ECE 421: Electronics for Instrumentation

MEMS Technology

MEMS Inertial Sensors

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Outline

- MEMS-Based Gyroscopes
  - Structure and concept
  - Specifications
  - Categories

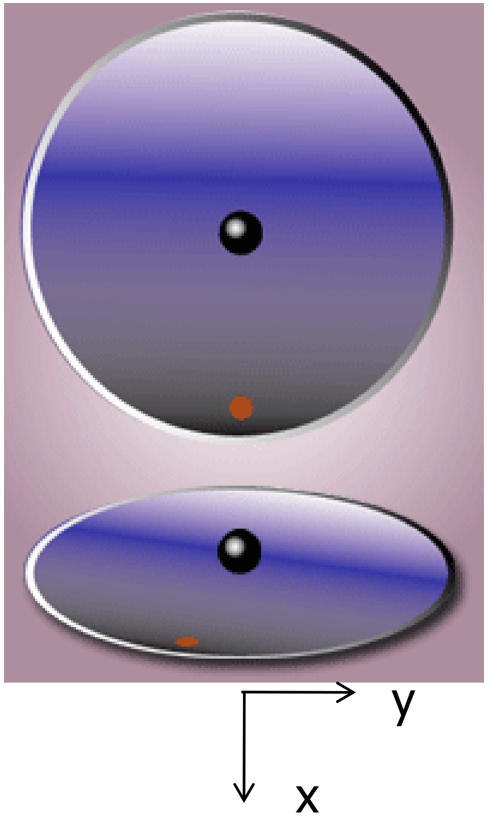
Gyroscopes

- Structure and concept
- Architectures
- Specifications

Vibratory Gyroscope Operation Principle

- Vibratory Gyroscopes are based on the Coriolis force effect.
- The Coriolis force affects objects moving in a rotating frame.
- Only seen in the rotating frame and so called fictional force.
- All vibratory gyroscopes are based on the Coriolis Effect: In a reference frame rotating at angular velocity Ω , a mass *M* moving with velocity V sees a force:

$$F=2M\,(V\mathrm{x}\Omega)$$

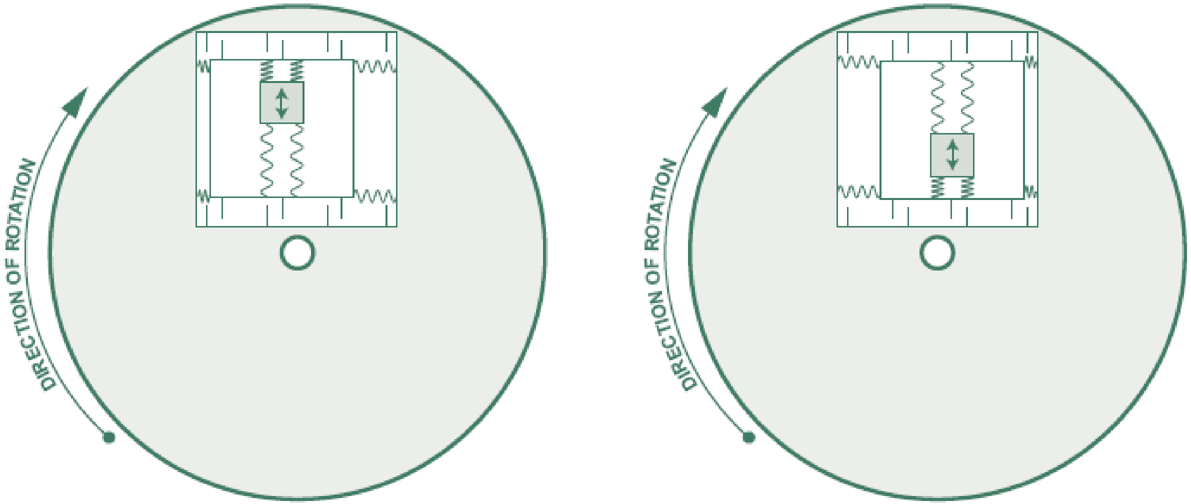


Coriolos force $(F_y)=-2m\Omega_z v_x$

Coriolis Effect in Sensors

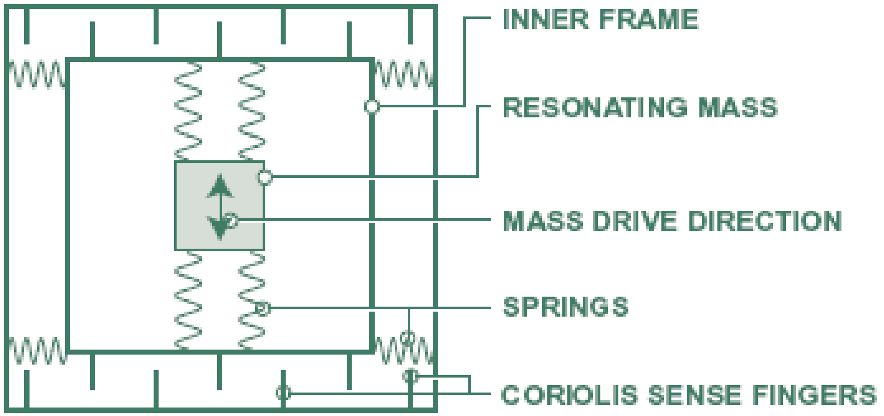
- On the rotating surface, a sensor element is vibrating in say the Y direction, a coriolis force will result in the perpendicular x direction.

- If the element is also free to move in x direction, a measure of its displacement could be used to measure the rotation rate in the z direction



Coriolis Sensor Device

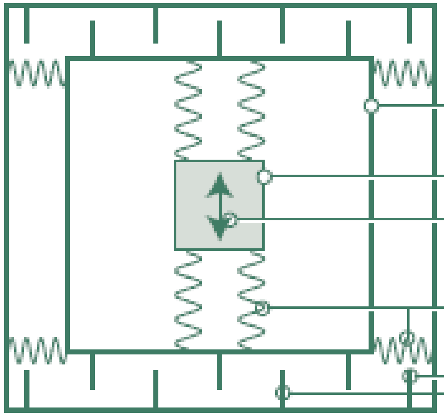
- The Coriolis Sensor device is a Mass that should
  - Have two degrees of mechanical freedom
  - Be Actuated to vibrate/move in one dimension
  - Be position sensed in another perpendicular direction



MEMS Gyro = Actuator + Sensor (Accelerometer)

Coriolis Vibratory Gyroscopes Concept

- Based on energy transfer between two orthogonal vibrations modes: the drive-mode and sense-mode (uncoupled at rest)



- With rotations, Coriolis force couples the modes and the drive-mode excites the sense-mode
- The sense-mode vibration amplitude is a measure of the of the rotation rate
- The fundamental challenge is that Coriolis force is very small and has to be measured in the presence of much larger electrical signals

Example: Coriolis force on a vibrating mass

- Let $x=1\ \mu m \sin(2\pi 10^4 t)$, $m=0.6$ nkg, $\Omega_z=2\pi$ rad/s

- Then, the velocity is given by the $v_x=dx/dt$:

  $$v_x = 2\pi * 10^4 * 1\ \mu \text{ cosin}(2\pi 10^4 t)$$

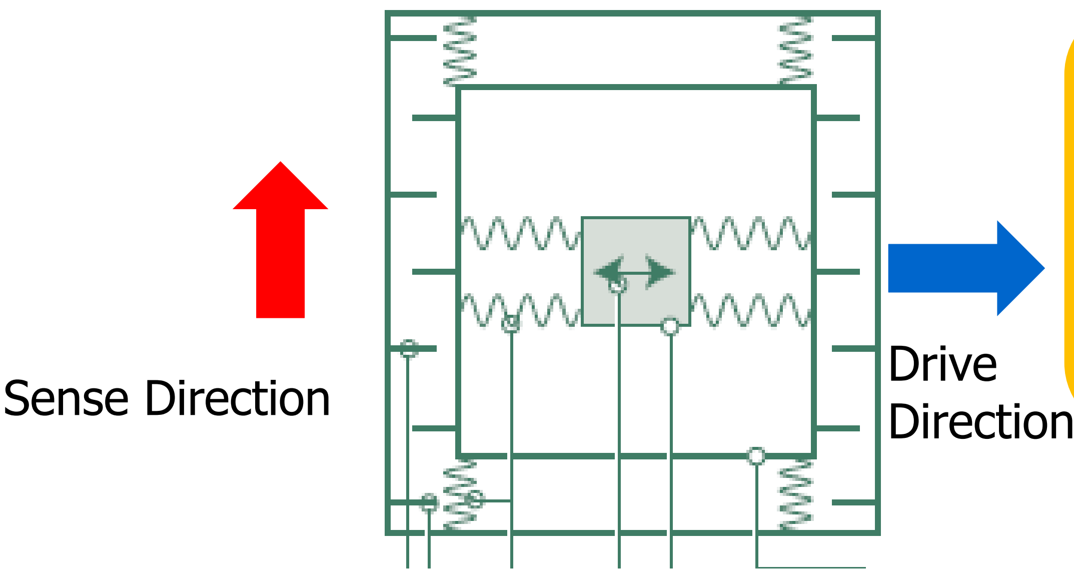
- The Coriolis force is given by $F_y=-2m\Omega_z v_x$
- Therefore, Coriolos force due to ($\Omega_z = 2\pi$)

  $F_y=-2 * 0.6\ n * 2\pi * 2\pi * 10^4 * 1\ \mu \text{ cosin}(2\pi 10^4 t)$

  $=-0.24\ nN \text{ cosin}(2\pi 10.10^3 t)$
- Very small oscillation at the resonance frequency but -90^o out-of-phase with the x-displacement

What is the main blocks in a vibratory gyroscope ?

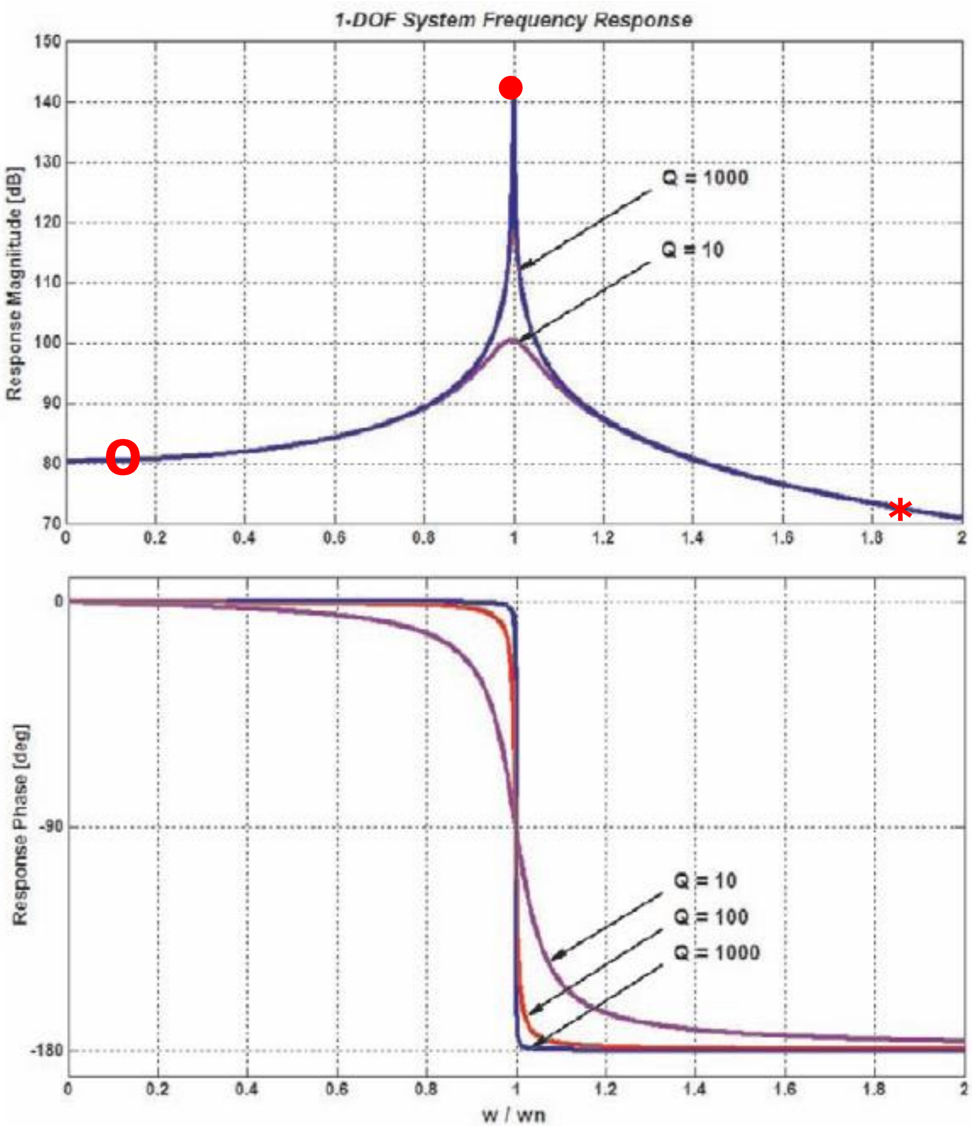
- A suspended mass moving in the drive direction (drive mode) using an actuator.
- A suspended frame that is allowed to move in the sense direction due to Coriolos force.



- This is a 2 DOF system.
- $Fc = 2\ m\ v_d\ .\ \Omega_z$

Drive Operation

- We should work in point "." for maximum drive displacement .
- $x_d = x_{od} \sin(\omega_{nd} t)$
- $v_d = \omega_{nd} x_{od} \cos(\omega_{nd} t)$
- $F_c = 2M.v_d. \Omega$



Coriolos Force Cases

- If Ω is constant: ($\Omega = \Omega_o$)

$$F_c = 2M.\ \omega_{nd}\, x_{od}\, \Omega_o \cos(\omega_{nd} t)$$

- F_c has the same frequency of drive displacement but with a 90 degree phase shift.

- If Ω is harmonic: ($\Omega = \Omega_o \cos(\delta t)$)

$$F_c = 2M.\ \omega_{nd}\, x_{od}\, \Omega_o \cos(\omega_{nd} t) \cos(\delta t)$$

$$= M.\ \omega_{nd}\, x_{od}\, \Omega_o [\cos(\omega_{nd} - \delta)t + \cos(\omega_{nd} + \delta)t$$

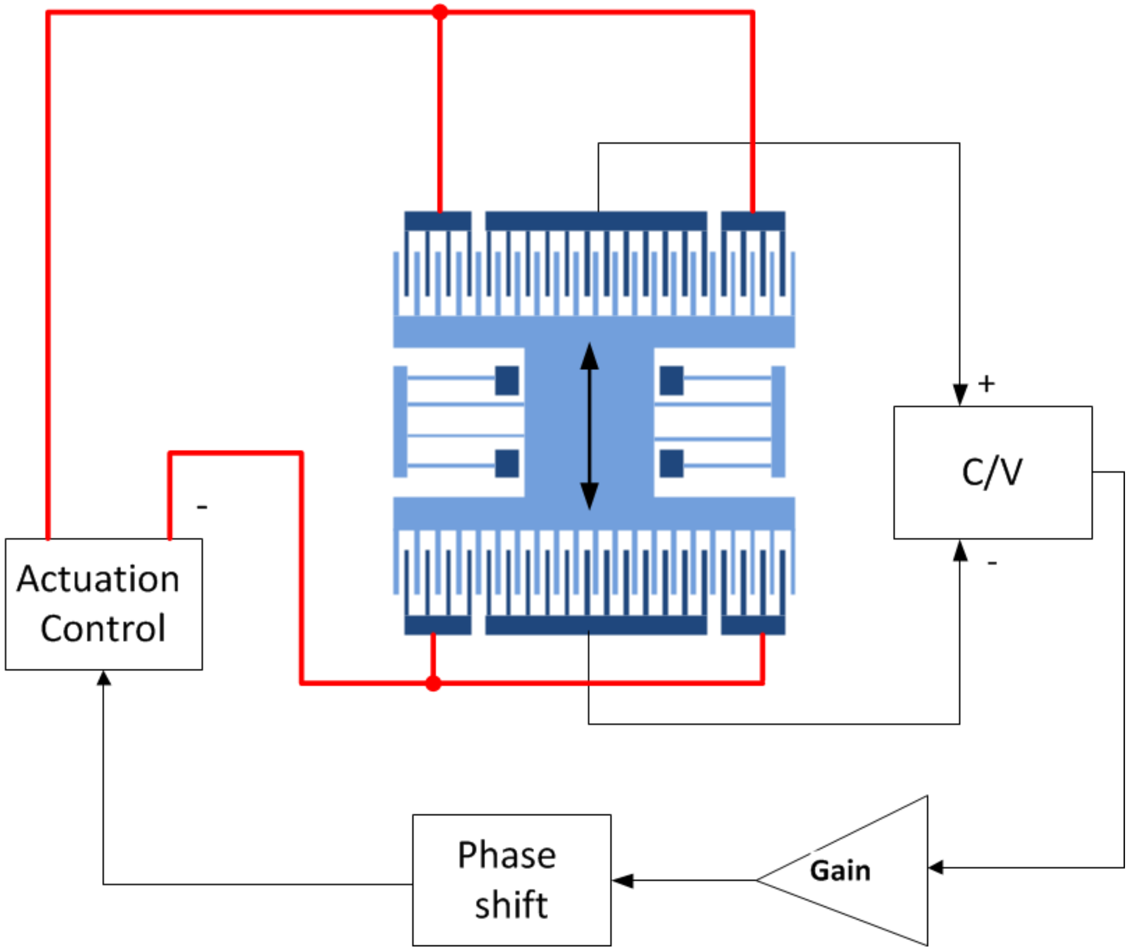
- F_c is an DSSC signal (Double side band suppressed carrier)

Drive frequency variation

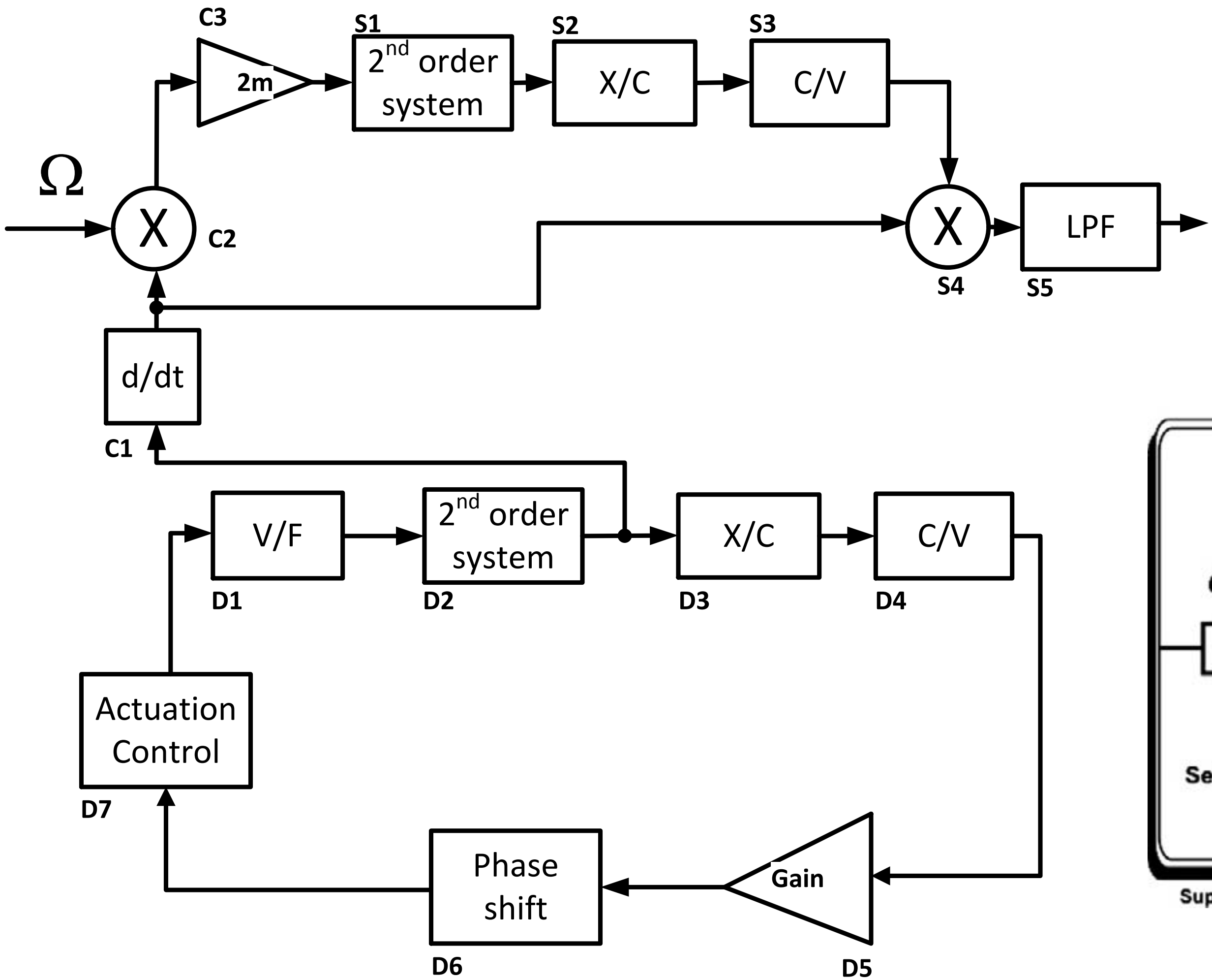
- During fabrication, ω_{nd} will vary from one part to another.
- Therefore, actuating the drive mode at constant frequency may lead to miss the peak of the frequency response.
- Therefore, we need to find a method to operate on the frequency of the peak response whatever its value is

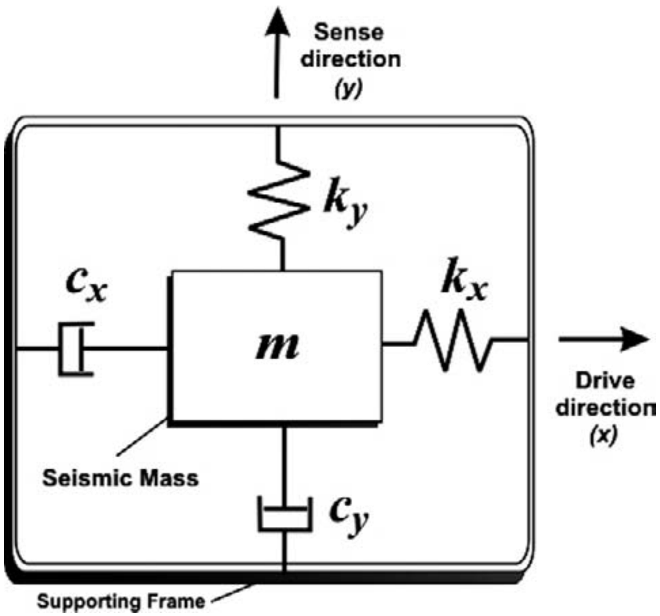
$\Rightarrow$ It makes the drive mode operate as a resonator instead of actuator

How to make a resonator ?



System Overall Block Diagram





MEMS Gyroscope (Part II)

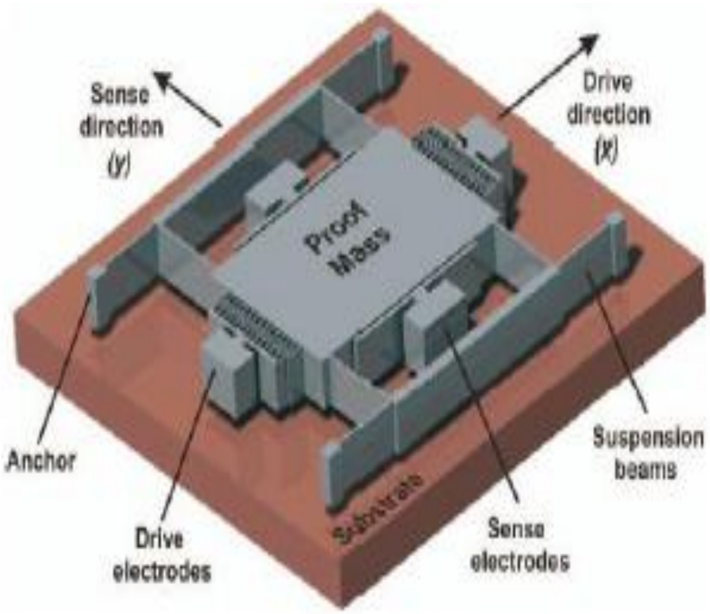
- Structure and concept
- Architectures
- Specifications

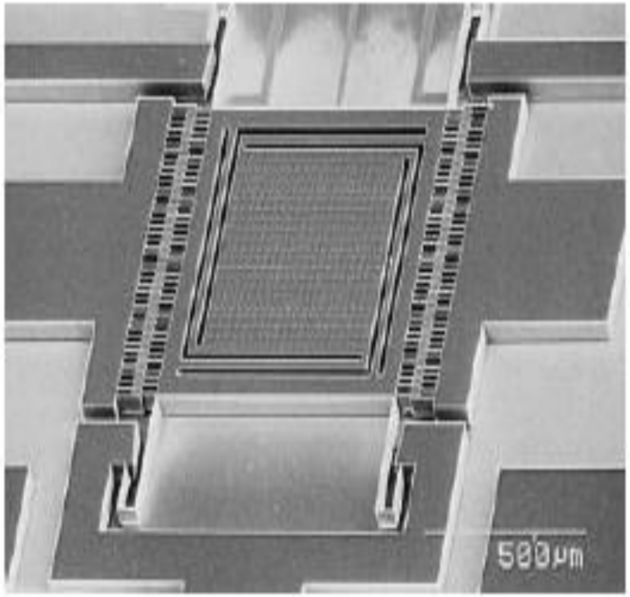
MEMS Gyro Design Varies Significantly

- Since its introduction, the comb-drive actuation and parallel-plate sensing has been the prevalent design
- Drive-mode and sense-mode resonance frequency varies between matching to completely separated.
- Some gyroscopes uses just one proof mass for both drive- and sense-mode but others use two or more masses to further to further decouple the drive- and sense-modes

Proof Mass Gyroscopes

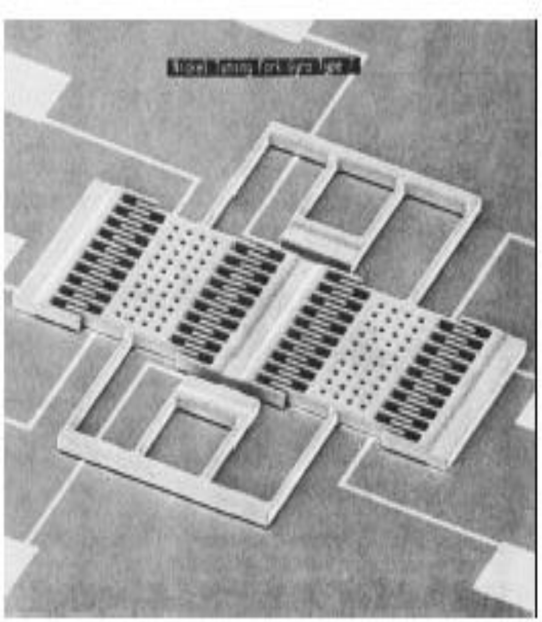
- Most reported MEMS gyroscopes
- Linear acceleration can be filtered out by using accelerometers (IMU)
- Can be in-plane or out-of-plane

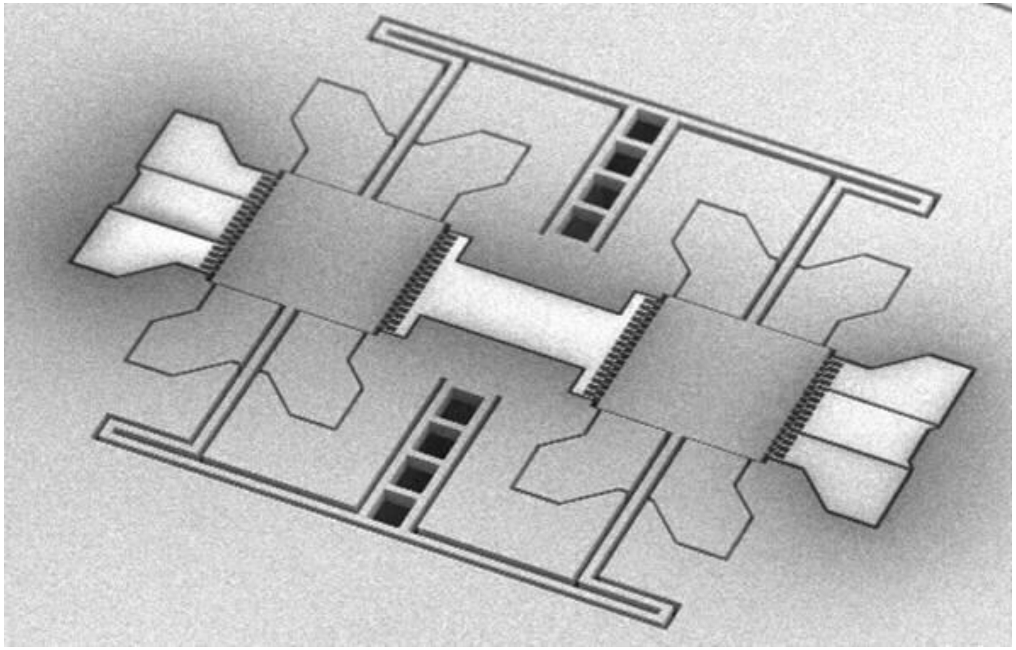




Tuning Fork Gyroscopes

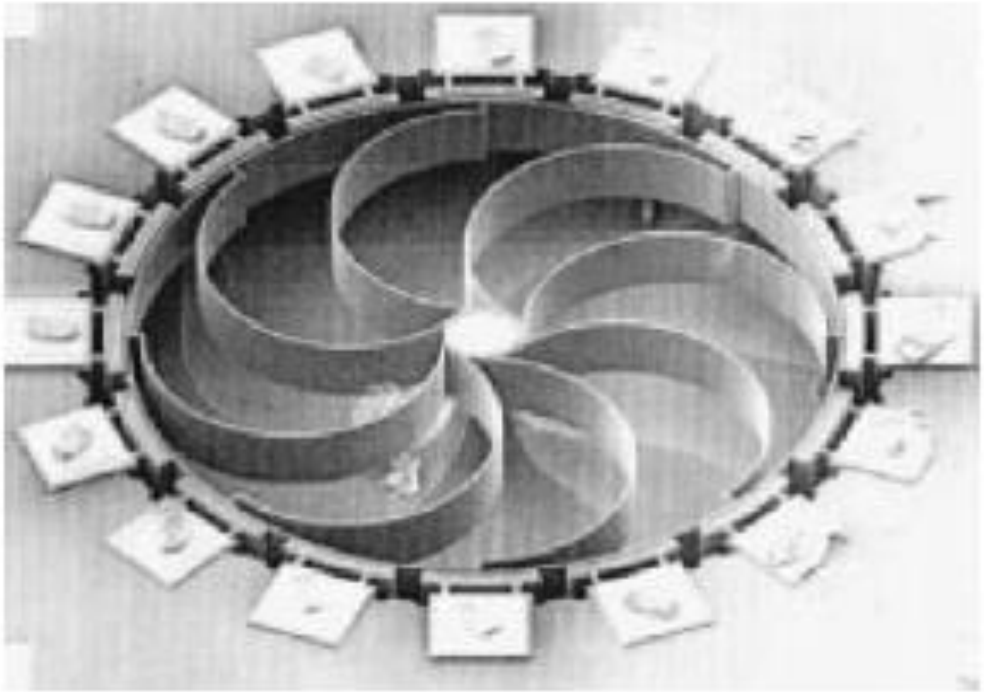
- Dependence of the output signal on linear acceleration can be electronically rejected.
- Reduces energy losses as no net motion at the junction and therefore can be mounted inertial stable at this junction.





Vibrating Rings

- Highest performance (reduced spurious vibrations, increased sensitivity and decreased temperature dependence)



MEMS Gyroscope (Part II)

- Structure and concept
- Specifications

Gyroscope Specifications

- Full- scale range [°/s]
- Resolution [°/(s/√ Hz]
- Scale factor: [V/(°/s)].
- Zero rate output
- Angular random walk
- Bias drift: The peak-to-peak value of the **slowly** varying output in the absence of a rotation rate [°/s or °/h]
- Maximum allowable shock (g in ms)

Gyroscope Grades

Parameters	Rate grade	Tactical grade	Inertial grade
Angle random walk (°/ √h)	>0.5	0.5 – 0.05	<0.001
Bias drift (°/h)	10 – 1000	0.1 – 10	<0.01
Scale factor accuracy (%)	0.1 –1	0.01 – 0.1	<0.001
Full scale range (°/s)	50 –1000	>500	>400
Max. shock in 1s, g's	10^3	$10^3 – 10^4$	10^3
Bandwidth (hz)	>70	~100	~100

Mechanical Gyroscopes

Ring Laser Gyroscopes

Fiber-optics Gyroscopes

MEMS/MOEMS