

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 $C(t_2) > C(t_1)$

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 5

Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:

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

Driven Vibration @ f_0

Coriolis (Sense) Response

Coriolis Torque

Side View

Top View

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 6

Basic Vibratory Gyroscope Operation

Principle of Operation

- Tuning Fork Gyroscope:

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

Driven Vibration @ f_0

Coriolis (Sense) Response

Coriolis Torque

Drive/Sense Response Spectra:

Amplitude

Drive Response

Sense Response

$f_0 (@ T_1)$

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

Driven Velocity

Rotation Rate

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

Beam Mass

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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 7

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 k ω_r^2 \vec{a}_c \vec{v} $\vec{\Omega}$

Coriolis (Sense) Response

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

Driven Vibration @ f_0

Coriolis Torque

- 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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 8

MEMS-Based Gyroscopes

Tuning Fork Gyroscope [Ayazi, GA Tech.]

Vibrating Ring Gyroscope [Michigan]

Nuclear Magnetic Resonance Gyro [NIST]

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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 9

MEMS-Based Tuning Fork Gyroscope

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

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]

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 10

MEMS-Based Tuning Fork Gyroscope

Labels: Drive Voltage Signal, Drive, Sense, Drive Electrode, Tuning Electrodes, Sense Electrodes, Ω , $\Delta\Phi$ compare, VCO, Digital PLL, VGA, (-) Sense Output Current, (+) Sense Output Current, From Sense, Instr. Amp, Demodulator, LPF, Rate Out.

Drive Oscillation Sustaining Amplifier

Differential TransR Sense Amplifier

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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 11

MEMS-Based Tuning Fork Gyroscope

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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 12

Mode Matching for Higher Resolution

UC Berkeley

- 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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 13

Issue: Zero Rate Bias Error

UC Berkeley

- 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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 14

Nuclear Magnetic Res. Gyroscope

UC Berkeley

- 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 Xe¹²⁹ nuclei by first polarizing e- of Rb⁸⁷ (a la CSAC), then allowing spin exchange

Challenge: suppressing the effects of B field

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 15

MEMS-Based Tuning Fork Gyroscope

UC Berkeley

Drive Oscillation Sustaining Amplifier

Differential TransR Sense Amplifier

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

EE C245: Introduction to MEMS Design LecM 15 C. Nguyen 11/18/08 16