

### Folded-Beam Suspension

- Use of folded-beam suspension brings many benefits
  - Stress relief: folding truss is free to move in y-direction, so beams can expand and contract more readily to relieve stress
  - High y-axis to x-axis stiffness ratio

**Comb-Driven Folded Beam Actuator**

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### Beam End Conditions

TABLE 4.1  
Types of commonly used support conditions for beams and frames

Type of support	Displacement boundary conditions	Force boundary conditions
FREE	None	All, as specified
PINNED	$u = 0$ $w = 0$	Moment is specified
ROLLER (vertical)	$u = 0$	Transverse force and moment are specified
ROLLER (horizontal)	$w = 0$	Horizontal force and bending moment are specified
FIXED or CLAMPED	$u = 0$ $w = 0$ $dw/dx = 0$	None specified

[From Reddy, Finite Element Method]

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### Common Loading & Boundary Conditions

- Displacement equations derived for various beams with concentrated load  $F$  or distributed load  $f$
- Gary Fedder Ph.D. Thesis, EECS, UC Berkeley, 1994

	cantilever	guided-end	fixed-fixed
(a) Concentrated load.			
$x$	$x = \frac{F_x L}{Ehw}$	$x = \frac{F_x L}{Ehw}$	$x = \frac{F_x L}{4Ehw}$
$y$	$y = 4 \frac{F_y L^2}{Eh w^3}$	$y = \frac{F_y L^2}{Eh w^3}$	$y = \frac{1}{16} \frac{F_y L^2}{Eh w^3}$
$z$	$z = 4 \frac{F_z L^2}{Ew h^3}$	$z = \frac{F_z L^2}{Ew h^3}$	$z = \frac{1}{16} \frac{F_z L^2}{Ew h^3}$
(b) Distributed load.			
$x$	$x = \frac{f_x L}{E}$	$x = \frac{f_x L}{E}$	$x = \frac{f_x L}{4E}$
$y$	$y = \frac{3}{2} \frac{f_y L^4}{Eh w^3}$	$y = \frac{1}{2} \frac{f_y L^4}{Eh w^3}$	$y = \frac{1}{32} \frac{f_y L^4}{Eh w^3}$
$z$	$z = \frac{3}{2} \frac{f_z L^4}{Ew h^3}$	$z = \frac{1}{2} \frac{f_z L^4}{Ew h^3}$	$z = \frac{1}{32} \frac{f_z L^4}{Ew h^3}$

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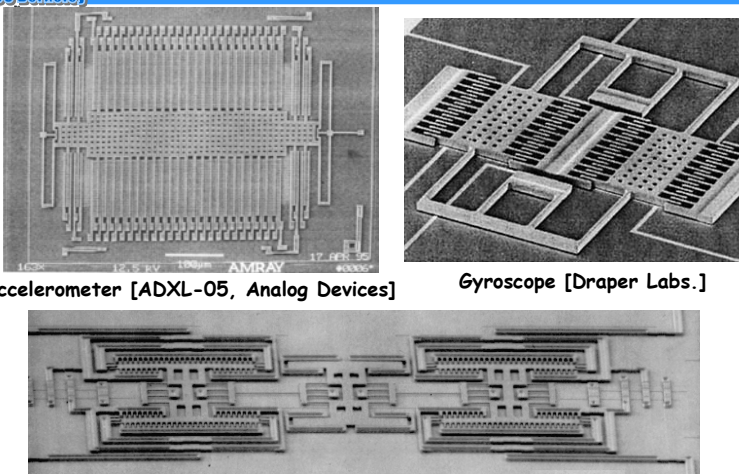
### Folded-Beam Stiffness Ratios

- In the x-direction:
 
$$k_x = \frac{24EI_z}{L^3}$$
- In the z-direction:
  - Same flexure and boundary conditions
$$k_z = \frac{24EI_x}{L^3}$$
- In the y-direction:
  - [See Senturia, §9.2]  $k_y = \frac{8EWh}{L}$
- Thus:
 
$$\frac{k_y}{k_x} = 4 \left( \frac{L}{W} \right)^2$$

**Much stiffer in y-direction!**

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### Folded-Beam Suspensions Permeate MEMS



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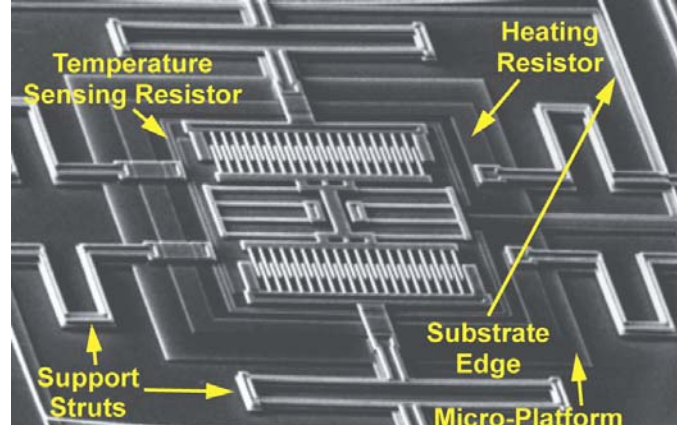
Accelerometer [ADXL-05, Analog Devices]

Gyroscope [Draper Labs.]

Micromechanical Filter [K. Wang, Univ. of Michigan]

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### Folded-Beam Suspensions Permeate MEMS



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- Below: Micro-Oven Controlled Folded-Beam Resonator

Temperature Sensing Resistor

Heating Resistor

Support Struts

Substrate Edge

Micro-Platform

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