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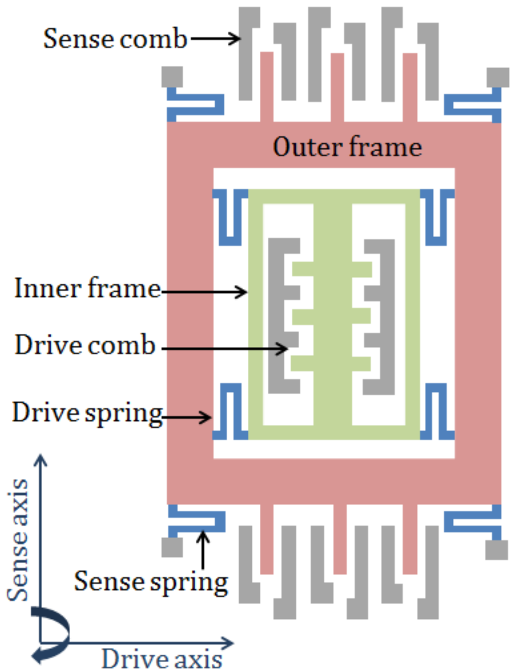
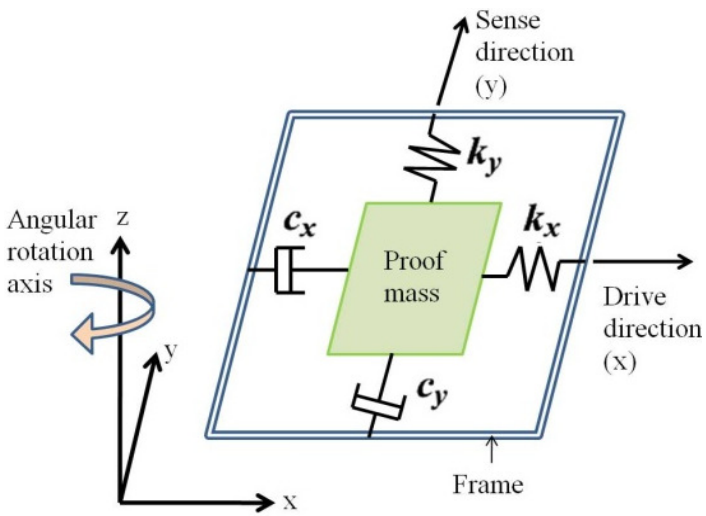
Performance of MEMS Vibratory Gyroscopes in Harsh Environments

Chandradip Patel and F. Patrick McCluskey
CALCE – Center for Advanced Life Cycle Engineering
A. James Clark School of Engineering
Department of Mechanical Engineering
University of Maryland,
College Park, MD, USA, 20740
Phone: (301) 405-0279
Email: mcclupa@umd.edu

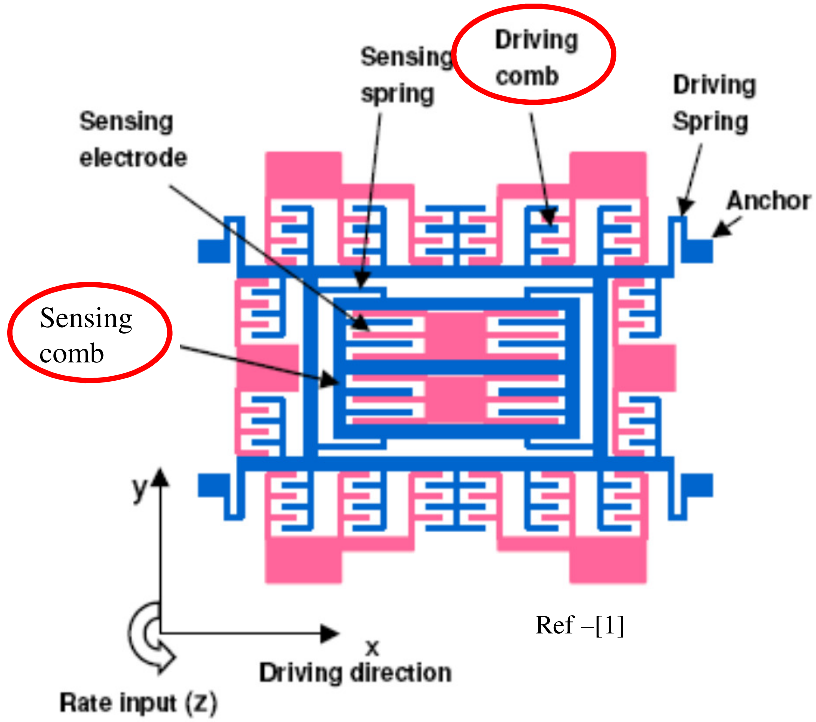
MEMS Gyroscope



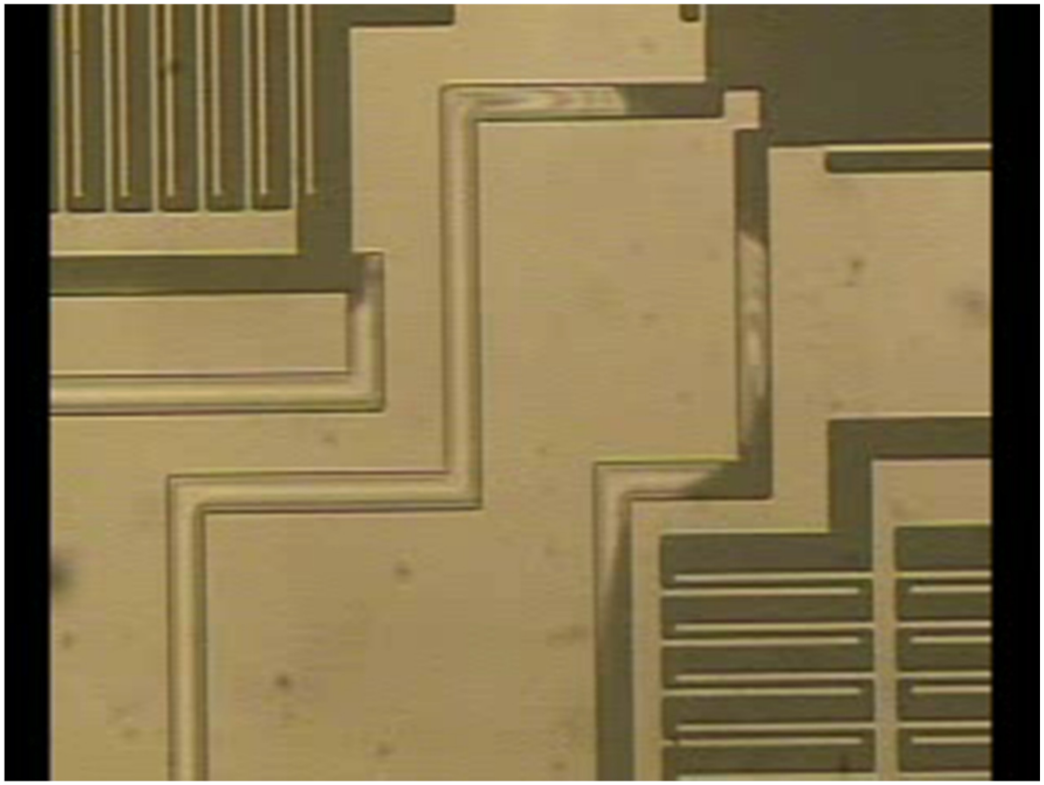


- ❑ MEMS gyroscope sensors measure the rate of change in angular orientation of an object (ω).
- ❑ They work on principle of transfer of energy between two coupled vibrating resonators caused by Coriolis acceleration.
- ❑ **Coriolis acceleration:** Coriolis acceleration arises in a rotating reference frame and is proportional to the rate of rotation. $\vec{a}_{cor} = 2\vec{V} \times \vec{\Omega}$
- ❑ When MEMS gyroscope is subjected to rotation, the Coriolis force creates an orthogonal force that can be sensed by a change in capacitance.
- ❑ This change in capacitance can be converted to angular velocity output.

MEMS Gyroscopes Comb Structure Movement



Schematic of comb type vibrating resonator gyroscope



Ref –[2]

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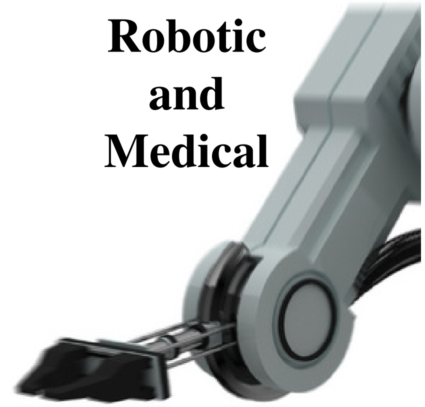
[1] M. C. Lee, S. J. Kang, K. D. Jung, S.-H. Choa, and Y. C. Cho, "A high yield rate MEMS gyroscope with a packaged SiOG process," *Journal of Micromechanics and Microengineering*, vol. 15, no. 11, pp. 2003–2010, Nov. 2005.
[2] http://www.me.umn.edu/labs/advcontrols/gyroscope.html

Electric Vehicle

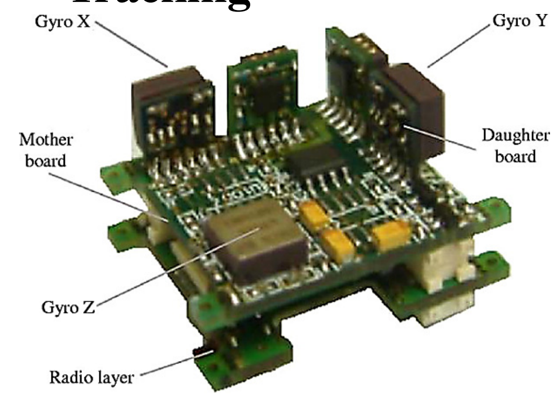
Consumer Electronics

Robotic and Medical

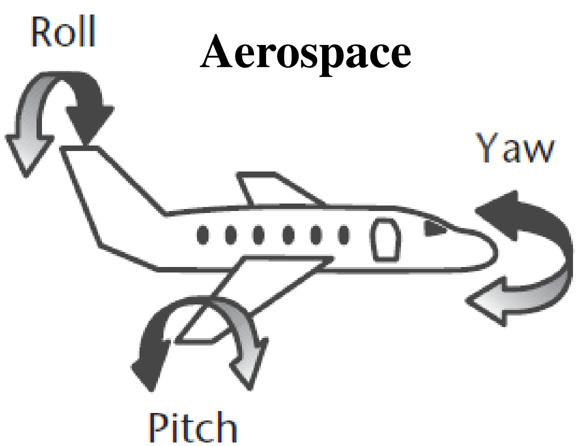


MEMS Gyroscope Applications

Navigation and Tracking



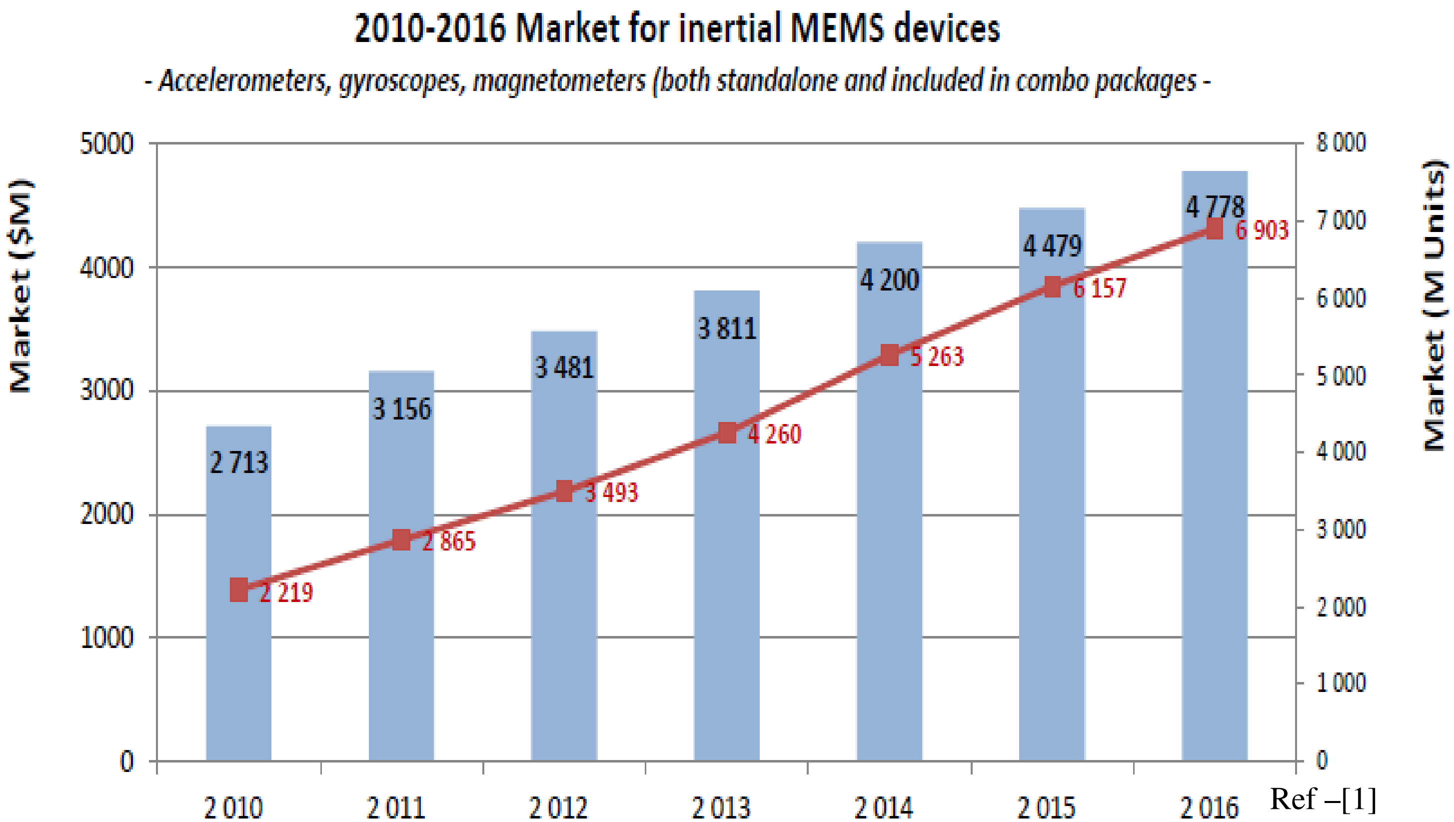
Aerospace



Automotive

Why Inertial Navigation is Important?

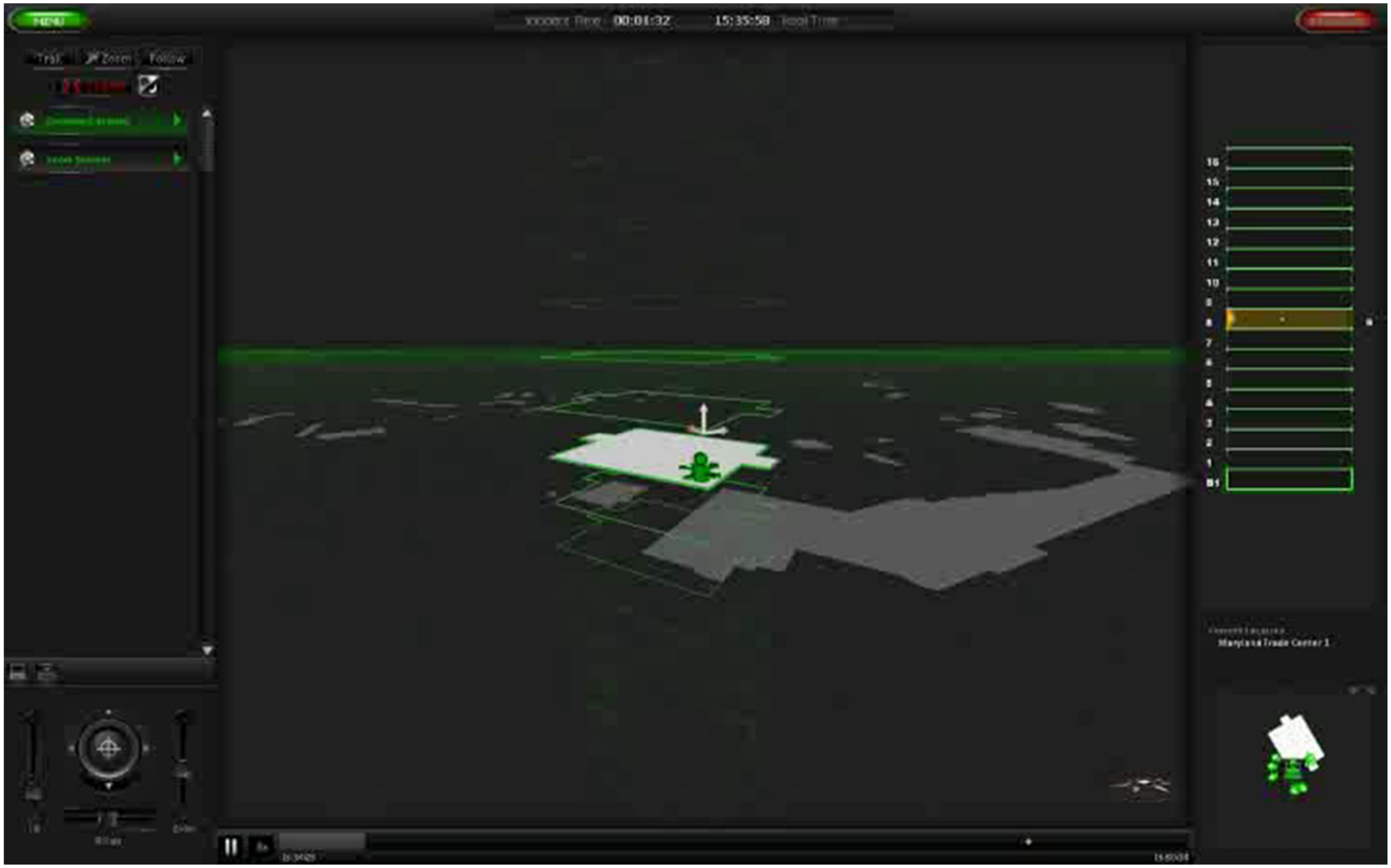
- Commonly used GPS technology has limitation for navigation and tracking application while being used near or inside building. High noise level generated in GPS signals near or inside a building, resulting from signal attenuation and reflection, limit GPS technology in such application. In such cases, MEMS inertial sensors based navigation system provides the best method for locating or tracking either inside or outside.



Ref –[1]

[1] "Technology Trends for Inertial MEMS," YOLE DEVELOPMENT, Jan. 2012

Inertial Navigation Unit



Ref –[1]

Key Customers:

Firefighter, Miners, Law Enforcement, Military Ground Forces, Safety & Inspection, Maritime Security, etc.

[1] http://www.trxsystems.com/

Why is It Important to Study the Effects of Harsh Environments on MEMS Gyroscope?

- Most of the commercial-off-the-shelf (COTS) MEMS gyroscopes have a limited operating temperature range (viz. -40˚C to +85˚C). This operating range can limit their use in applications, such as navigation and tracking, deep energy exploration, down-hole drilling and other high-temperature industrial applications where the MEMS gyroscope sensor experiences temperatures that are beyond the manufacturer's recommended temperature range.

Environmental Challenge: Design Specs for PASS Device

- 500°F (260°C) for 5 minutes
- 350°F (177°C) for 15 minutes
- Submerged 10 ft. – maintain 95dB
- Cold-hot cycling (-4°F to 160°F)
- 442 lb compressive load
- 10 ft. drop test
- Vibration testing
- Direct flame exposure

PASS Device: PASS (Personal Alert Safety System) is a personal safety device used primarily by firefighters entering a hazardous (IDLH) environment such as a burning building, which sounds a loud audible alert to notify others in the area that the firefighter is in distress.

List of Harsh Environmental Conditions

MEMS gyroscopes are often required to perform its intended function in harsh conditions arising from the environment. These harsh environmental conditions include:

- **High-G Mechanical Shock/Drop**
- **High Frequency Mechanical Vibration**
- **High Frequency Acoustic Noise**
- **High Temperature**
- **High Humidity**
- **High Radiation**
- **High Atmospheric Pressure**
- **High Magnetic and Electric Fields**
- **High Corrosive Gases, etc.**

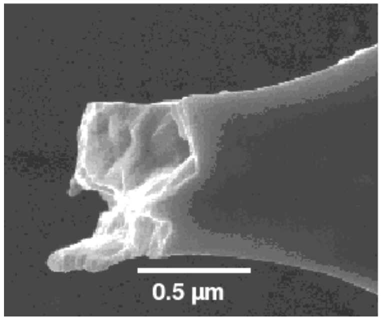
High-G Mechanical Shock/Drop Environment

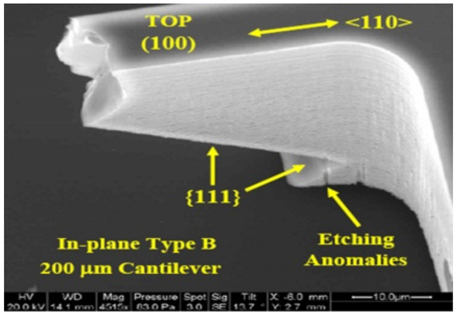
- With the increasing use of MEMS gyroscopes in consumer hand-held applications along with custom applications in military, automotive, and avionic markets, high reliability in shock/drop has become very critical.

- As the mass of the suspended structure is typically very small; a MEMS gyroscope is generally quite robust to typical shock/drop stress levels.

- High-G levels of shock/drop can induce:
  - A crack in a suspended mass, which leads to fracture and device failure.
  - It can break off a small piece from the suspended structure which may cause either short-circuit or block the movement of the vibrating mass.

- An effective way to avoid the stress concentration is by providing a fillet to sharp corners that minimize fracture.





Mechanical fracture of a silicon cantilever. A clear brittle fracture signature is observed. [1]

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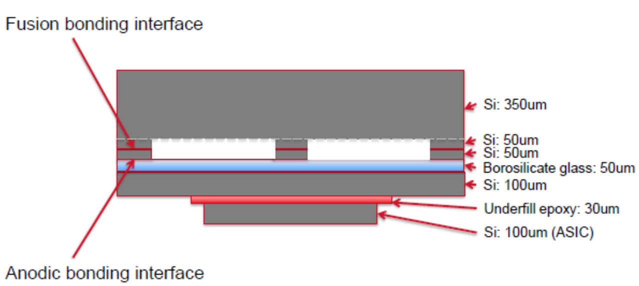
[1] M. P. de Boer, B. D. Jensen, and F. Bitsie, "A small area in-situ MEMS test structure to measure fracture strength by electrostatic probing," SPIE Proceedings, v. 3875, Materials and Device Characterization in Micromachining, Santa Clara, CA Sept. 1999.

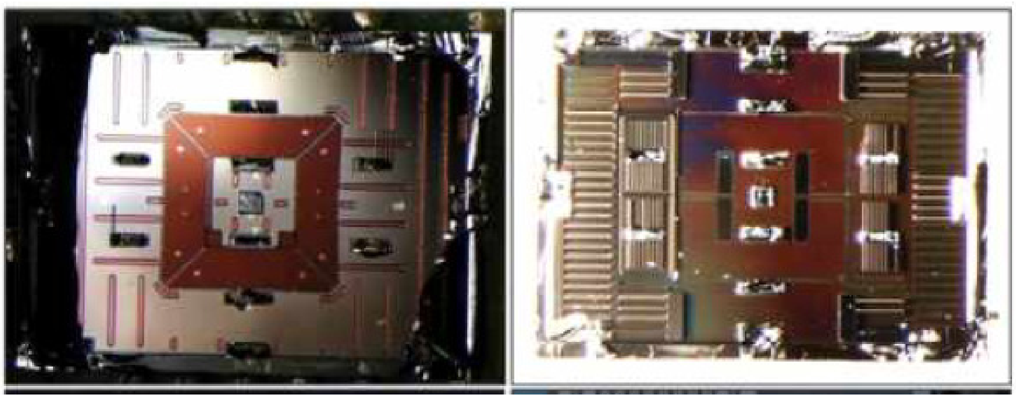
High-G Mechanical Shock/Drop Environment

- Army Research Laboratory (ARL) conducted both ground and flight tests to determine the feasibility of using MEMS gyroscopes in an artillery and a rocket application where high-G loadings were encountered [1] [2]. The MEMS devices were subjected to up to 35,000 G shock. It was found that MEMS gyroscopes showed encouraging results for both surviving the loading and measuring the pitching and yawing behavior of the munitions. This study concluded that MEMS sensors were rugged enough to survive both low-g and high-g launch [2].

- A recent study was performed by Hannes Hyvönen at Aalto University where MEMS gyroscopes were characterized in a high-G shock environment up to 35,500 G. After the first drop, it was observed that all the MEMS gyroscopes failed. The preliminary failure analysis revealed that MEMS gyroscopes failed by fracture very near the glass layer at the anodic bonding interface [3].



Cross section of MEMS gyroscopes [3]



Images of failed MEMS gyroscopes [3]

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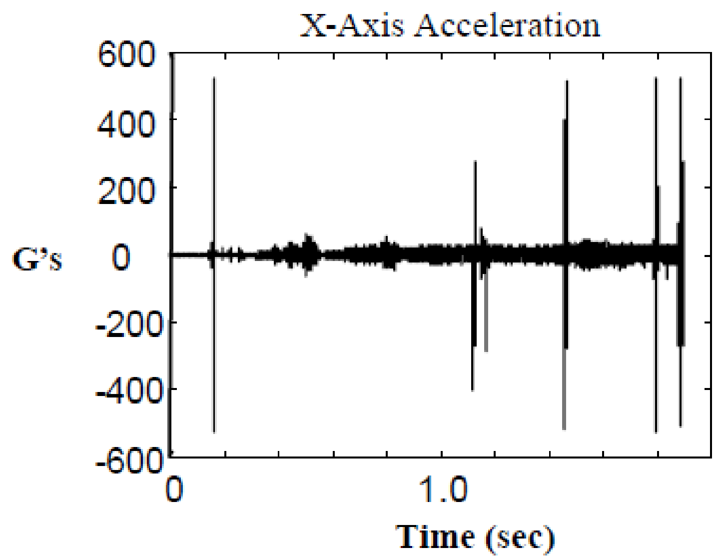
[1] T. G. Brown, "Harsh Military Environments and Microelectromechanical (MEMS) Devices," in *Proceedings of IEEE Sensors, 2003*.
[2] T. G. Brown, et al "Strap-Down MEMS Sensors for High-G Munition Applications," *IEEE Transactions on Magnetics*, 2001.
[3] H. Hyvönen, "Thermomechanical and Mechanical Characterization of a 3-Axial MEMS Gyroscope," Aalto University, 2011.

High Frequency Mechanical Vibration Environment

- MEMS gyroscopes are susceptible to high frequency external mechanical vibration when they are being used unshielded. It can couple into MEMS gyroscope and cause erroneous measurements.

- Typical missile environments include [1]: high roll rates, up to 2000° per second, up to 50G's steady state and 800G's transient and high frequency exceeding 20KHz.

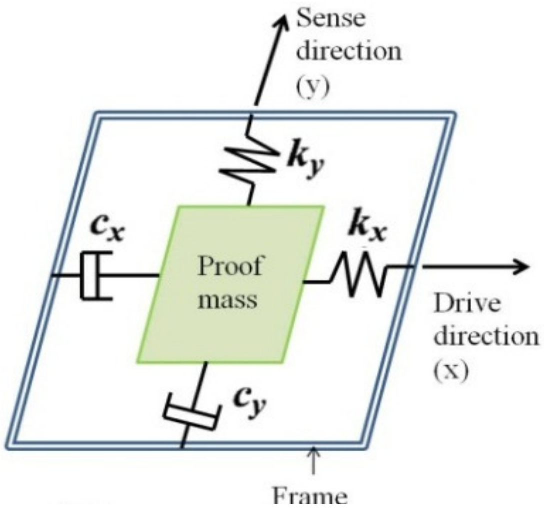


- Tanner et al.[2] performed a vibration test to surface-micromachined microengines that had a peak acceleration of 120G and spanned frequencies from 20 to 2000Hz. Failure analysis revealed that adhesion and shorting of comb fingers to ground planes were prime failures.

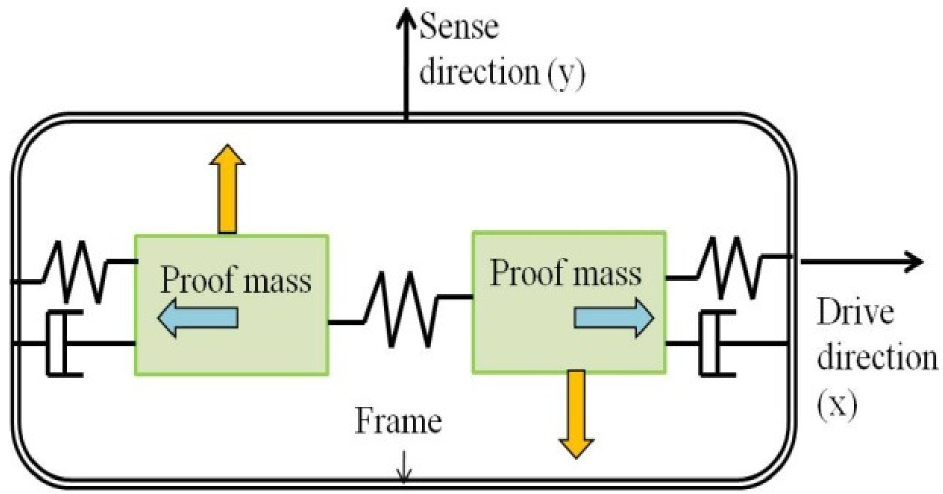
[1] R. N. Dean et al." Vibration Isolation of MEMS Sensors for Aerospace Applications", 2002
[2] Tanner, D. et al, "MEMS Reliability in a Vibration Environment", Sandia National Laboratories, 2000

High Frequency Mechanical Vibration Environment

- In order to mitigate this, some of the MEMS gyroscopes have two proof masses instead a single mass, placed on either side. This special arrangement helps to nullify the external inertial inputs caused by undesirable ambient vibration.

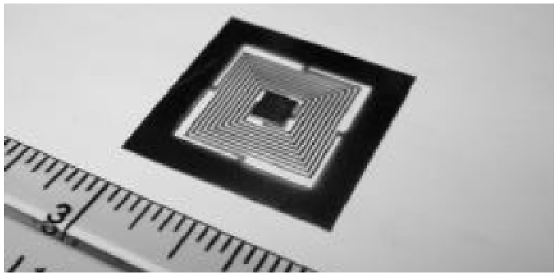


MEMS Gyroscope with Single Proof Mass



MEMS Gyroscope with Two Proof Masses

- A mechanical low-pass filter as part of the die-level packaging was suggested to minimized the effects of high frequency mechanical vibration [1].



A Prototype Silicon Mechanical Filter Structure [2].

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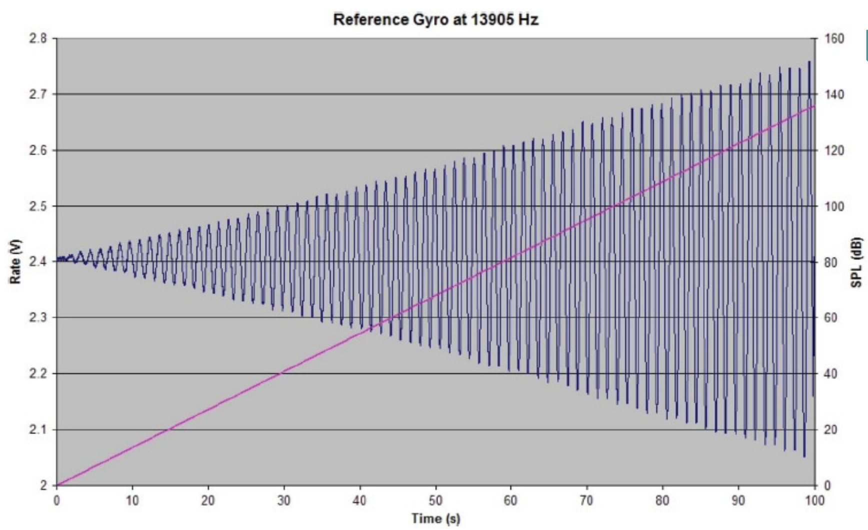
[1] R. N. Dean et al." Vibration Isolation of MEMS Sensors for Aerospace Applications", 2002

High Frequency Acoustic Environment

- MEMS gyroscope's performance can be strongly affected by an environment where acoustic frequencies are close to the MEMS gyroscope's resonant frequency. For this reason, MEMS gyroscopes are designed to have a resonant frequency that is well above detection bandwidth.

- Robert Dean et al. [1] have demonstrated that MEMS gyroscopes are susceptible to high-power, high-frequency acoustic noise. This study quantitatively shows how the MEMS gyroscope's performance can be degraded in harsh acoustic environments. High acoustic examples include supersonic aerospace vehicles, machines that utilize high-pressure nozzles, underwater applications, and some audio systems [2].



MEMS Gyroscope Output (v) vs. Single Acoustic Tone (dB) at MEMS Gyroscope's Resonance Frequency. [1]

- The effect of high frequency acoustic environment can be mitigated by the use of several types of acoustic foams. A noteworthy study was performed by Grant Roth, where a model was developed to simulate the effects of high frequency acoustic noise on a MEMS Gyroscope [3]. This model was used to determine what type and amount of isolation required to mitigate the adverse effects on the gyroscope's rate output due to acoustic noise.

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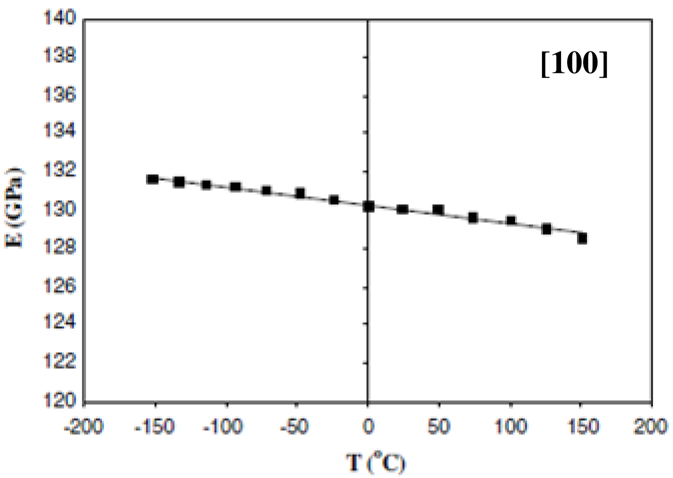
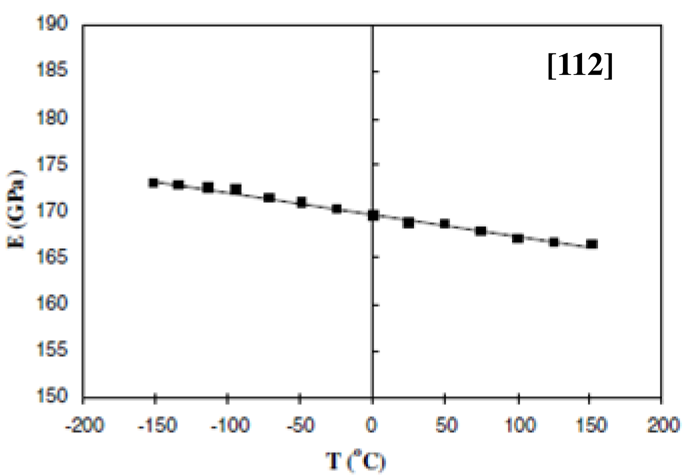
[1] R. N. Dean et al." A Characterization of the Performance of a MEMS Gyroscope in Acoustically Harsh Environments",2011.
[2] R. N. Dean et al." On the Degradation of MEMS Gyroscope Performance in the Presence of High Power Acoustic Noise, 2007.
[3] G. Roth, "Simulation of the Effects of Acoustic Noise on MEMS Gyroscopes," thesis, Auburn University, 2009.

High Temperature Environment

Short Term Temperature Effects on MEMS Gyroscope





Ref –[1]

- The Young's modulus (E) of the material and therefore the spring constants are a function of temperature changing the frequency response of the structure [2].
- Temperature can also cause expansion (α) of the beams and spaces changing the capacitance of the structure.
- Temperature dependent viscous forces and damping coefficient (C) that affect output gain and Q factor [3].
- Gyroscopes have a high sensitivity to displacements on the order of nanometers.
- These combine effect can change the angular velocity measured by the sensor in both rotational and stationary modes.

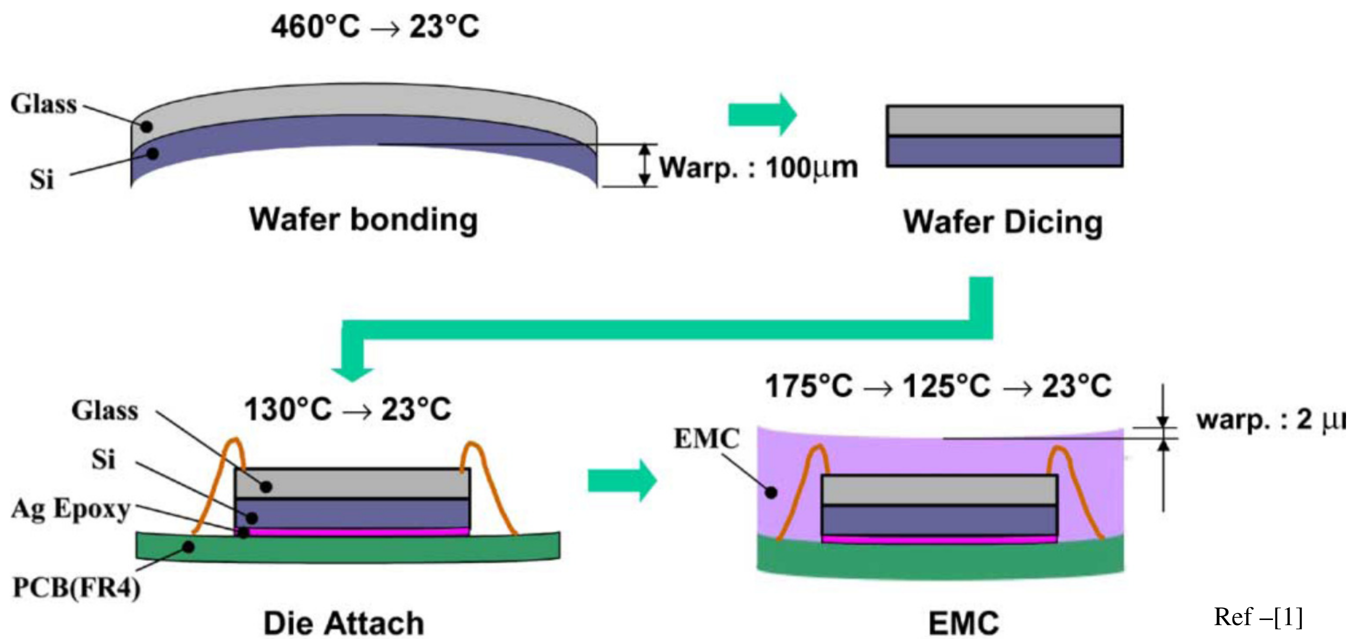
[1] C.H Cho, "Characterization of Young's modulus of silicon versus temperature using a "beam deflection" method with a four-point bending fixture" J. of current applied physics, Vol 9, No 2, Pages 538-545, 2009.

[2] K. Shcheglov, C. Evans, R. Gutierrez, and T. K. Tang, "Temperature dependent characteristics of the JPL silicon MEMS gyroscope," in *Aerospace Conference Proceedings, 2000 IEEE*, 2000, vol. 1, pp. 403–411 vol.1.

[3] R. Feng, A. P. Qiu, Q. Shi, X. H. Zhu, L. Yang, and Y. Su, "A Research on Temperature Dependent Characteristics of Quality Factor of Silicon MEMS Gyroscope," *Advanced Materials Research*, vol. 159, pp. 399–405, Dec. 2010.

High Temperature Environment

Long Term Temperature Effects on MEMS Gyroscope



Ref –[1]

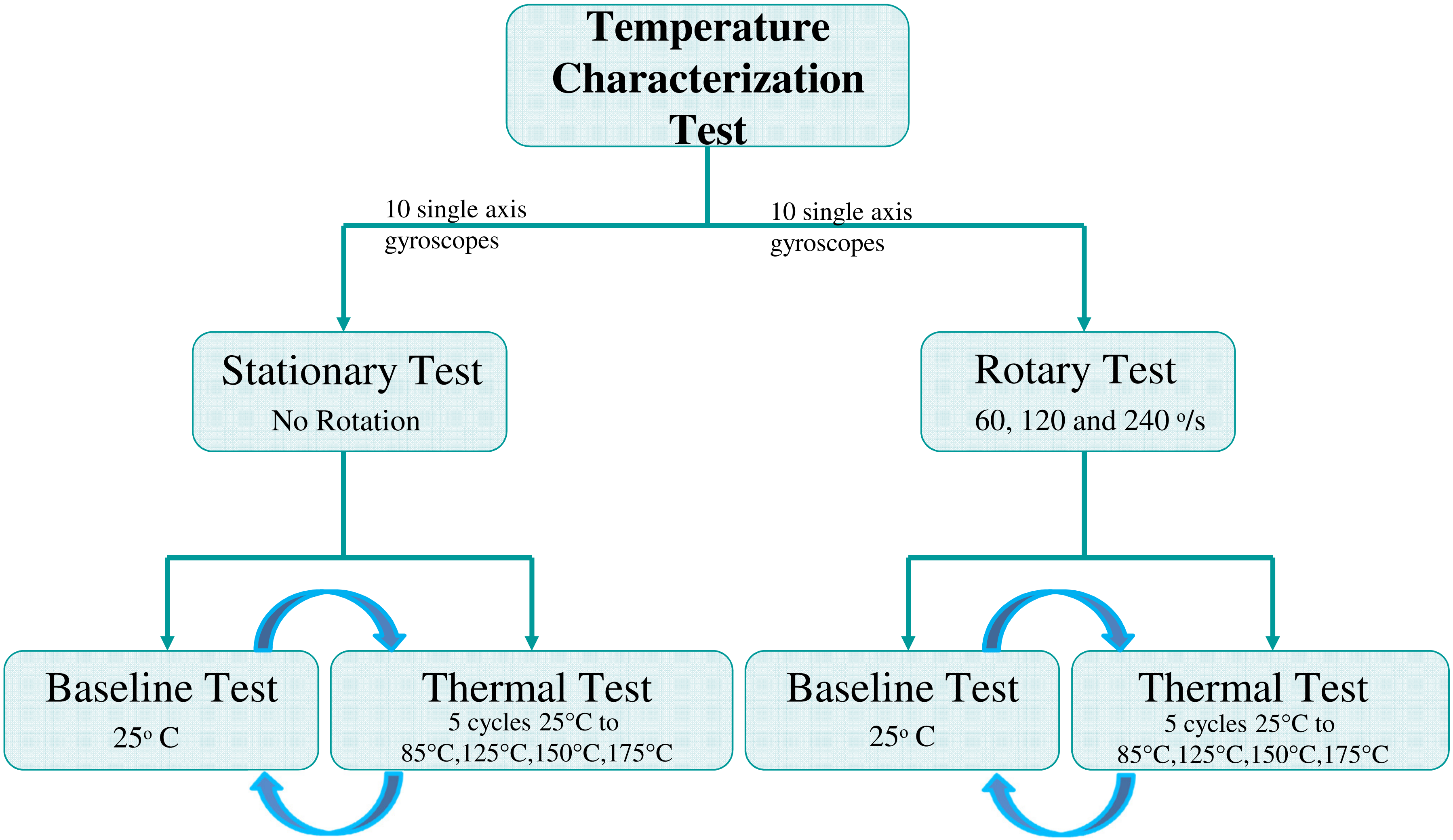
- Long term temperature exposure induces package stress and cracks by :
  - (1) Epoxy mold compound shrinkage
  - (2) CTE Mismatch between package elements

- Both the factors lead to warping of the gyroscope package, which deforms the spring elements of the gyroscope resulting a change in the resonant frequency of the driving and especially sensing comb. This will eventually change angular velocity output.

[1] J-W Joo and S-H Choa, "Deformation Behavior of MEMS Gyroscope Sensor Package Subjected to Temperature Change," IEEE Trans. Comp. Pkg. Tech., 30 (2), pp. 345-354, 2007

High Temperature Environment

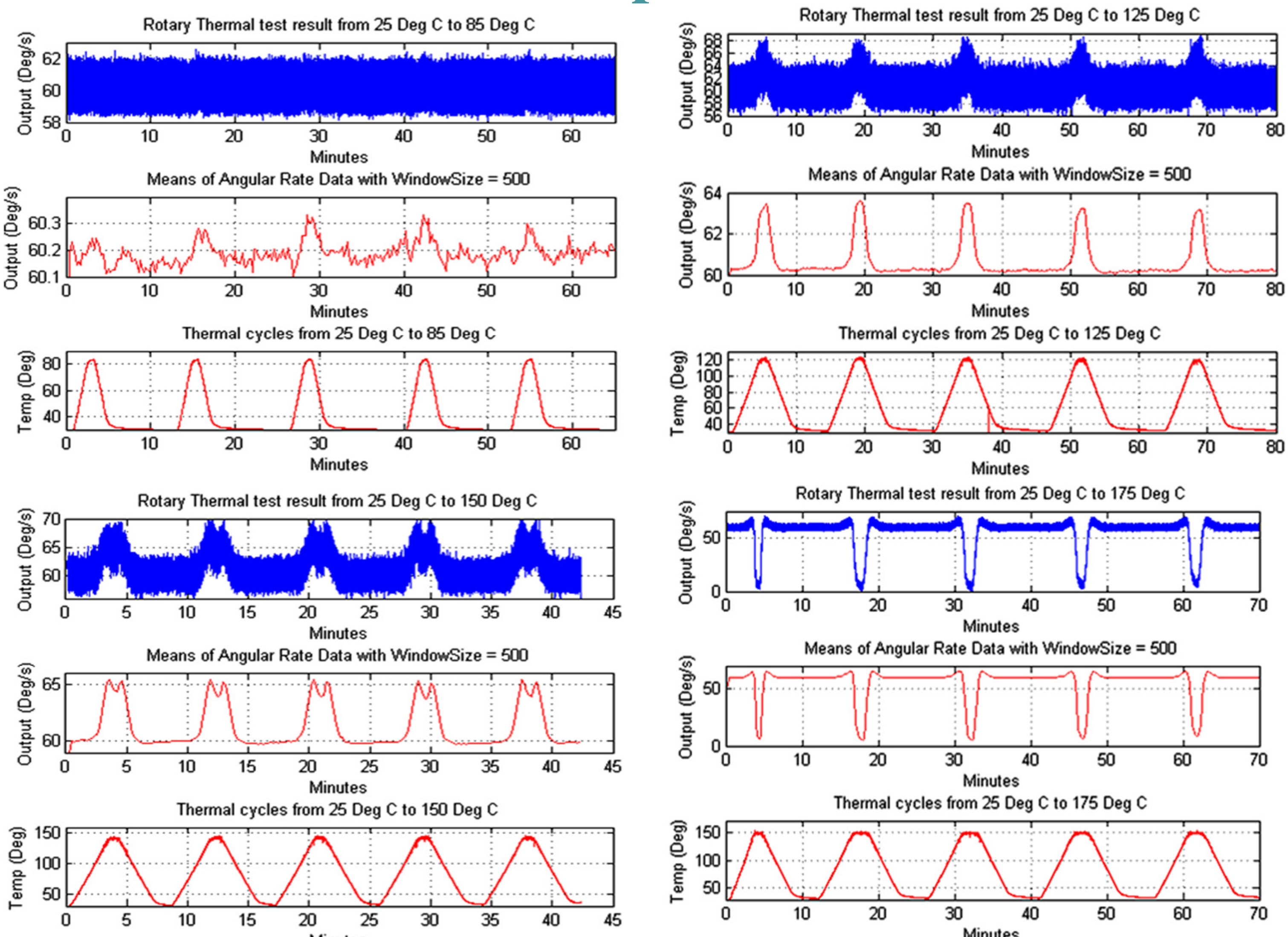
Short Term Temperature Test Procedure



Note: Single axis MEMS gyroscopes are internally calibrated from -40˚C to +85˚C.

High Temperature Environment

Short Term Temperature Test Results



Rotary Thermal Test Results from 25°C to 85°C, 25°C to 125°C, 25°C to 150°C, 25°C to 175°C, Respectively, at 60 °/s Angular Rotation. First Window: Raw Angular Velocity Data from MEMS Gyroscope; Second Window: Mean of Angular Rate Data with Windowsize = 500; Third Window: Thermal Cycle Range [1].

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[1] C. Patel et al" Temperature Effects on Performance and Reliability of MEMS Gyroscope Sensors" *InterPACK‘,* 2009.
[2] F.P McCluskey, C. Patel, D. Lemus."Performance and Reliability of MEMS Gyroscopes and Packaging at High Temperatures", High Temperature Electronic (HiTEC),2010,

High Temperature Environment

Short Term Temperature Test Conclusion

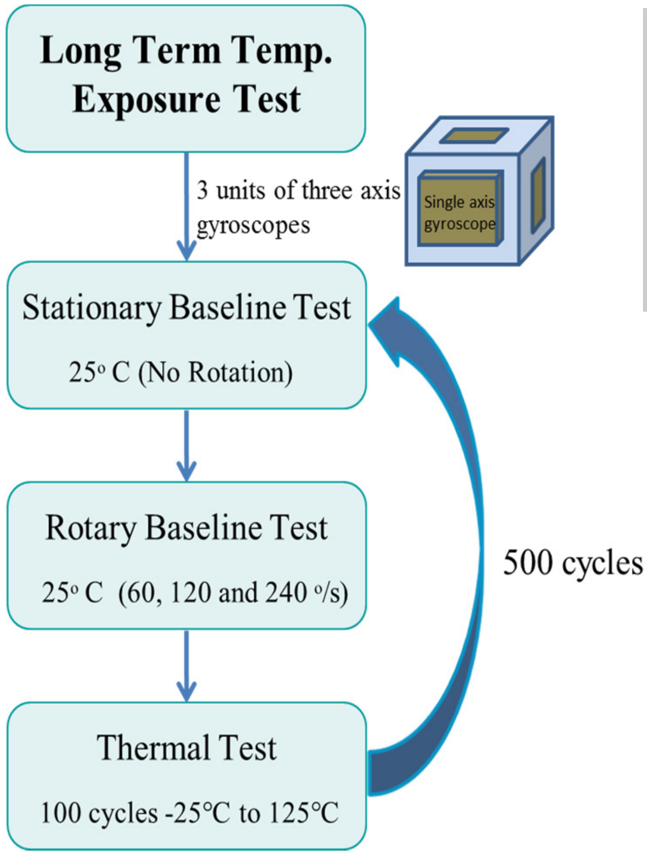
- There was a monotonic increase in the angular velocity measured by the gyroscope with temperature when the gyroscope was operated above 85°C during rotary testing, that did not correspond to any actual change in the angular velocity of the table. This increase was a temperature related drift in performance that must be accounted for when using the angular velocity measurements for tracking.

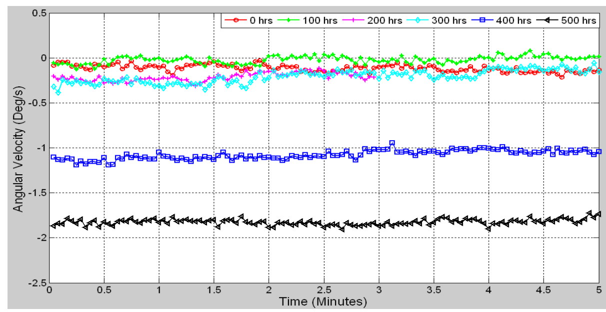
- There was an increase in the noise levels when the gyroscope was operated at temperatures above 85°C during stationary temperature cycling. The noise level returned to normal when the temperature dropped below 85°C with no apparent decrease in durability as a result of the effect.

- When the MEMS gyroscope was subjected to temperatures above 150ºC, the gyroscopes ceased to function.

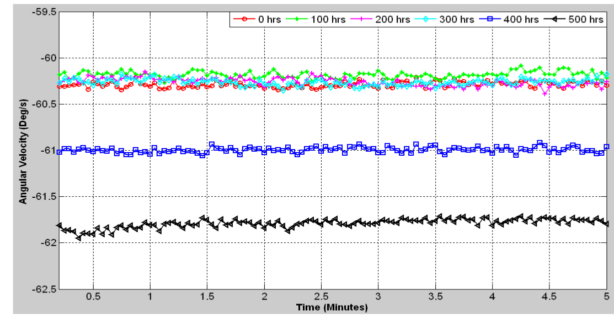
High Temperature Environment

Long Term Temperature Test Procedure and Result

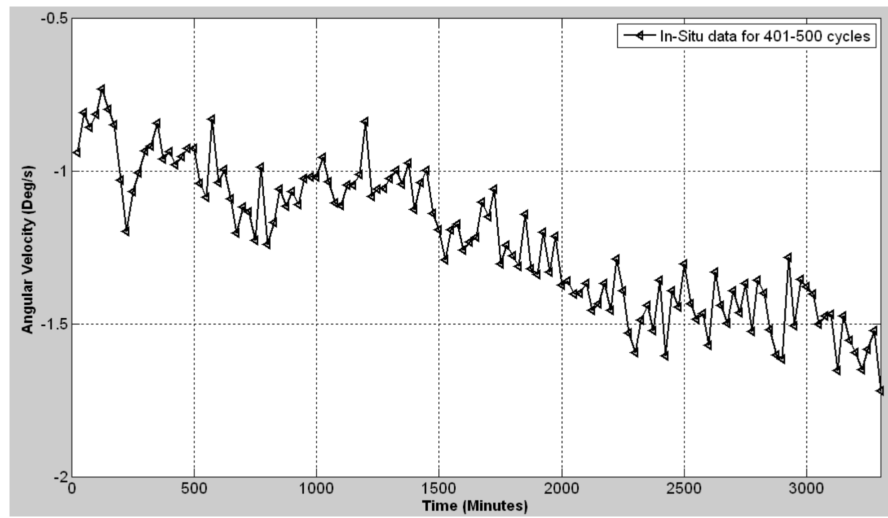




Gyroscope Output During Stationary Baseline Test



Gyroscope Output During Rotary Baseline Test at 60°/s



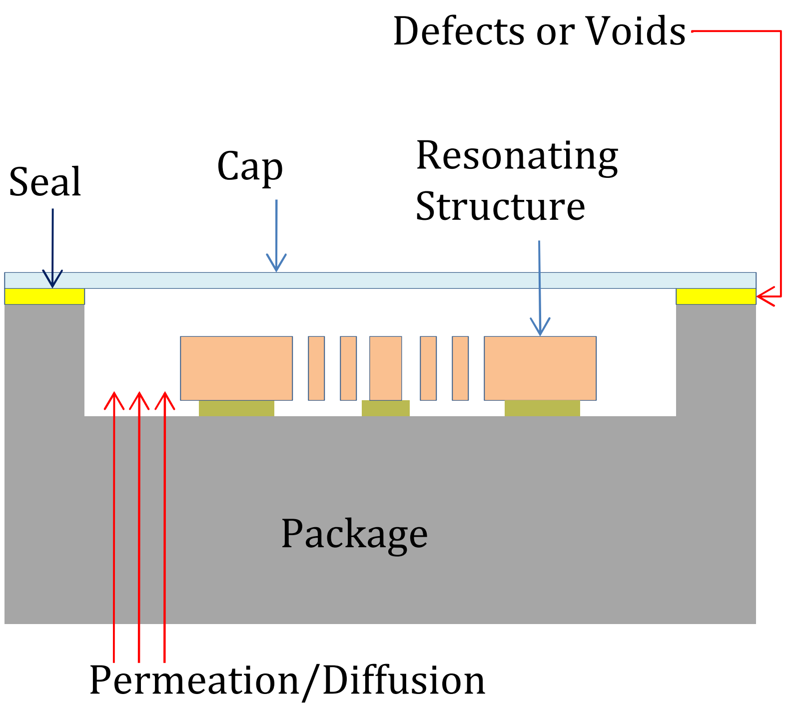
In-Situ Degradation of MEMS Gyroscope Output for 401-500 Thermal Cycles [1]

Sample No.	Maximum angular velocity shift (°/s)
Sample-1	1.8
Sample-2	1.0
Sample-3	0.9

- Experimental results showed that there was a significant effect of long-time thermal cycling exposure on the MEMS gyroscope. Five-hundred thermal cycling had permanently shifted the MEMS gyroscope measurement by 1.8°/s in both stationary and rotary conditions in one of the three samples.

[1] C. Patel, F.P McCluskey, D. Lemus "Performance and reliability of MEMS gyroscopes at high temperatures," ITherm 2010.

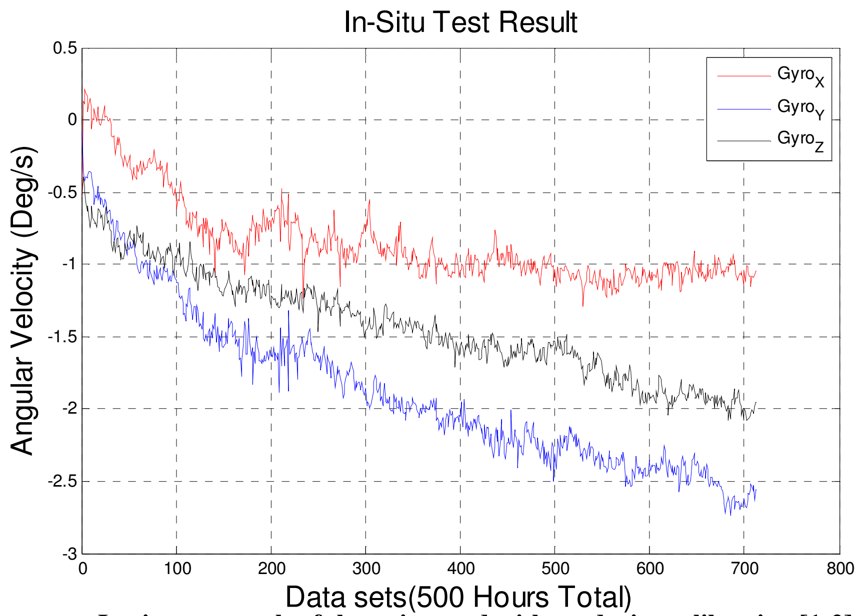
High Humidity Environment



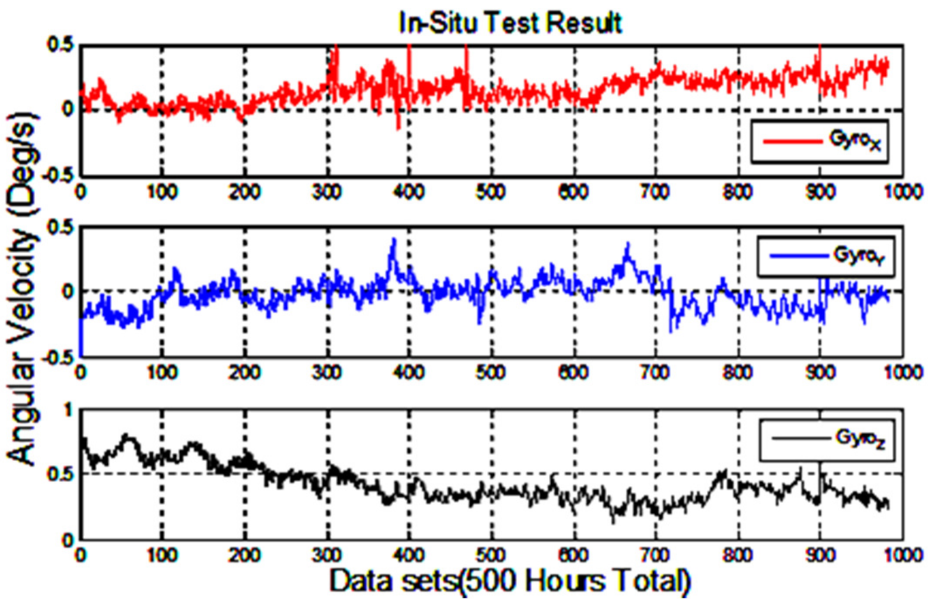
- Moisture can ingress through two possible sources:
  - Permeation or diffusion through package
  - Defects or voids in the bonding interface
- Moisture ingress affects the internal environment of MEMS gyroscope that leads to change in damping coefficient (C) and damping factor (ξ).
- Affected damping coefficient (C) and damping factor (ξ) changes desired output gain and Q factor.
- Moisture can also increases the mass of resonating structure that change resonance frequency and device output.
- If resonating structure and embedded electronic are on the same die, then humid environment causes corrosion that changes device output.

High Humidity Environment

Temperature Humidity Bias (THB) Test at 60˚C temperature and 90%RH for 500 hours



In-situ test result of the unit tested without device calibration [1-2]



In-situ test result of the unit tested with device calibration

- It was confirmed that the performance of MEMS vibratory gyroscopes can be affected by sustained exposure to humidity environment. The unit tested without in-situ device calibration which had three single axis gyroscopes mounted on Cartesian directions, experienced minimum and maximum in-situ drift of 1.3˚/s and 2.2˚/s respectively over 500 hours.

- It was also observed that if the MEMS vibratory gyroscopes are calibrated frequently over time during harsh environment exposure, output drift can be minimized.

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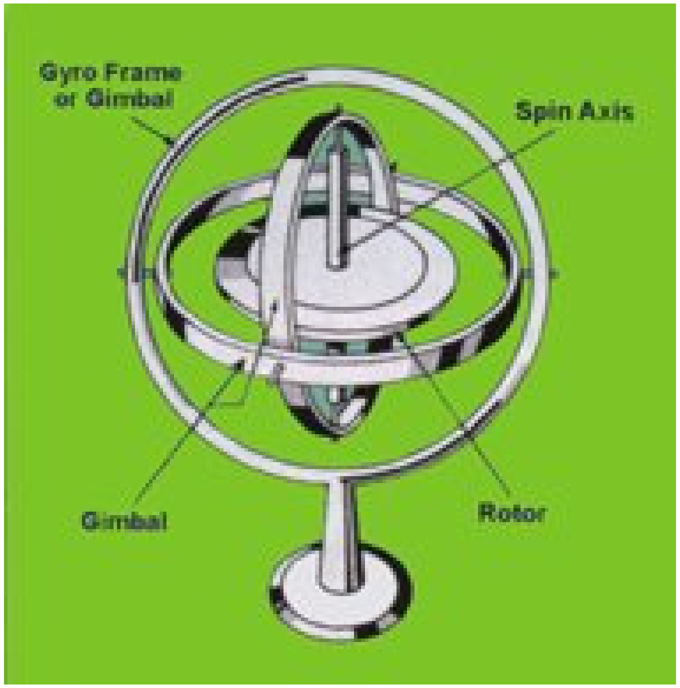
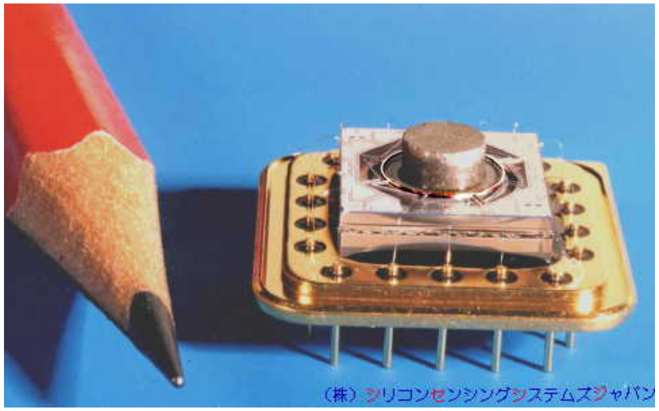
[1] C. Patel, F.P McCluskey " Combined Temperature and Humidity Effects on MEMS Vibratory Gyroscope Sensor" InterPack, 2011.
[2] C. Patel, F.P McCluskey " Performance Degradation of the MEMS Vibratory Gyroscope in Harsh Environments", IMECE, 2011.

Questions?

Thank You



Mechanical Gyroscope



MEMS Gyroscope