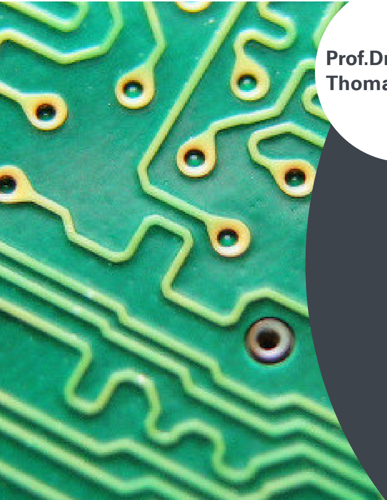
Universität Stuttgart



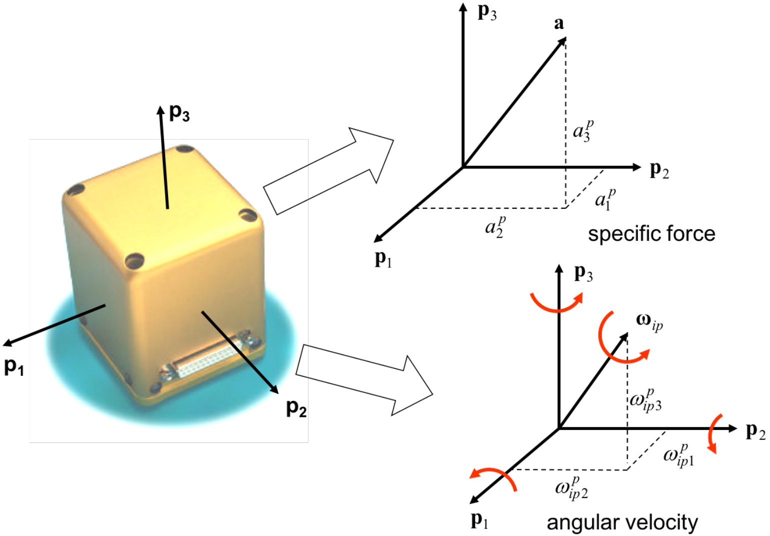
Prof.Dr.
Thomas Hobiger

Integrated Positioning and Navigation

Sensors

7

Sensors



p3
p1
p2
p3
a
a_3^p
p2
a_1^p
a_2^p
p1
specific force
p3
ω_{ip}
ω_{ip3}^p
p2
ω_{ip1}^p
ω_{ip2}^p
p1
angular velocity

Sensors - cont'd

Accelerometers – Spring suspended mass

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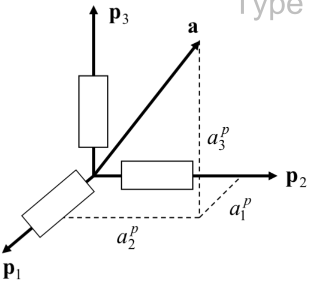
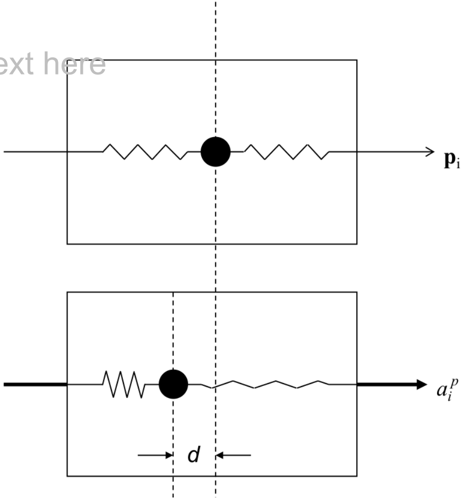




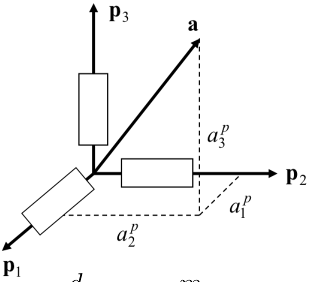
$$d = \frac{m}{k} \cdot a_i^p$$

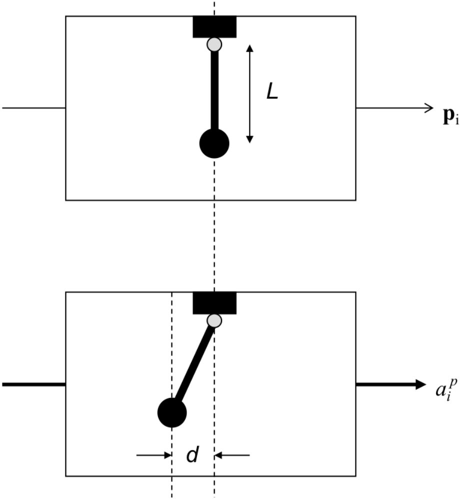
k: spring parameter [kg/s^2]

m: mass [kg]

Sensors - cont'd

Accelerometers – Pendulum





$$\frac{d}{L} \approx \alpha = \frac{m}{k} \cdot a_i^p$$

k: hinge parameter

L: pendulum length

m: mass

Sensors - cont'd

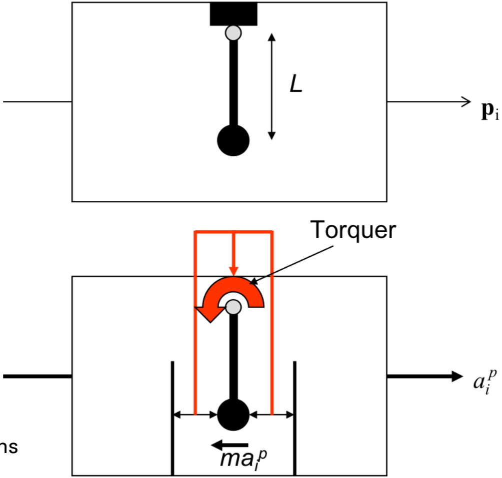
Accelerometers – Closed loop pendulum

$$T = m \cdot L \cdot a_i^p$$

L: pendulum length

m: mass

T: torque to be supplied by torquer to re-balance mass



- Closed-loop operation also for other types of accelerometers
- Closed-loop operation removes non-linearity problems

Sensors - cont'd

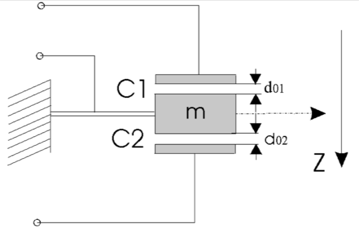
Accelerometers – Common Types

- Capacitive: metal beam or micro machined feature produces capacitance, change in capacitance related to acceleration
- Piezoelectric: piezoelectric crystal mounted to mass – voltage output converted to acceleration
- Piezoresistive: beam or micro machined feature whose resistance changes with acceleration
- Hall Effect: motion converted to electrical signal by sensing of changing magnetic fields
- Magnetoresistive: material resistivity changes in presence of magnetic field
- Heat Transfer: Location of heated mass tracked during acceleration by sensing temperature

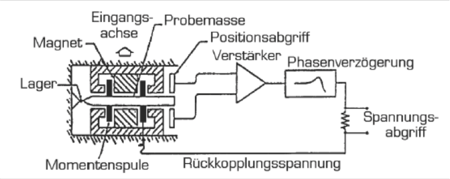
Sensors - cont'd

Accelerometers

Capacitive Measurement



Closed loop pendulum accelerometer



Sensors - cont'd

Accelerometers – Vibrating string

$$f = \frac{1}{2l}\sqrt{\frac{F}{\mu}}$$

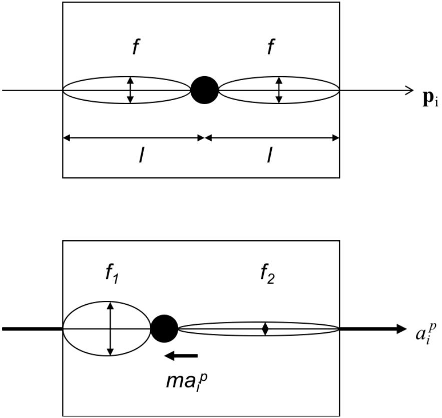
F: force
m: mass
μ: string mass per unit length

For small displacements:

$$f_1 = \frac{1}{2l}\sqrt{\frac{F - m a_i^p}{\mu}}$$

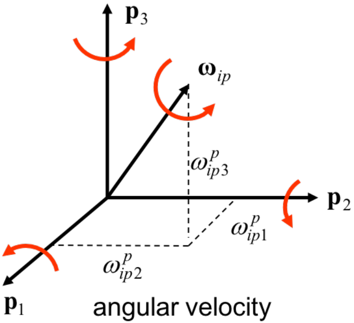
$$f_2 = \frac{1}{2l}\sqrt{\frac{F + m a_i^p}{\mu}}$$

$$f_1^2 - f_2^2 = \frac{m}{2\mu l^2} a_i^p$$



Sensors - cont'd

Gyroscopes (Rotation Rate Sensors)



Types of Gyroscopes:

- Mechanical (rotating mass)
- Optical (Laser, Fibre Optics)
- MEMS (vibrating mass)

Sensors - cont'd

Gyroscopes (Rotation Rate Sensors)

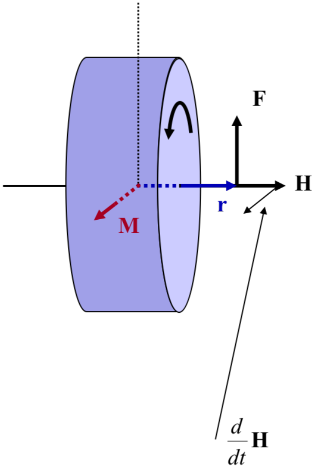
Type	mechanical	optical	MEMS
Drift [$^\circ/h$]	0.1 - 0.001	FOG: 0.1-100 RLG: 0.01 - 1 (0.00001)	1-500
Price [EUR]	> 10,000	1,000 - 50,000	10-100

Market segments

Market segment	Drift class [$^\circ/h$]	Size [cm^3]	Price [EUR]	Application
Mass market	5-100	10	10-500	automotive, games camera, guided projectiles, medical
Tactical navigation	0.1-1	1,000	2,000	guided munitions AHRS, missiles targeting
Precise navigation	<0.01	10,000	5,000 - 100,000	Military aircraft, land & marine nav., strategic aircraft, space

Sensors - cont'd

Mechanical Gyroscopes



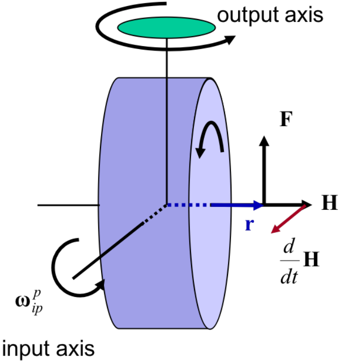
Law of Conservation of Angular Momentum

$$\frac{d}{dt}\boldsymbol{H} = \boldsymbol{M}$$
$$\boldsymbol{M} = \boldsymbol{r} \times \boldsymbol{F}$$
$$\boldsymbol{H} = \boldsymbol{I}\boldsymbol{\omega}$$

$\boldsymbol{M}$: Torque
$\boldsymbol{H}$: Angular momentum
$\boldsymbol{F}$: Force
$\boldsymbol{r}$: Lever Arm
$\boldsymbol{I}$: Tensor of Inertial
$\boldsymbol{\omega}$: rotational velocity

Sensors - cont'd

Mechanical Gyroscopes



Rotational velocity about input axis generates force $\boldsymbol{F}$

Force $\boldsymbol{F}$ generates torque $\boldsymbol{M}$

Torque is equal to change in angular momentum

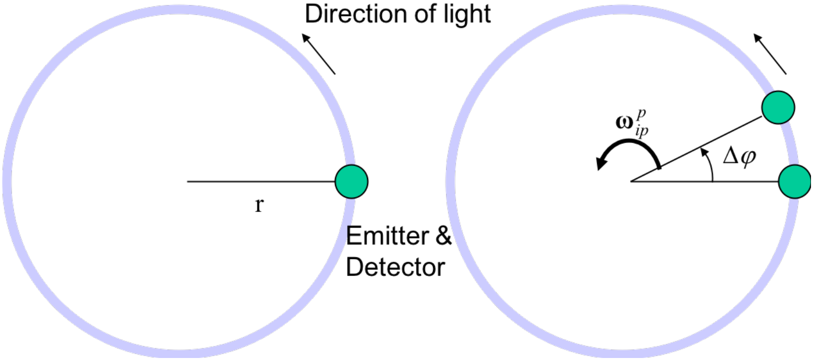
Torque generator on output axis keeps angular momentum constant

Amount of torque generated on output axis (voltage) is a measure for rotational velocity about input axis

The torque generated is proportional to rotational velocity

Sensors - cont'd

Optical Gyroscopes



without rotation

travel time $\Delta t = \frac{2\pi r}{c}$

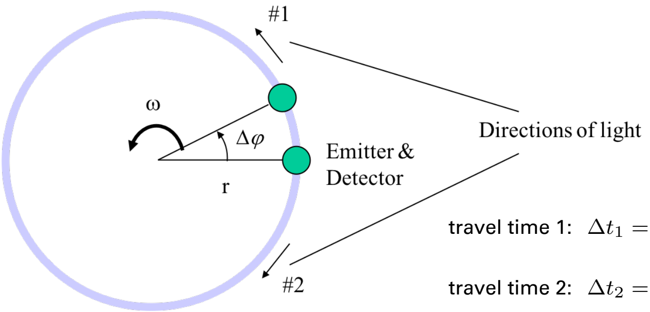
with rotation

$$\Delta t = \frac{2\pi r + r\Delta\varphi}{c}$$

$$\Delta\varphi \approx \frac{2\pi r}{c}\omega_{ip}^{p}$$

Sensors - cont'd

Optical Gyroscopes



travel time 1: $\Delta t_1 = \dfrac{2\pi r + r\Delta\varphi}{c}$

travel time 2: $\Delta t_2 = \dfrac{2\pi r - r\Delta\varphi}{c}$

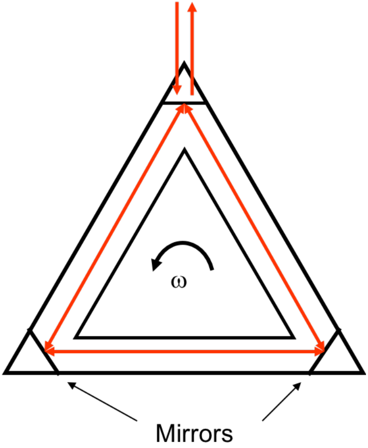
from the difference: $\omega_{ip}^{p} = \dfrac{c^2(\Delta t_1 - \Delta t_2)}{4\pi r^2}$

Measured time difference is proportional to

- rotational velocity
- area enclosed by light path

Sensors - cont'd

Optical Gyroscopes - Lasergyro

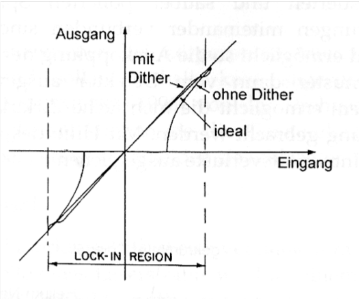


Advantages:

- Insensitive to accelerations
- Large working range

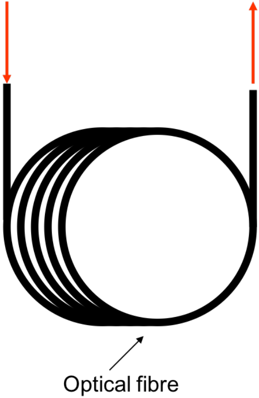
Disadvantage

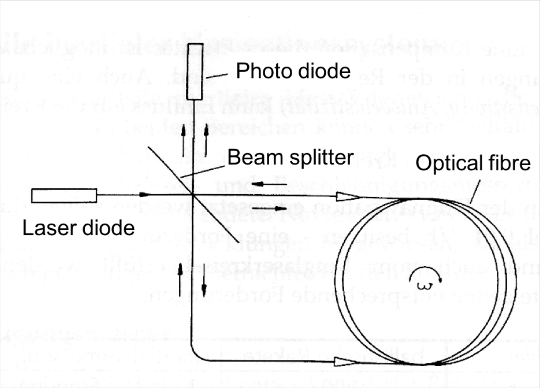
- lock in effect (minimized by small high frequency movements)



Sensors - cont'd

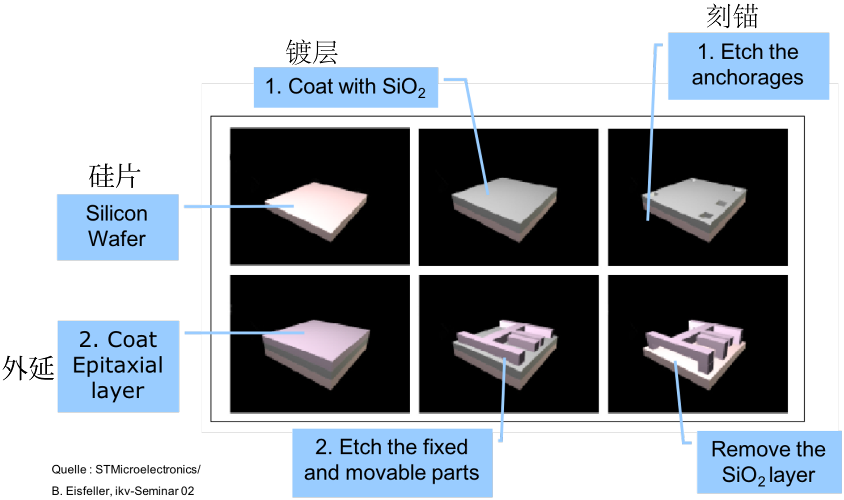
Optical Gyroscopes - Fibre-optics Gyro
For details see guest lecture next week!





Sensors - cont'd

Vibrating Mass Gyroscopes (MEMS) - Production

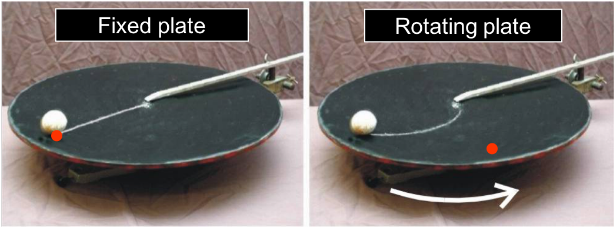


Quelle : STMicroelectronics/
B. Eisfeller, ikv-Seminar 02

Sensors - cont'd

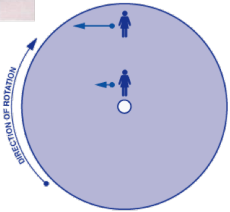
Vibrating Mass Gyroscopes – Principle

Work on the basis of the Coriolis force: $\boldsymbol{F}_c = 2 \cdot \boldsymbol{M} \cdot (\boldsymbol{v} \times \boldsymbol{\omega})$



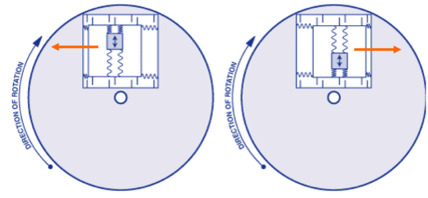
from: FH Merseburg

Person on a moving plate walking outwards

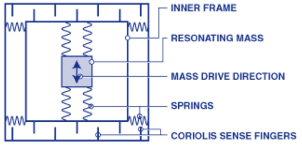


Sensors - cont'd

Vibrating Mass Gyroscopes – Principle



$$F_c = 2 \cdot \boldsymbol{M} \cdot (\boldsymbol{v} \times \boldsymbol{\omega})$$



from: Analog Devices

Principle:

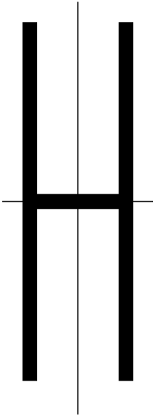
- Capacitive sensing element attached to the resonator

Advantage

- Immunity to shocks and vibrations

Sensors - cont'd

Vibrating Mass Gyroscopes (Tuning fork)



Conservation of Linear Momentum

$$\frac{d}{dt}(m\dot{\boldsymbol{x}}) = \boldsymbol{F}$$

Constant mass, force-free:

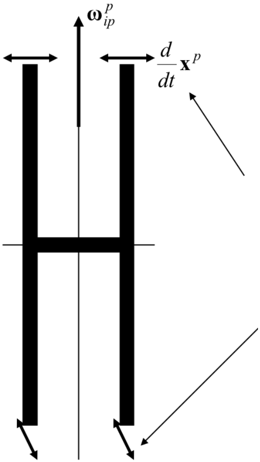
$$m\frac{d^2}{dt^2}\boldsymbol{x} = \boldsymbol{0}$$

Transform from i-system to p-system
(c.f. Module 5)

$$\frac{d^2}{dt^2}\boldsymbol{x}^p + 2\boldsymbol{\Omega}^p_{ip} \cdot \frac{d}{dt}\boldsymbol{x}^p + \boldsymbol{\Omega}^p_{ip} \cdot \boldsymbol{\Omega}^p_{ip} \cdot \boldsymbol{x}^p = \boldsymbol{0}$$

Sensors - cont'd

Vibrating Mass Gyroscopes (Tuning fork)



Re-arrange equation

$$\frac{d^2}{dt^2}\boldsymbol{x}^p = -2\boldsymbol{\Omega}_{ip}^p \cdot \frac{d}{dt}\boldsymbol{x}^p - \boldsymbol{\Omega}_{ip}^p \cdot \boldsymbol{\Omega}_{ip}^p \cdot \boldsymbol{x}^p$$

Induce high linear velocity (vibrations), then first term on r.h.s. dominates

$$\frac{d^2}{dt^2}\boldsymbol{x}^p \approx -2\boldsymbol{\Omega}_{ip}^p \cdot \frac{d}{dt}\boldsymbol{x}^p = -2\boldsymbol{\omega}_{ip}^p \times \frac{d}{dt}\boldsymbol{x}^p$$

Vibrating mass reacts with accelerations proportional and orthogonal to

- linear velocity
- rotational velocity

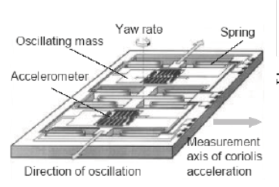
Sensors - cont'd

音叉

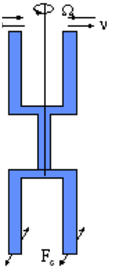
Vibrating Mass Gyroscopes (Tuning fork)

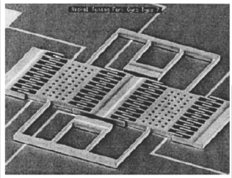
Principle:

- Two masses driven to oscillate with equal amplitude in opposite directions
- Rotation generates a Coriolis force $\rightarrow$ orthogonal vibration results
- Capacity is a measure for the angular rate (Amplitude & $\Delta\varphi$)



Bosch silicon dual mass tuning forc design





First working prototype of the Draper Lab comb drive tuning fork

Disadvantage:

- Very sensible to shocks and vibrations

Watch: `https://www.youtube.com/watch?v=W12KARSKNhQ`

Sensors - cont'd

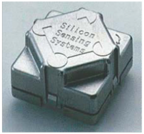
共鸣器
Vibrating Mass Gyroscopes (Wine glass resonator / Hemispherical Resonator Gyros)

Principle:

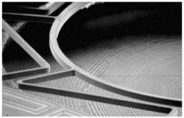
- A vibrating ring is driven to resonance 共振
- Rotation displaces nodal points $\rightarrow$ measure of angular rate
- E.g.: Gyro of Sumito und British Aerospace (29x29x18 mm^3)

Advantage:

- non-sensitive against shocks and vibrations

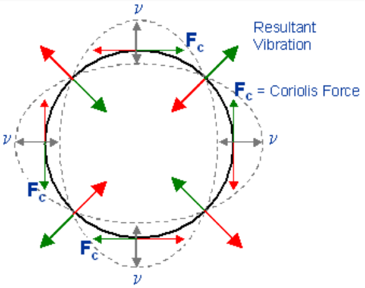


from: Silicon Sensing Systems



Part of a vibrating ring

from: sensormag.com



Shell Resonator
Wine glass, ring

Sensors - cont'd

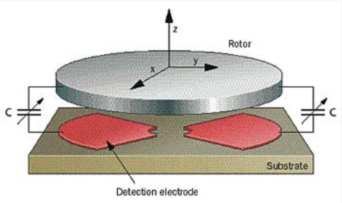
Vibrating Mass Gyroscopes (Vibrating Wheel)

Principle:

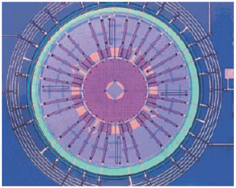
- Wheel is driven to vibrate around its axis of symmetry
- Rotation about either in plane axis results in the wheels tilting
- Changes detected with capacitive electrodes under the wheel
- Degree of angular rate

Advantage:

- Sensitive in 2 directions



Schematic design concept for Robert Bosch vibrating wheel



Polysilicon surface-micromachined vibrating wheel from Berkley Sensors and Actuators Center

Sensors - cont'd

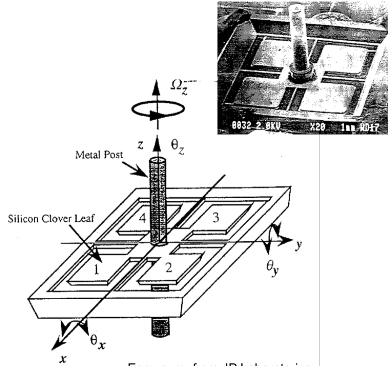
Vibrating Mass Gyroscopes (Foucault pendulum gyroscope)

Principle:

- Vibrating rod
- Rotation around the rod leads to an orthogonal oscillation
- Amplitude and Phase are a measure for the rate of rotation

Disadvantage:

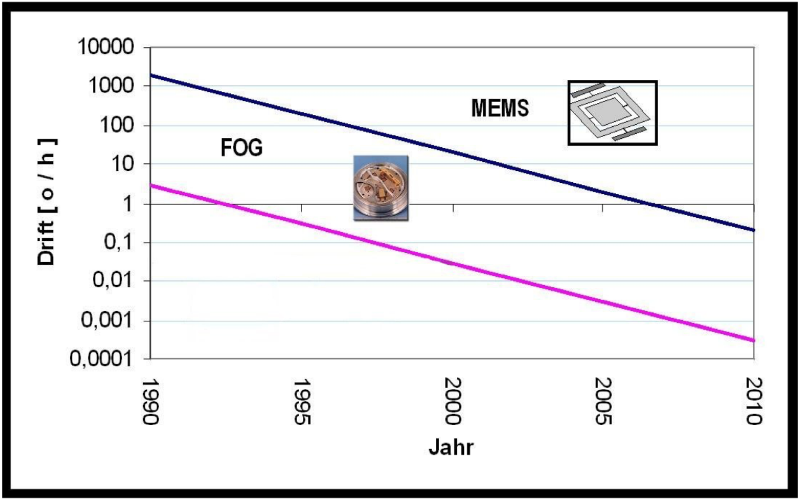
- Relative large metal rod necessary
- No planar realization possible



Esp.: gyro from JP Laboratories, (Pasadena)

Sensors - cont'd

Preview



Quelle: Vortrag Prof. Eissfeller, ikv-Seminar 02

Sensors - cont'd

Accelerometer and Gyroscope Measurements (cf. module 04)

Most modern Inertial Measurement Units (IMU) provide digital readouts at regular time intervals

Readouts (measurements) at time t_k are integrals (sums) of the sensed specific force and rotational velocity since the last readout at time t_{k-1}

Velocity increment: $$\Delta \boldsymbol{v}^p(t_k) = \int_{t_{k-1}}^{t_k} \boldsymbol{a}^p(\tau) d\tau$$

Angular increment: $$\Delta \boldsymbol{\alpha}_{ip}^p(t_k) = \int_{t_{k-1}}^{t_k} \boldsymbol{\omega}_{ip}^p(\tau) d\tau$$

- Measurement output rates are 50Hz – 200Hz
- Internal sampling rate can be in kHz-range
- Any non-linear platform motion within readout interval cannot be recovered from readout data