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# EE C247B - ME C218 Introduction to MEMS Design Spring 2014

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Lecture Module 15: Gyros, Noise, & MDS

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## Lecture Outline

- Reading: Senturia, Chpt. 14, Chpt. 16, Chpt. 21
- Lecture Topics:
  - ↳ Gyroscopes
  - ↳ Gyro Circuit Modeling
  - ↳ Minimum Detectable Signal (MDS)
    - Noise
    - Angle Random Walk (ARW)

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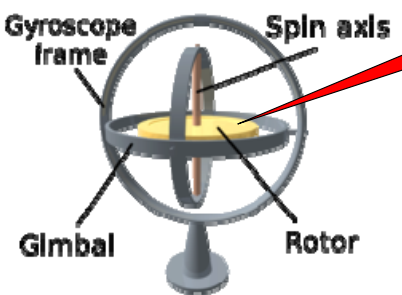
# Gyroscopes

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## Classic Spinning Gyroscope

- A gyroscope measures rotation rate, which then gives orientation → very important, of course, for navigation
- Principle of operation based on conservation of momentum
- Example: classic spinning gyroscope



Rotor will preserve its angular momentum (i.e., will maintain its axis of spin) despite rotation of its gimbled chassis



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### Vibratory Gyroscopes

- Generate momentum by vibrating structures
- Again, conservation of momentum leads to mechanisms for measuring rotation rate and orientation
- **Example:** vibrating mass in a rotating frame

Mass at rest  $y'$   $x'$   $C(t)$   
 Driven into vibration along the y-axis  
 y-displaced mass  
 Capacitance between mass and frame = constant  
 Rotate 30°  
 Get an  $x'$  component of motion  $C(t_2) > C(t_1)$

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### Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:

Input Rotation  $\vec{\Omega}$  Driven Vibration @  $f_0$   
 Coriolis (Sense) Response  $\vec{a}_c$   
 Coriolis Torque  
 Side View  
 pole  
 rotation

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### Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:

Input Rotation  $\vec{\Omega}$  Driven Vibration @  $f_0$   
 Coriolis (Sense) Response  $\vec{a}_c$   
 Coriolis Torque  
 Drive/Sense Response Spectra:  
 Amplitude  
 Drive Response  
 Sense Response  
 $f_0$  ( $@ T_1$ )  
 Coriolis Acceleration  
 Driven Velocity  
 Rotation Rate  
 $\vec{a}_c = 2\vec{v} \times \vec{\Omega}$   
 Coriolis Force  
 $\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2}$   
 Coriolis Displacement  
 Beam Mass  
 Beam Stiffness  
 Sense Frequency

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### Vibratory Gyroscope Performance

Principle of Operation

- Tuning Fork Gyroscope:

$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2} \quad \vec{a}_c = 2\vec{v} \times \vec{\Omega}$$

Beam Mass  $m$  Beam Stiffness  $k$  Sense Frequency  $\omega_r$  Driven Velocity  $\vec{v}$

- To maximize the output signal  $x$ , need:
  - ↳ Large sense-axis mass
  - ↳ Small sense-axis stiffness (Above together mean low resonance frequency)
  - ↳ Large drive amplitude for large driven velocity (so use comb-drive)
  - ↳ If can match drive freq. to sense freq., then can amplify output by Q times

Input Rotation  $\vec{\Omega}$  Driven Vibration @  $f_0$   
 Coriolis (Sense) Response  $\vec{a}_c$   
 Coriolis Torque

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### MEMS-Based Gyroscopes

**Tuning Fork Gyroscope [Ayazi, GA Tech.]**

**Vibrating Ring Gyroscope [Michigan]**

**Nuclear Magnetic Resonance Gyro [NIST]**

Labels in diagrams: Central Post, Proof Mass, Laser, Polarizer, Rb/Xe Cell, Photodiode, 3.2 mm, 1 mm,  $\dot{\theta}$ .

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### MEMS-Based Tuning Fork Gyroscope

**Drive Mode**

**Sense Mode**

- In-plane drive and sense modes pick up z-axis rotations
- Mode-matching for maximum output sensitivity
- From [Zaman, Ayazi, et al, MEMS'06]

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### MEMS-Based Tuning Fork Gyroscope

**Drive Voltage Signal**

**(-) Sense Output Current**

**(+) Sense Output Current**

**Drive Oscillation Sustaining Amplifier**

**Differential TransR Sense Amplifier**

Labels in diagram: Sense Electrodes, Sense, Tuning Electrodes, Drive Electrode, Drive,  $\Omega$ ,  $\Delta\phi$  compare, VCD, Digital PLL, VOA, From Sense, Instr. Amp, Demodulator, EPF, Rate Out.

[Zaman, Ayazi, et al, MEMS'06]

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### MEMS-Based Tuning Fork Gyroscope

**Problem: if drive frequency changes relative to sense frequency, output changes  $\Rightarrow$  bias drift**

**Need: small or matched drive and sense axis temperature coefficients to suppress drift**

Labels in diagram: Sense Electrodes, Sense, Tuning Electrodes, Drive Electrode, Drive, Amplitude, Drive Response, Sense Response,  $T_1$ ,  $T_2$ ,  $f_0(@T_1)$ ,  $f_0(@T_2)$ ,  $\omega$ .

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