

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

Get an x' component of motion

Rotate 30°

$C(t_2) > C(t_1)$

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Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:

Input Rotation $\vec{\Omega}$ z \vec{v} \vec{a}_c \vec{v} \vec{a}_c

Driven Vibration @ f_0

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 (y-direction)

Sense Response (x-direction)

f_0 (@ T_1)

ω

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

Driven Velocity

Rotation Rate

Beam Mass

Coriolis Force $\vec{F}_c = m\vec{a}_c = \frac{\vec{a}_c}{\omega_r^2}$

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

Beam Stiffness

Sense Frequency

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Vibratory Gyroscope Performance

Principle of Operation

- Tuning Fork Gyroscope:

Input Rotation $\vec{\Omega}$ z \vec{v} \vec{a}_c \vec{v} \vec{a}_c

Driven Vibration @ f_0

Coriolis (Sense) Response

Coriolis Torque

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

Beam Mass m k ω_r \vec{a}_c \vec{v} $\vec{\Omega}$

Beam Stiffness k

Sense Frequency ω_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 $\rightarrow \vec{x} = \frac{Q\vec{F}_c}{k}$

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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, $\dot{\theta}$, Flexure.

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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: 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: Sense Electrodes, Drive Electrode, Tuning Electrodes, Proof Mass, Instr. Amp, Demodulator, LPF, Rate Out, $\Delta\phi$ compare, VCO, Digital PLL, V_{REF}.

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

Amplitude vs ω graph showing Drive Response and Sense Response curves with frequencies $f_0(@T_1)$ and $f_0(@T_2)$.

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Mode Matching for Higher Resolution

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- 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

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- 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

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- 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

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Drive Oscillation Sustaining Amplifier

Differential TransR Sense Amplifier

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

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