraulic)	120	600
McGill/MIT Electromagnetic Motor	15	200
Polyacrylic Acid/Polyvinyl Alcohol Polymeric Actuator	17	6
NiTi Shape Memory Alloy	20	6
Human Biceps Muscle	20	50
Burleigh Piezoelectric Inchworm	3	0.1

Table of general comparisions of (macroscopic) robotics motors and human skeletal muscle, in terms of torque/mass and power/mass ratios. After Hollerbach, et al. (1991).

From Kovacs, Micromachined Transducers Sourcebook

Type of Actuator	Stress (MPa)	Strain (%)	Strain Rate (Hz)	Power Density (W/kg)	Efficiency %
Electrostatic (macroscopic composite)	0.04	> 10	> 1	> 10	> 20
Cardiac Muscle (human)	0.1	> 40	4	> 100	> 35
Polymer (polyacrylic acid/polyvinyl alcohol)	0.3	> 40	0.1	> 5	30
Skeletal Muscle (human)	0.35	> 40	5	> 100	> 35
Polymer (polyaniline)	180	> 2	> 1	> 1,000	> 30
Piezoelectric Polymer (PVDF)	3	0.1	> 1	> 100	< 1
Piezoelectric Ceramic	35	0.09	> 10	> 1,000	> 30
Magnetostrictive (Terfenol-D)	70	0.2	1	> 1,000	< 30
Shape Memory Alloy (NiTi bulk fiber)	> 200	> 5	3	> 1,000	> 3

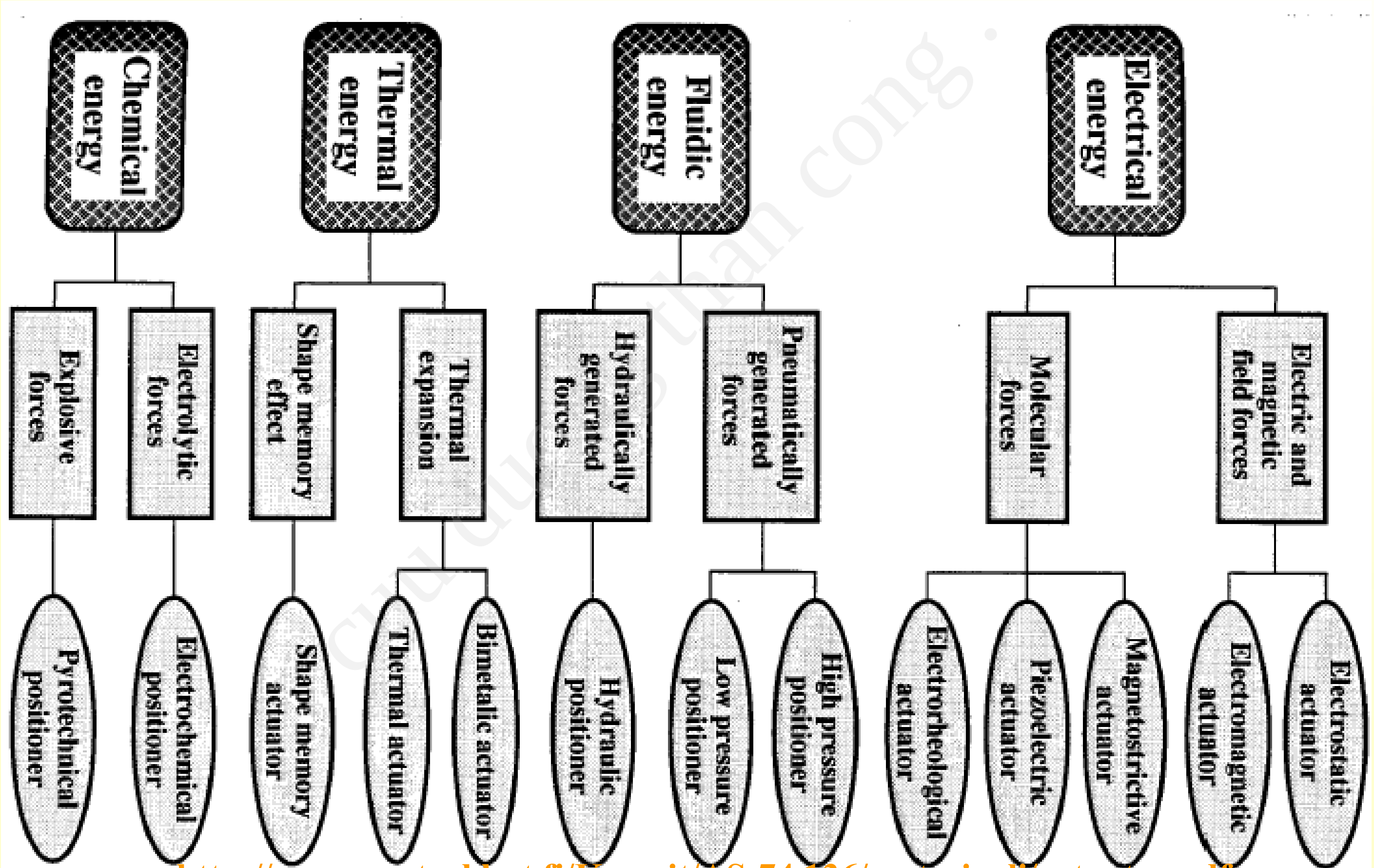
From Kovacs, Micromachined Transducers Sourcebook

Table of linear actuator materials. After Hunter and Lafontaine (1992). The authors noted that the values provided did not always represent optimal materials, as development is active in many of these categories and that the power needed for accessory systems, such as cooling, were not included in the calculations.

- Classification by motion

  Linear motion actuator

  Rotational actuator – micromotor
- Classification by energy source



http://www.control.hut.fi/Kurssit/AS-74.136/materiaali/actuator.pdf

- Characterization parameters

Accuracy: error between expected and actual position

Repeatability: variation of actuator output during operation

Resolution: smallest positioning increment achievable

Linearity: deviation from the linear reference response

Electrostatic Actuator

Use attraction or repulsion between two charged plates

(+) Low power consumption

(+) Good scaling factor

(+) Easy to fabricate

(-) High voltage

(-) Small deflection range

(-) Small force

(-) Packaging

- Coulomb's law

Force between two charged particles:

$F = (1/4\pi\varepsilon_r\varepsilon_0)(q_1 q_2/z^2)$

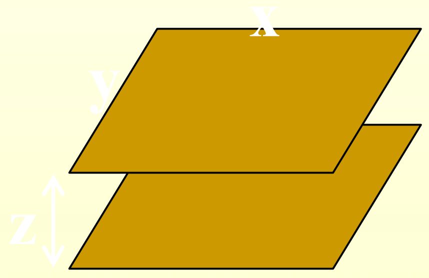
Energy stored in a parallel-plate capacitor:

$W = -\frac{1}{2} CV^2 = -\frac{1}{2}\ \varepsilon_r\varepsilon_0 AV^2/z$

$F_z = -dW/dz = \frac{1}{2}\ \varepsilon_r\varepsilon_0 AV^2/z^2$

$F_x = -dW/dx = \frac{1}{2}\ \varepsilon_r\varepsilon_0\ yV^2/z$

$F_y = -dW/dy = \frac{1}{2}\ \varepsilon_r\varepsilon_0\ xV^2/z$



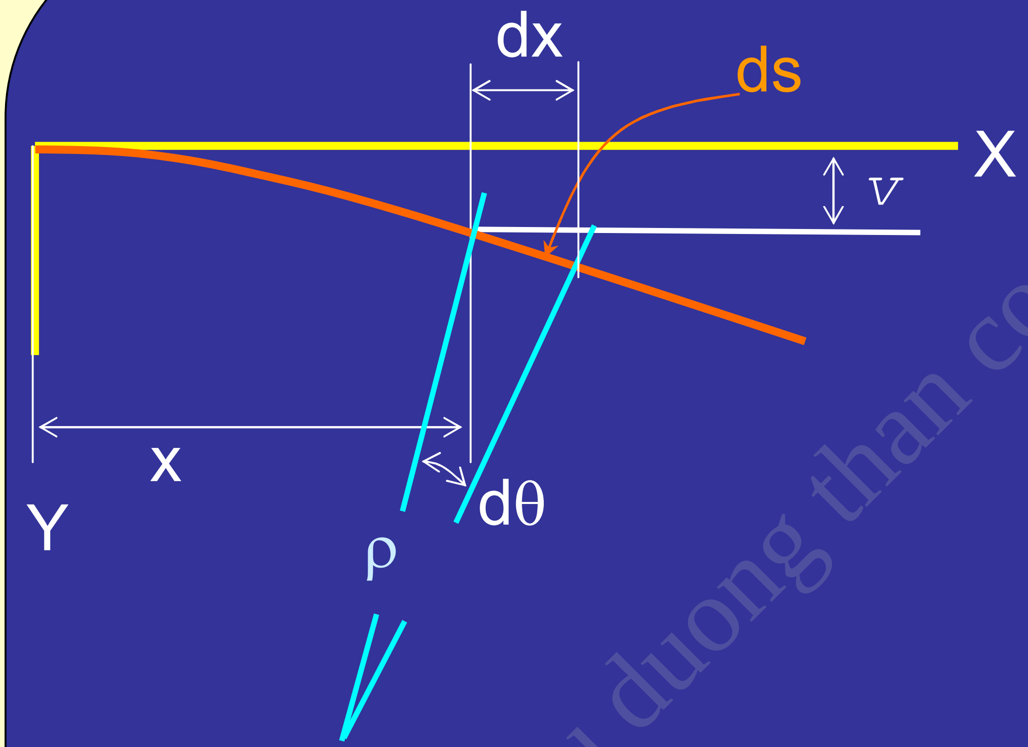
Voltage-force relationship is not linear

- Example

For 1000 μm x1000 μm parallel plate actuator with 5 μm gap separated by air, determine the potential required to generate 1 mN force?

Cantilever beam actuator

- Has a fixed support at one end and free at the other
- Neither translate nor rotate at the fixed support whereas do both at the free end
- Both force and moment reactions may exist at the fixed support
- Si cantilever beam is one of the building blocks for MEMS actuators and sensors.



See elastic curve of beam

For very small deflection,

$\tan\theta = dv/dx$

$\theta = dv/dx$ for very small θ

$d\theta/dx = d^2v/dx^2$

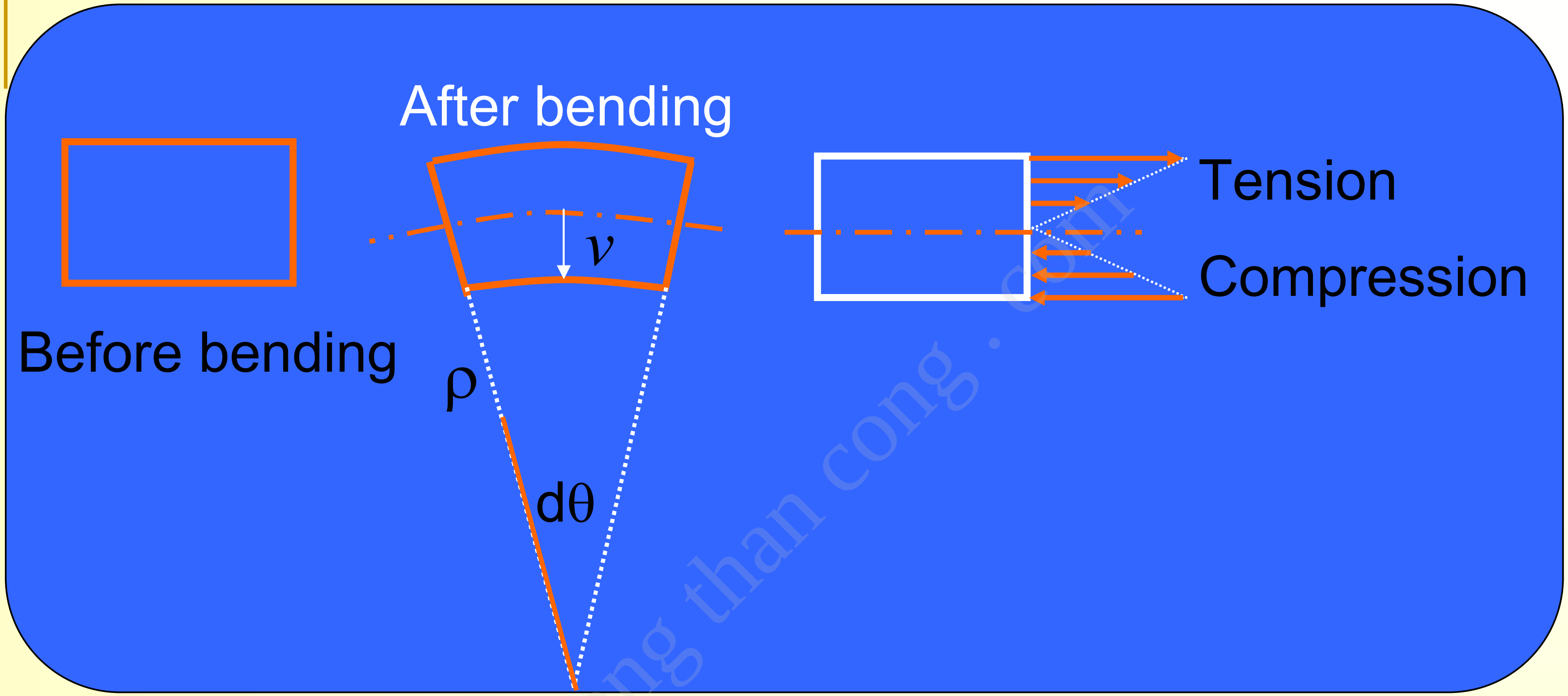
$ds = \rho\, d\theta$,

ρ=radius of curvature

over arc ds

$1/\rho = d\theta/ds \approx d\theta/dx$

$1/\rho = d^2v/dx^2$



- Original length: $\rho d\theta$
- Final length: $(\rho - v)d\theta$
- Normal strain: $\varepsilon_x = -v d\theta / \rho d\theta = -v/\rho$

$$= -\kappa v$$

- $\sigma_x = -E\varepsilon_x = -E\kappa y$
- Force, $dF = \sigma_x \, dA$
- Bending moment M_0 = force x length
- Moment, $dM = (dF)_x \, y = \sigma_x \, dA \, y$

$M = \int \sigma_x \, y dA = -E\kappa \int y^2 dA$

$M = -E\kappa I$, where $I = \int y^2 dA$: moment of intertia

(example)

$I = wt^3/12$

- Curvature: $\kappa = 1/\rho = -M/EI$

Where M is bending moment and EI is the flexural regidity of beam

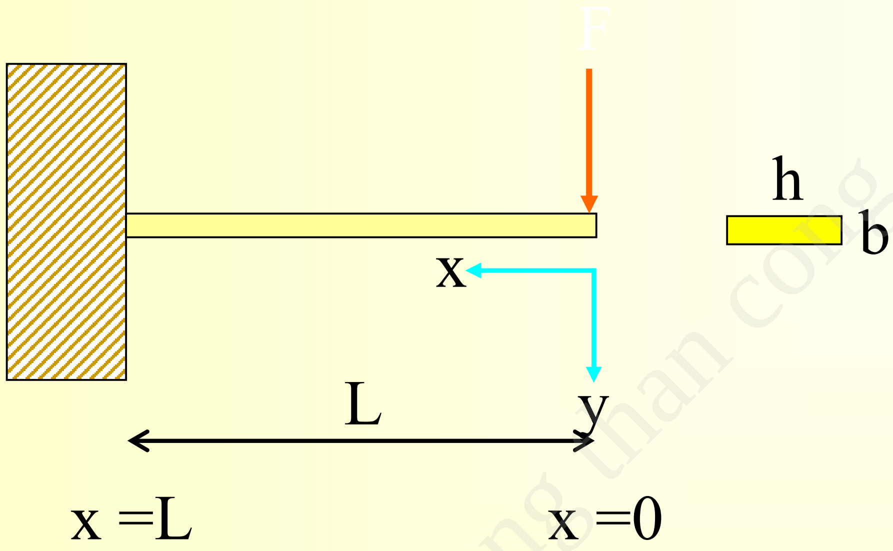
- $d^2v/dx^2 = -M/EI$
- Relation between deflection(v), moment(M), shear force(V) and distributed loading(q)

$EIv'' = -M$ (force*length)

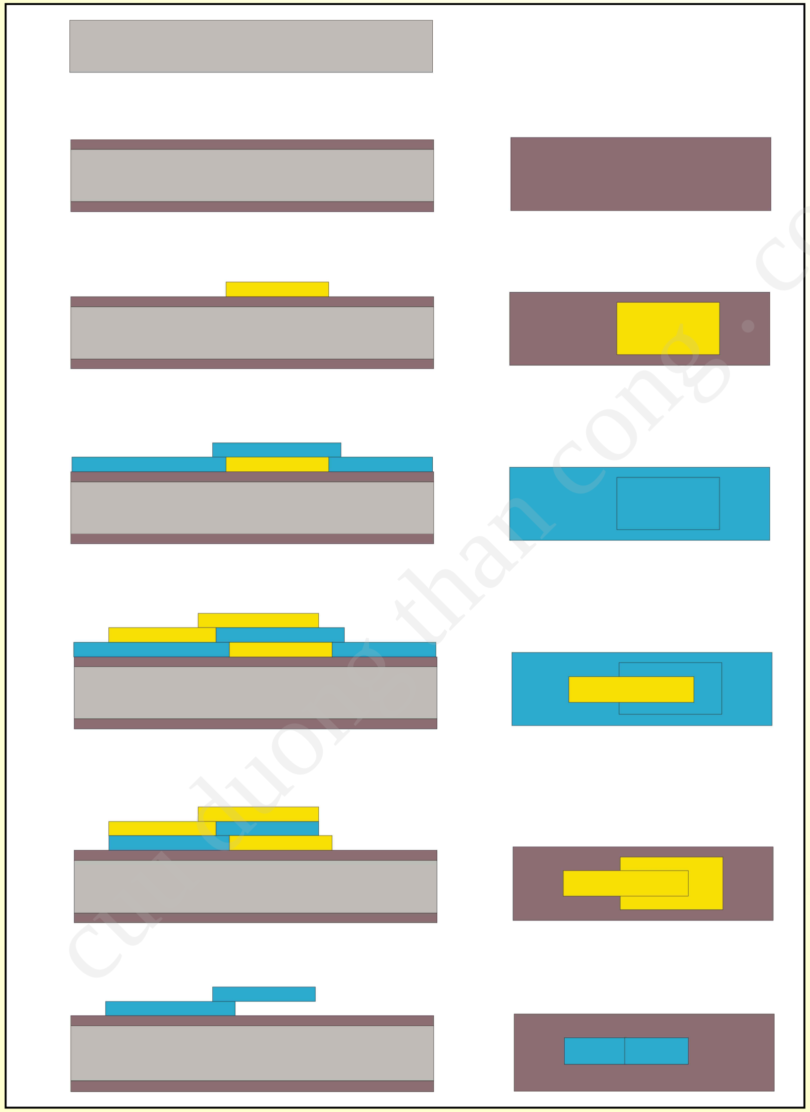
$EIv''' = -dM/dx = -V$ (force)

$EIv^{(4)} = -dV/dx = q$ (force/length)

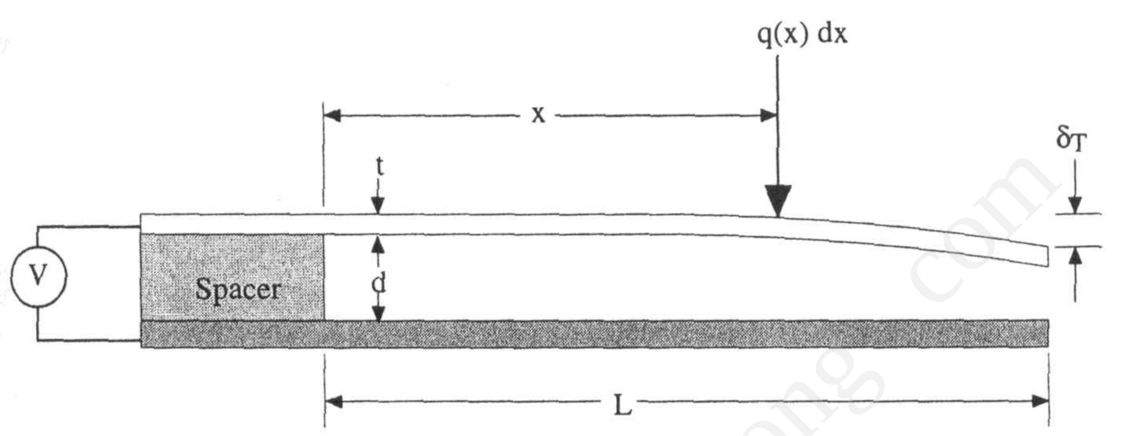
Example



$Y\ (x=0) = FL^3/3EI$



From www.eng.uah.edu/~coe/EE691EE692.ppt



For concentrated load at a position, x, from the fixed end of a cantilever beam, tip deflection is,

$$(d\delta)_T = \frac{x^2}{6EI}(3L - x)wq(x)\,dx$$

Electrostatic force is,

$$q(x) = \frac{\varepsilon_0}{2}\left(\frac{V}{d - d(x)}\right)^2$$

where,

E = Young's modulus of the cantilever
I = moment of inertia of the cantilever
L = beam length
x = distance of force (load) from the fixed end of the beam
d = gap between cantilever and deflection electrode

Total tip deflection can be found by integrating from x=0 to x=L.

$$\delta_T = w\int_0^L \frac{(3L - x)}{6EI} x^2 q(x)\, dx$$

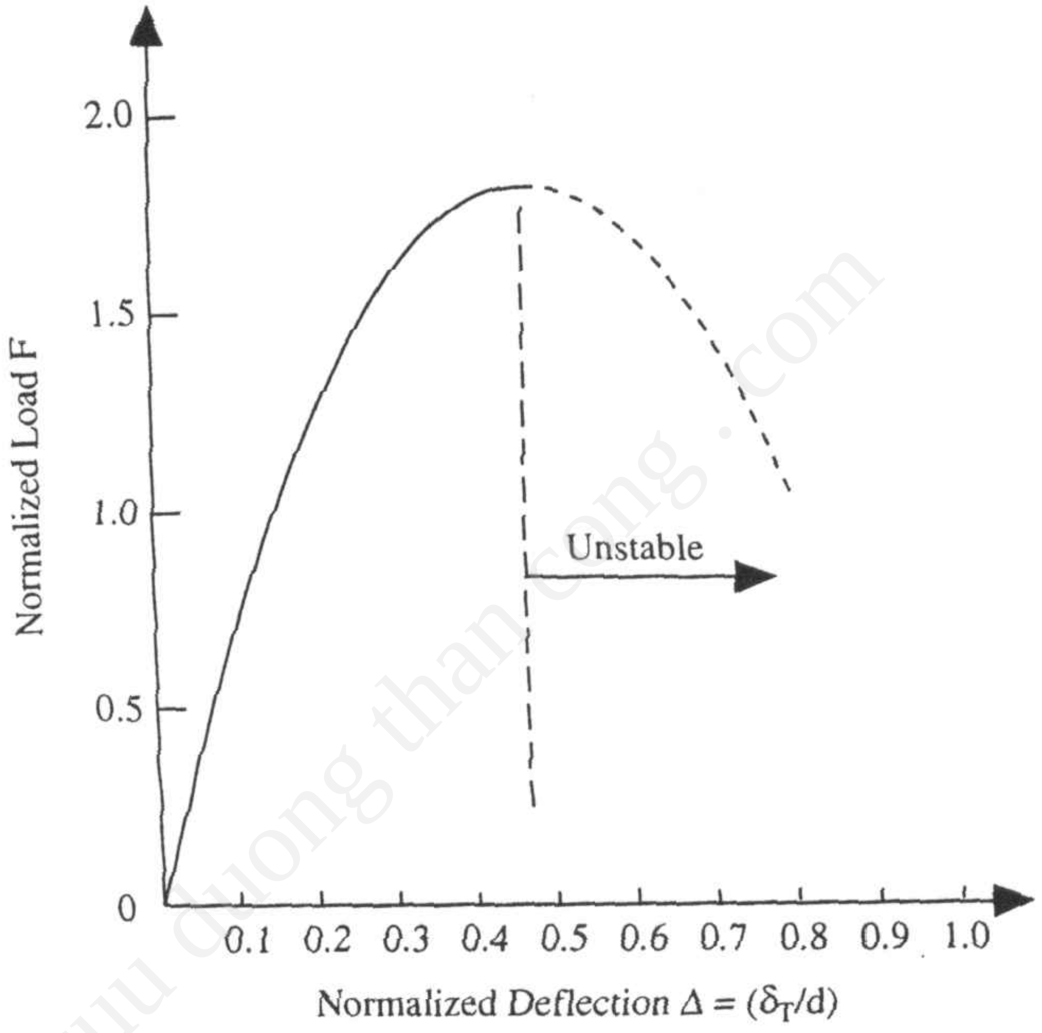
Assume a square-law curvature of the beam at any point along its length.

$$\delta(x) \approx \left(\frac{x}{L}\right)^2 \delta_T$$

This, in turn yields a normalized load, F, required to produce a specified tip deflection,

$$F \equiv \frac{\varepsilon_o w L^4 V^2}{2EId^3} = 4\Delta^2\left(\frac{2}{3(1-\Delta)} - \frac{\tanh^{-1}\sqrt{\Delta}}{\sqrt{\Delta}} - \frac{\ln(1-\Delta)}{3\Delta}\right)^{-1}$$

where Δ is the deflection at the tip (δ_T/d)



Plot showing the normalized load, F, versus the normalized deflection, Δ, for an electrostatically deflected cantilever. Adapted from Petersen (1978a). Beyond a certain threshold deflection, spontaneous collapse of the cantilever occurs.

From Kovacs, Micromachined Transducers Sourcebook

Threshold voltage is,

$$V_{th} \approx \sqrt{\frac{18EId^3}{5\varepsilon_o L^4 w}}$$

Effective Young's modulus/momentum of inertial product for a composite structure (metal/silicon dioxide) is,

$$(EI)_{eff} \approx \left(\frac{wt_1^3}{12}\right)\left(\frac{4+6\frac{t_2}{t_1}+\frac{E_1t_1}{E_2t_2}}{1+\frac{E_1t_1}{E_2t_2}}\right)$$

t_1, t_2, E_1, E_2 are the thickness and Young's modulus, respectively, of the lower(1) and upper(2) layer of the beam

The first resonant frequency is,

$$f_{R1} = \frac{3.52}{2\pi}\sqrt{\frac{EI}{\nu L^4}}$$

K. E. Peterson, "Dynamic Micromechanics on Silicon: Techniques and Devices," IEEE Trans. On Electron Devices, vol. ED-25, no. 10, Oct. 1978, pp. 1241-1250