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# EE C247B - ME C218 Introduction to MEMS Design Spring 2017

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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

Gyroscope frame Spin axis Gimbal Rotor

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

The diagram illustrates the operation of a vibratory gyroscope in three stages:

- Mass at rest:** A mass is shown at rest in a frame. The frame has a coordinate system with  $y$  and  $x$  axes. The mass is connected to the frame by springs and has a capacitance  $C(t)$ .
- Driven into vibration:** The mass is driven into vibration along the  $y$ -axis, as indicated by a red double-headed arrow. The mass is now  $y$ -displaced.
- Rotate 30°:** The frame is rotated 30 degrees. The mass is now in a new frame with  $y'$  and  $x'$  axes. The mass is  $y'$ -displaced. The capacitance between the mass and the frame is constant, but the capacitance values are now  $C(t_1)$  and  $C(t_2)$ , where  $C(t_2) > C(t_1)$ .

Labels in the diagram include: "Mass at rest", "Driven into vibration along the  $y$ -axis", "y-displaced mass", "Capacitance between mass and frame = constant", "Rotate 30°", "Get an  $x'$  component of motion", and " $C(t_2) > C(t_1)$ ".

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# Basic Vibratory Gyroscope Operation

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## Principle of Operation

- Tuning Fork Gyroscope:

The diagram illustrates the operation of a Tuning Fork Gyroscope in two views:

- Side View:** Shows a U-shaped tuning fork structure. The left arm is labeled "Input Rotation" with angular velocity  $\vec{\Omega}$ . The right arm is labeled "Driven Vibration @  $f_0$ " with angular velocity  $\vec{\omega}$ . The arms are connected by a central pivot. The left arm has a mass  $m$  and a spring constant  $k$ . The right arm has a mass  $m$  and a spring constant  $k$ . The left arm is labeled "Coriolis (Sense) Response" and the right arm is labeled "Coriolis Torque". The left arm has a displacement  $\vec{a}_c$  and the right arm has a displacement  $\vec{v}$ . The left arm has a force  $\vec{F}_c$  and the right arm has a force  $\vec{F}_r$ . The left arm has a displacement  $\vec{a}_c$  and the right arm has a displacement  $\vec{v}$ . The left arm has a force  $\vec{F}_c$  and the right arm has a force  $\vec{F}_r$ .
- Top View:** Shows the tuning fork structure from above. The left arm has a mass  $m$  and a spring constant  $k$ . The right arm has a mass  $m$  and a spring constant  $k$ . The left arm has a displacement  $\vec{a}_c$  and the right arm has a displacement  $\vec{v}$ . The left arm has a force  $\vec{F}_c$  and the right arm has a force  $\vec{F}_r$ . The left arm has a displacement  $\vec{a}_c$  and the right arm has a displacement  $\vec{v}$ . The left arm has a force  $\vec{F}_c$  and the right arm has a force  $\vec{F}_r$ .

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# Basic Vibratory Gyroscope Operation

## Principle of Operation

- Tuning Fork Gyroscope:

## Drive/Sense Response Spectra:

Amplitude

Drive Response

Sense Response

$f_0 (@ T_1)$

Coriolis Acceleration

Driven Velocity

Rotation Rate

Coriolis Force

Beam Mass

Coriolis Displacement


Beam Stiffness

Sense Frequency

$$\vec{a}_c = 2\vec{v} \times \vec{\Omega}$$

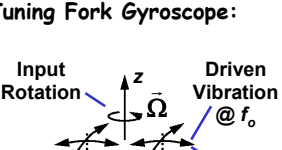
$$\vec{x} = \frac{\vec{F}_c}{k} = \frac{m\vec{a}_c}{k} = \frac{\vec{a}_c}{\omega_r^2}$$

# Vibratory Gyroscope Performance



## Principle of Operation

- Tuning Fork Gyroscope:
 



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

$$\vec{a}_c = 2 \vec{v} \times \vec{\Omega}$$

- 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

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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]

Labels in diagram: Sense Electrodes, Drive Electrode, Tuning Electrodes, Proof Mass, Anchors, Quadrature Cancellation Electrodes, Sense Electrodes.

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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, Tuning Electrodes, Drive Electrode, Drive, Sense,  $\Omega$ ,  $\Delta\Phi$  compare, VCO, Digital PLL, VGA, Demodulator, Instr. Amp, LPF, 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, Drive Electrode, Tuning Electrodes, Proof Mass, Anchors, Quadrature Cancellation Electrodes, Sense Electrodes.

Graph labels: Amplitude,  $\omega$ ,  $f_0(@T_1)$ ,  $f_0(@T_2)$ ,  $T_1$ ,  $T_2$ , Drive Response, Sense Response.

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### Mode Matching for Higher Resolution

- For higher resolution, can try to match drive and sense axis resonance frequencies and benefit from Q amplification

**Problem:** mismatch between drive and sense frequencies  $\Rightarrow$  even larger drift!

**Need:** small or matched drive and sense axis temperature coefficients to make this work

Amplitude vs  $\omega$  graph showing Drive Response and Sense Response curves. Resonance frequencies are marked at  $f_o(@T_1)$  and  $f_o(@T_2)$ .

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### Issue: Zero Rate Bias Error

- Imbalances in the system can lead to zero rate bias error

**Mass imbalance**  $\Rightarrow$  off-axis motion of the proof mass

**Drive imbalance**  $\Rightarrow$  off-axis motion of the proof mass

**Output signal in phase with the Coriolis acceleration**

**Quadrature output signal that can be confused with the Coriolis acceleration**

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### Nuclear Magnetic Res. Gyroscope

- The ultimate in miniaturized spinning gyroscopes?
- from CSAC, we may now have the technology to do this

Better if this is a noble gas nucleus (rather than e-), since nuclei are heavier  $\Rightarrow$  less susceptible to B field

**Soln:** Spin polarize  $Xe^{129}$  nuclei by first polarizing e- of  $Rb^{87}$  (a la CSAC), then allowing spin exchange

**Challenge:** suppressing the effects of B field

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### MEMS-Based Tuning Fork Gyroscope

**Drive Voltage Signal**

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**Drive Oscillation Sustaining Amplifier**

**Differential TransR Sense Amplifier**

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

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