

### 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  $y$   $x$   $y'$   $x'$

Driven into vibration along the  $y$ -axis

$C(t)$

$y$ -displaced mass

Capacitance between mass and frame = constant

Rotate 30°

Get an  $x'$  component of motion

$C(t_2) > C(t_1)$

$C(t_1)$

$C(t_2)$

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### Basic Vibratory Gyroscope Operation

**Principle of Operation**

- Tuning Fork Gyroscope:

Input Rotation  $\vec{\Omega}$

Driven Vibration @  $f_0$

$\vec{v}$  ← drive direction

Coriolis (Sense) Response

Coriolis Torque

Side View

Top View

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Coriolis (Sense) Response

Coriolis Torque

Drive/Sense Response Spectra:

Amplitude

Drive Response

Sense Response

$f_0$  (@  $T_1$ )

$\omega$

Coriolis Acceleration

Driven Velocity

Rotation Rate

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

Coriolis Force

Beam Mass

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

Coriolis Displacement

Beam Stiffness

Sense Frequency

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### Vibratory Gyroscope Performance

**Principle of Operation**

- Tuning Fork Gyroscope:

Input Rotation  $\vec{\Omega}$

Driven Vibration @  $f_0$

$\vec{v}$

Coriolis (Sense) Response

Coriolis Torque

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

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

Beam Mass

Beam Stiffness

Sense Frequency

Driven Velocity

- 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

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

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

**Drive Mode**

**Sense Mode**

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### MEMS-Based Tuning Fork Gyroscope

Labels: (-) Sense Output Current, (+) Sense Output Current, Drive Voltage Signal, Drive Electrode, Sense Electrodes, Tuning Electrodes,  $\Omega$ ,  $\Delta\Phi$  compare, VCO, VOA, Digital PLL, Demodulator, Instr. Amp, Rate Out,  $\frac{1}{s^2}$ .

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

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### MEMS-Based Tuning Fork Gyroscope

Labels: Sense Electrodes, Drive Electrode, Tuning Electrodes, Proof Mass, Anchors, Quadrature Cancellation Electrodes, Sense Electrodes, Amplitude,  $\omega$ ,  $f_0(@T_1)$ ,  $f_0(@T_2)$ ,  $T_1$ ,  $T_2$ .

**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

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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

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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  $\text{Xe}^{129}$  nuclei by first polarizing e- of  $\text{Rb}^{87}$  (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**

**(-) Sense Output Current**

**(+) Sense Output Current**

**Drive Oscillation Sustaining Amplifier**

**Differential TransR Sense Amplifier**

**Rate Out**

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

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