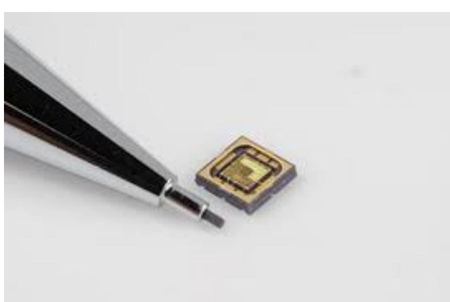
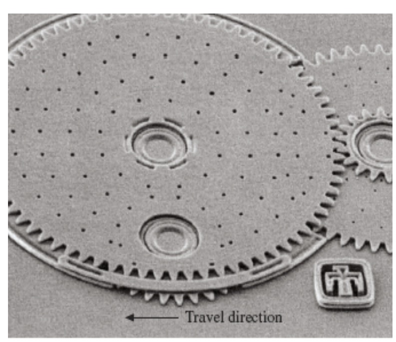
MEMS:
Microelectromechanical Systems

What are MEMS?

- Micro-electro-mechanical systems
- miniaturized mechanical and electro-mechanical elements
- having some sort of mechanical functionality
- convert a measured mechanical signal into an electrical signal



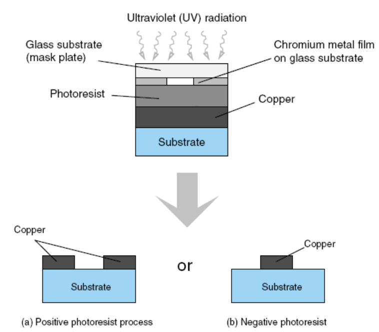


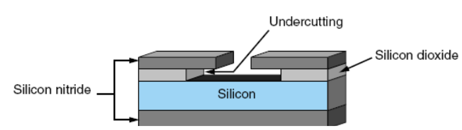
Fundamentals of MEMS Devices

- Silicon
  - Already in use
  - Manipulatable conductivity
  - Allows for integration
- Thin-Film Materials
  - Silicon dioxide
  - Silicon nitride

Micromachining Fabrication

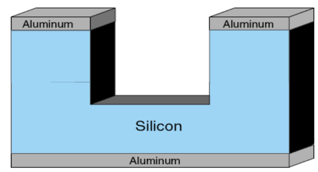
- Thin Films
  - Layers (μm) put on Si
  - Photomask
    - Positive or negative
- Wet Etching
  - Isotropic
  - Anisotropic
  - KOH



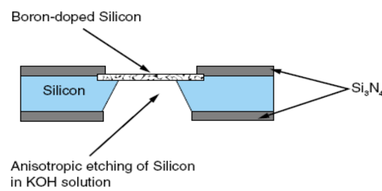


Micromachining Fabrication II

- Dry Etching
  - RIE
  - DRIE

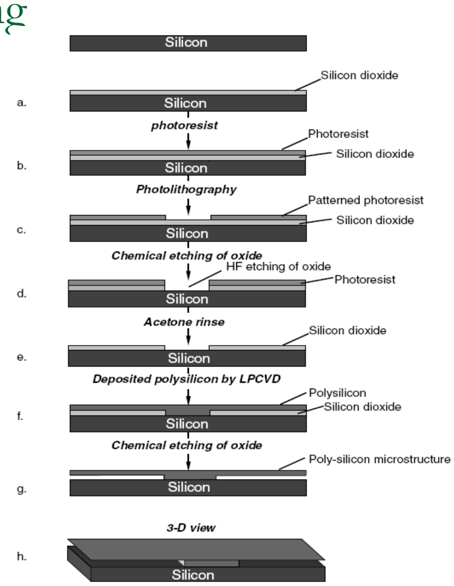


- Rate-Modified Etching
  - Cover with Boron
  - Wet etch with KOH



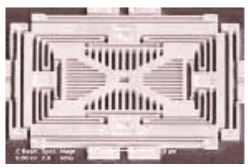
Surface Micromachining

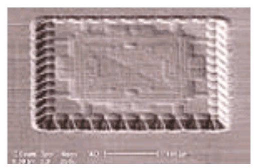
- Grow silicon dioxide
- Apply photoresist
- Expose and develop
- Etch silicon dioxide
- Remove photoresist
- Deposit polysilicon
- Remove silicon dioxide



MEMS Packaging

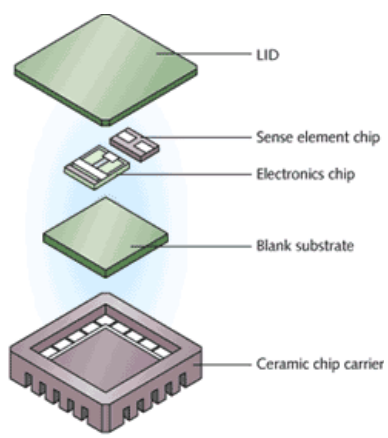
- Purposes
  - Reduce EMI
  - Dissipate Heat
  - Minimize CTE
  - Deliver Required Power
  - Survive Environment





Types of MEMS Packages

- Ceramic Packaging
  - Hermetic when sealed
  - High Young's Modulus
  - Flip Chip or Wirebonding
- Plastic Packaging
  - Not Hermetic
  - Postmolding
  - Premolding
- Metal Packaging
  - Hermetic when sealed
  - Easy to assemble
  - Low Pin Count



Typical MEMS Devices

- Sensors
  - Pressure Sensors
  - Accelerometers
- Actuators
  - Gyroscopes
  - High Aspect Ratio Electrostatic Resonators
  - Thermal Actuators
  - Magnetic Actuators
  - Comb-drives

Typical MEMS Devices

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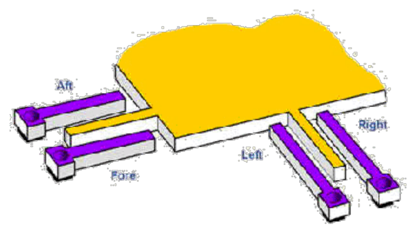
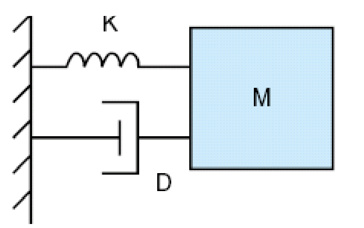
Accelerometers

- Applications:
  - Air bag crash sensors
  - Active suspension systems
  - Antilock brake systems
  - Ride control systems
- Units of mV/g

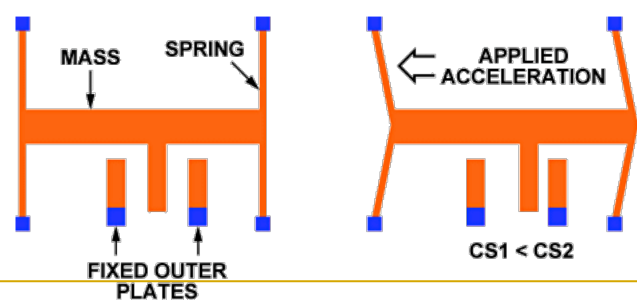


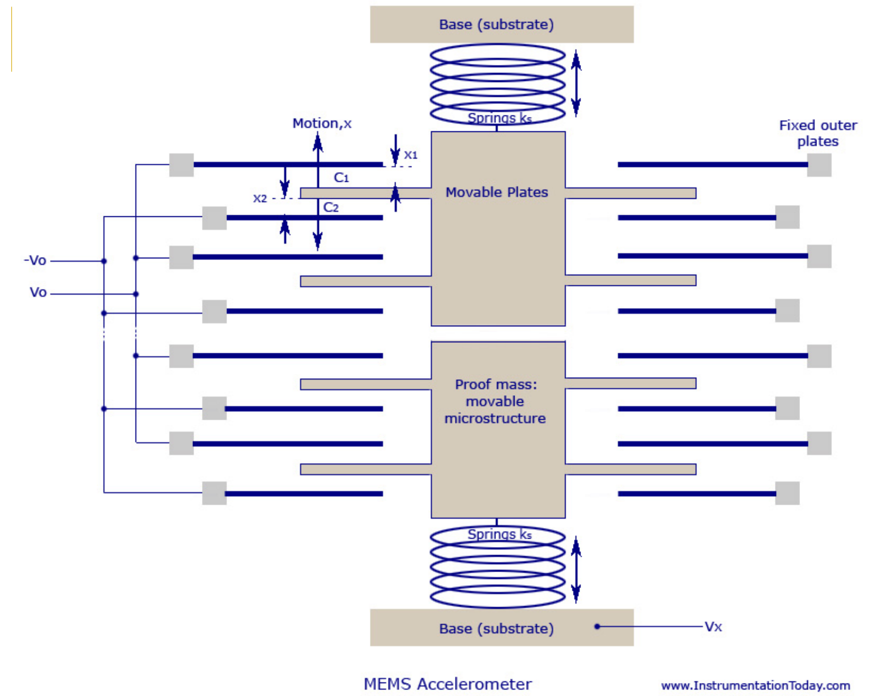
MEMS Accelerometer

Mass, Spring, Damper Model

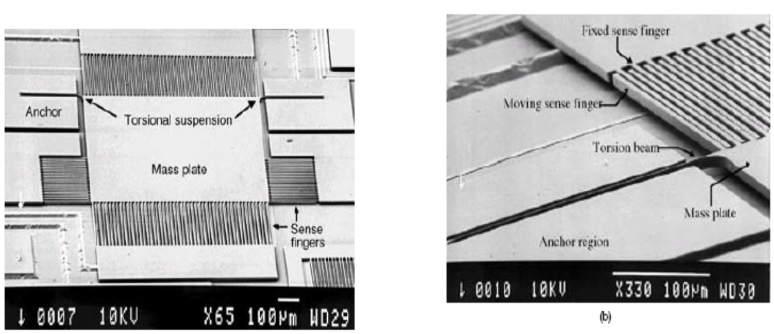


$$\underbrace{F}_{\text{external force}} = \underbrace{M \cdot \frac{d^2x}{dt^2}}_{\text{proof mass inertia}} + \underbrace{D \cdot \frac{dx}{dt}}_{\text{damping force}} + \underbrace{K \cdot x}_{\text{mechanical restoring force}}$$





MEMS Accelerometer (cont' d)

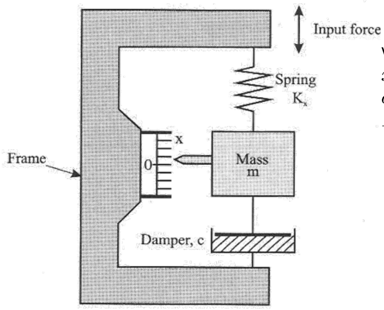


(b)

FIGURE 14.18 (a) SEM view of a silicon-on-glass torsional MEMS accelerometer; (b) close-up of the torsional beam and the sense fingers. (Courtesy of Prof. Khalil Najafi, University of Michigan)

Accelerometer Principle

- mass-spring type accelerometer



$$F = m\left(\frac{d^2x}{dt^2}\right) + c\left(\frac{dx}{dt}\right) + Kx$$

where
$x =$ displacement from the rest position of the mass
$c =$ damping coefficient
$K =$ spring stiffness

if $c\left(\frac{dx}{dt}\right) = 0$

$$m = -\frac{m}{K}a$$

- To increase accelerometer sensitivity : m large or K small

Accelerometer Principle

- Analog Devices ADXL202
  - surface-micromachined accelerometer
- Sensor Principle $x = -\frac{m}{K}a$

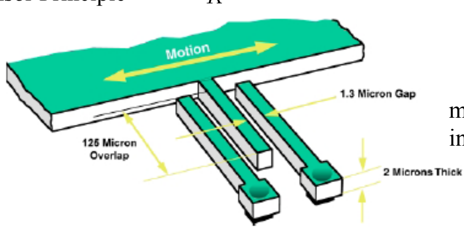


Figure 1. Beam Dimensions for a Single Finger.

measure capacitance, which is inversely proportional to the gap

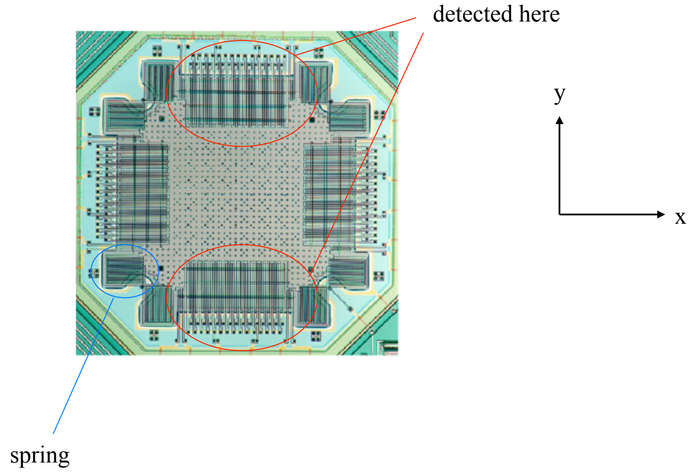
$$C = \frac{\epsilon A}{d}$$

ϵ : permittivity
A : contact area

- To increase accelerometer sensitivity :
  - large m, small K, large A

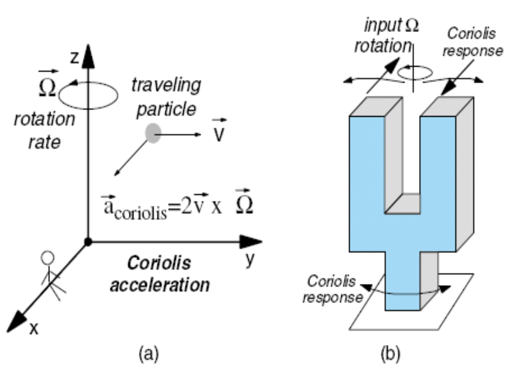
ADXL 202 Dual Axis Accelerometers

- To increase the mass, common beam mass is used

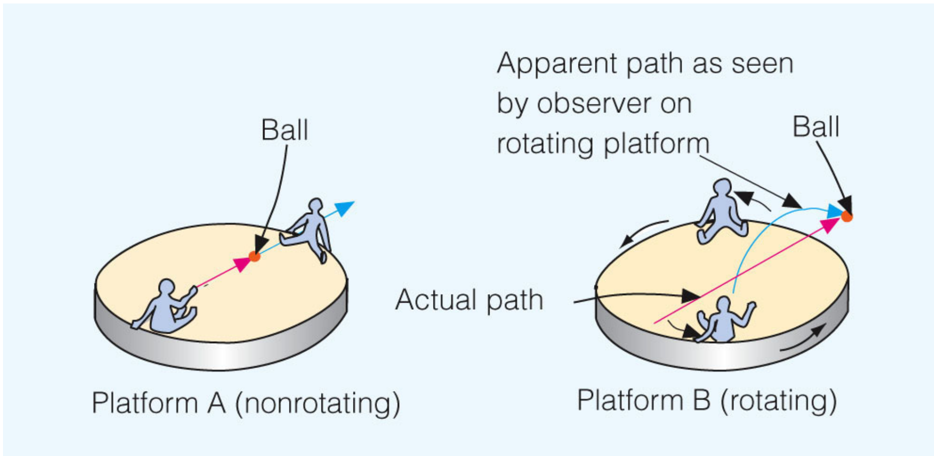


MEMS Gyroscopes

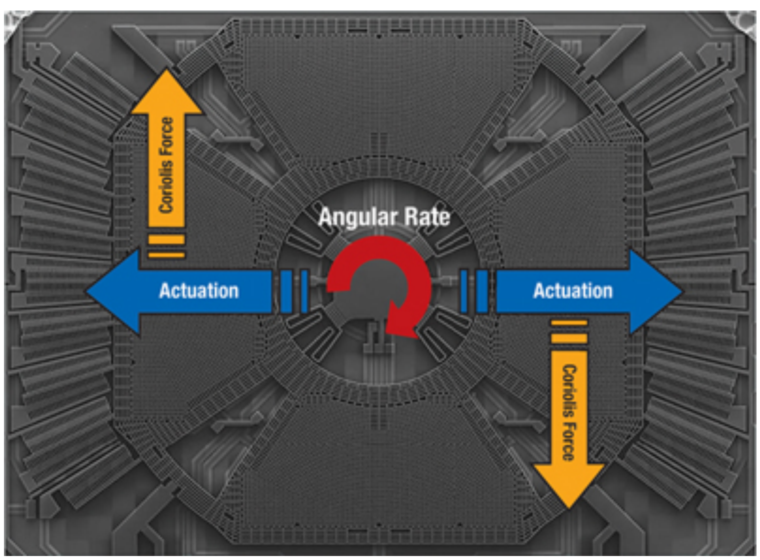
- Typically Vibratory Gyroscopes
  - Utilize Coriolis Acceleration (“fictional force”)
  - Due to rotating reference frame



Coriolis force

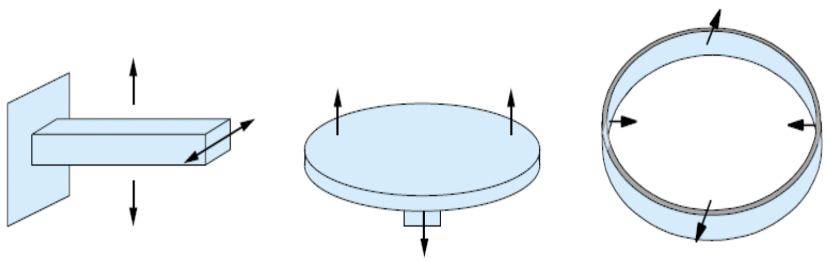


Coriolis force



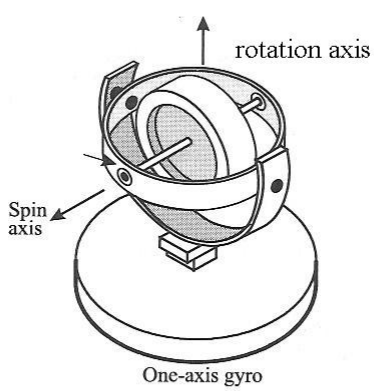
Types of Vibratory Gyroscopes

Vibrating Beam, Vibrating Disk, Vibrating Shell



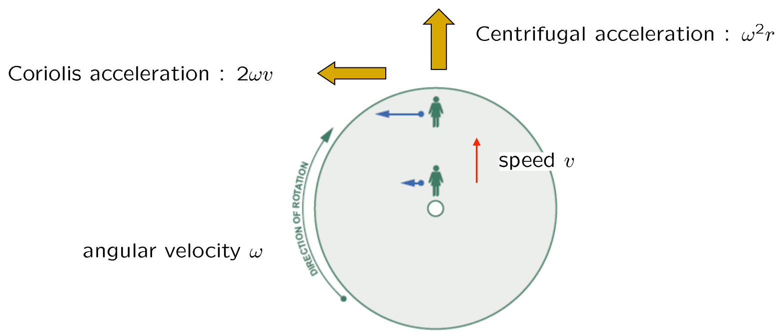
Gyroscope

- Gyroscopic Precession
  - What will happen if there is rotation around the rotation axis



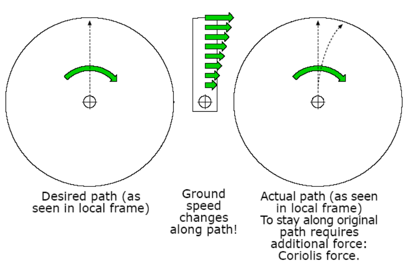
Coriolis Acceleration

- Coriolis acceleration
  - A person moving northward toward the outer edge of a rotating platform must increase the westward speed component (blue arrows) to maintain a northbound course. The acceleration required is the Coriolis acceleration.

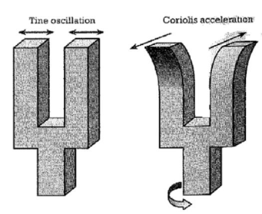


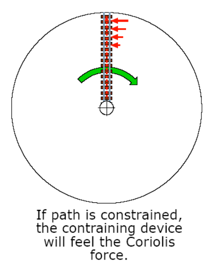
Coriolis Acceleration

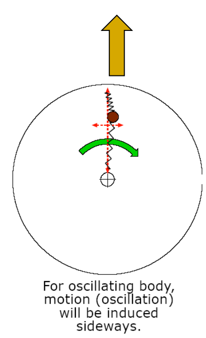
- Constrained motion means force is applied



turning fork gyroscope







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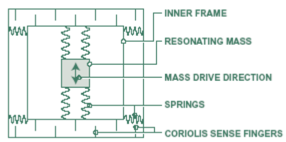
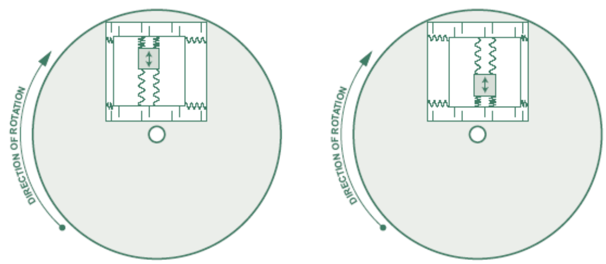
Gyroscope using Coriolis effect

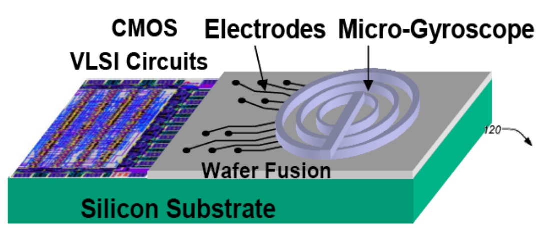
- Schematic of the gyro's mechanical structure

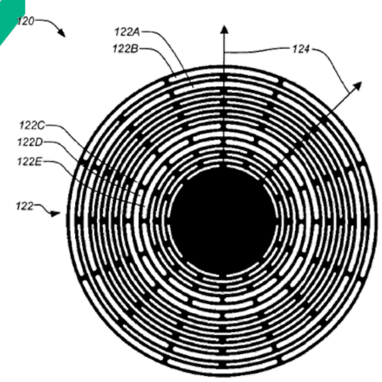


- The displacement is proportional to the rotation speed



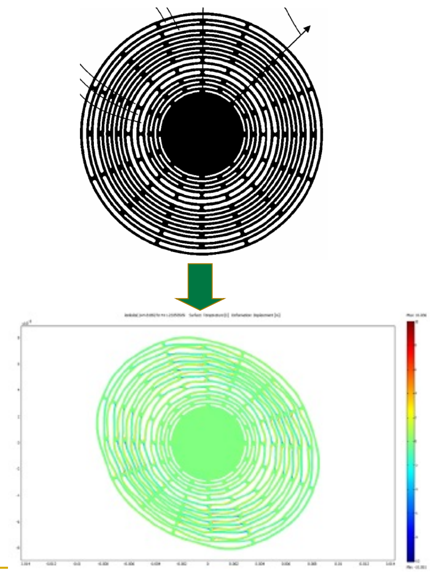
Disc Resonating Gyro Basics



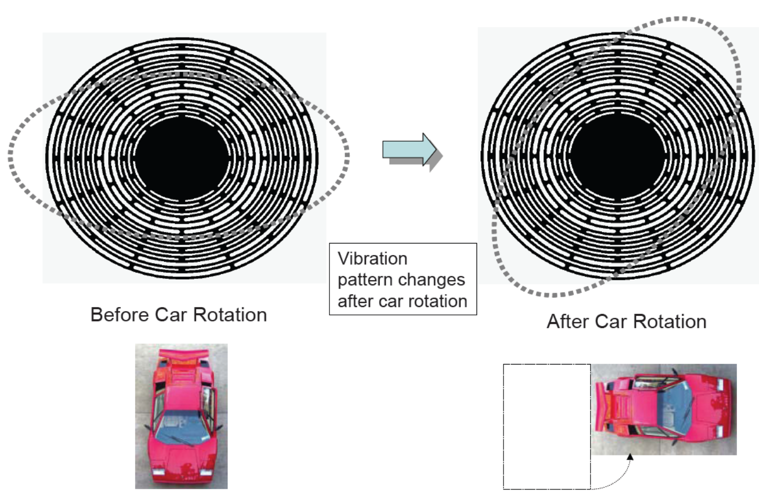


Disc Resonating Gyro Basics

- Gyroscope is driven to resonate in-plane
- Electrodes sense deflection in outer ring sockets
- Electrodes actuate in inner ring sockets
- Circuits process the signal and feedback into the system



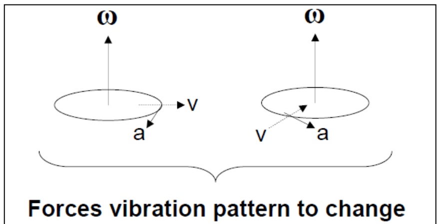
Operation Principle of the DRG



Courtesy of Boeing, ***US Patent: 7,040,163, May 9, 2006***

Coriolis Effect

- Coriolis acceleration (a) occurs if a resonating disc is pterturbed
- Depends on velocities on the disc ➔ higher frequencies allow Coriolis acceleration to dominate centrifugal acceleration
- Coriolis acceleration is what the electrodes sense through change in capacitance



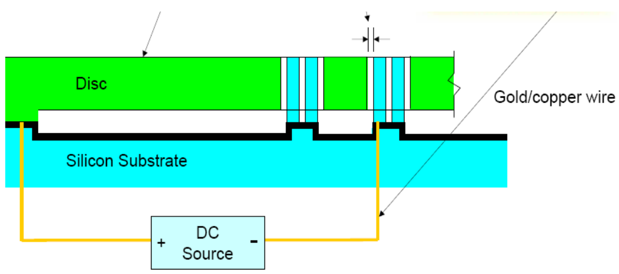
$$\mathbf{a} = -2\boldsymbol{\omega} \times \mathbf{v}$$

Car rotation velocity

Velocity of a material point on the disc during car rotation

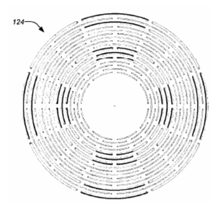
How Does the DRG Work?

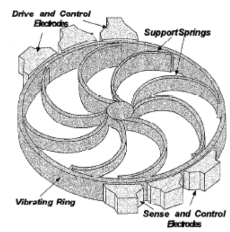
- DC Source creates an electrostatic force that moves the disc
- Proper control of these electrodes can put the system into resonance
- Similarly, the sensing electrodes use gap changes to gauge system changes



One Ring or Many?

- One major advantage of this system is its large area
- Compared to a single ring gyro, has much more control over actuation and sensing
- Single rings require flexible support beams as well

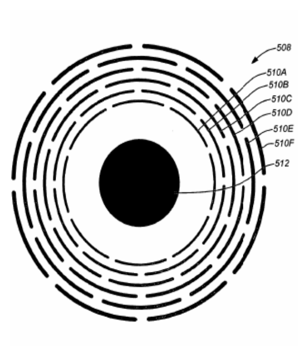


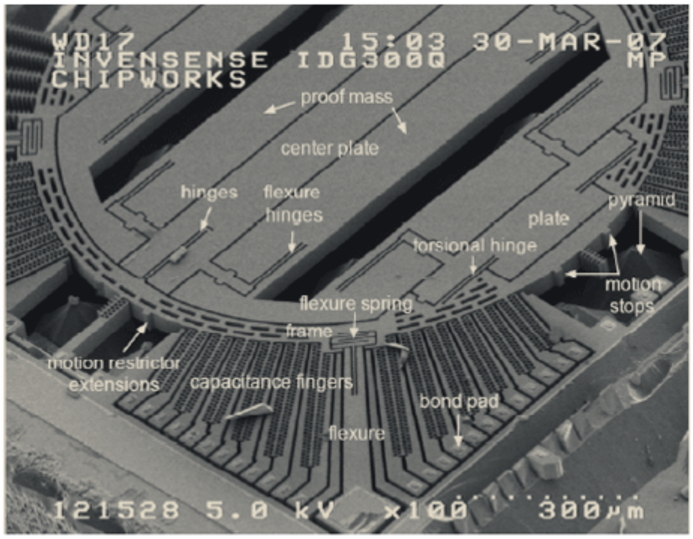


Why Cut the Circles?

•With full concentric circles, the structure tends to be rigid

•By using arcs instead, the structure becomes more flexible, allowing for better accuracy and performance





2. Coriolis gyros needn't use a linear configuration. Detecting angular rotation with the Coriolis effect simply requires a structure that's forced to vibrate normally at its resonant frequency. This is a microphotograph of the InvenSense IDG300 MEMS gyro, which uses a vibrating ring.

Invensense MPU-6050
6-axis gyroscope and accelerometer

4 x 4 x 1 mm

MPU-6050

Supply voltage of 2.375V – 3.46V

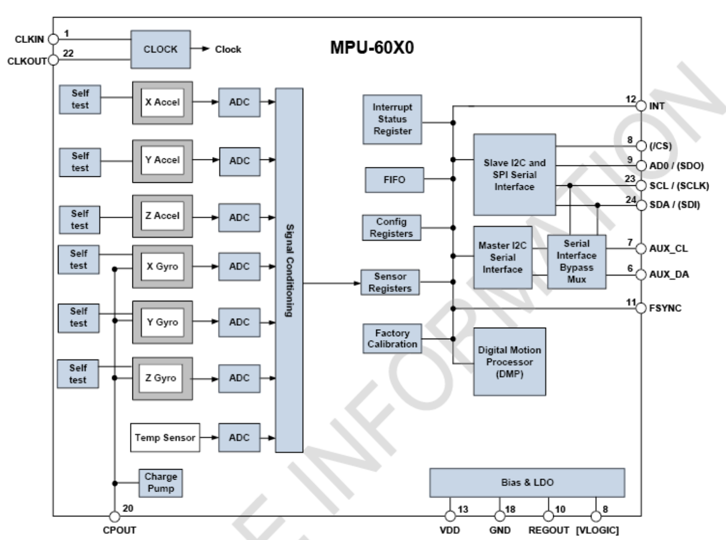
Current of 3.9mA

Uses an I2C bus

Selectable gyroscope and accelerometer ranges

1MHz internal clock

7.5 Block Diagram

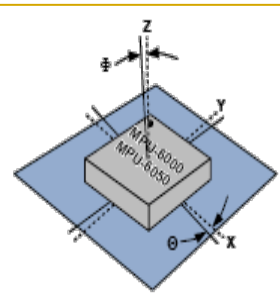


Sample Gyro (3-axis) data [degrees/second]

```
starting loop
 X: -4 Y: 109 Z: -9  // these are values when the gyro isn't moving
 X: -5 Y: 72 Z: -17
 X: 22 Y: 81 Z: 5
 X: 13 Y: 75 Z: 30
 X: 11 Y: 75 Z: 67
 X: 9 Y: 89 Z: 4
 X: 0 Y: 95 Z: 38
 X: -12 Y: 88 Z: 32
 X: 18 Y: 66 Z: 49
 X: 19 Y: 93 Z: 70

 X: 27406 Y: -2091 Z: -29629  // these are values after a quick move of the gyro
                              // inside loop

 X: 35 Y: 67 Z: 12     // next values after motion stopped
 X: 26 Y: 74 Z: 50
```



Package Gyro & Accel Axes (– – –) Relative to PCB Axes (——) with Orientation Errors (Θ and Φ)

The table below shows the cross-axis sensitivity as a percentage of the gyroscope or accelerometer's sensitivity for a given orientation error, respectively.

Cross-Axis Sensitivity vs. Orientation Error

Orientation Error (θ or Φ)	Cross-Axis Sensitivity (sinθ or sinΦ)
0º	0%
0.5º	0.87%
1º	1.75%

The specifications for cross-axis sensitivity in Section 6.1 and Section 6.2 include the effect of the die orientation error with respect to the package.