IMU IN UAVs

(Unmanned Aerial Vehicles)

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INTRODUCTION & WORKING PRINCIPLE

INTRODUCTION

An inertial measurement unit (IMU) is an electronic device that measures and reports a body's specific force, angular rate, and sometimes the orientation of the body, using a combination of accelerometers, gyroscopes, and sometimes magnetometers. IMUs are typically used to maneuver aircraft, including unmanned aerial vehicles (UAVs), among many others, and spacecraft, including satellites and landers.

IMUs are used for a variety of applications in UAVs and drones. They allow the aircraft to maintain stability and control while experiencing high winds or performing steep turning maneuvers. They can also be used to enable highly accurate station-keeping or autonomous waypoint following.

Inertial measurement units may be used to provide data for an AHRS (Attitude and Heading Reference System), which calculates real-time attitude and heading for manned and unmanned aircraft, or an INS (Inertial Navigation System), which calculates position in addition to orientation.

INTRODUCTION

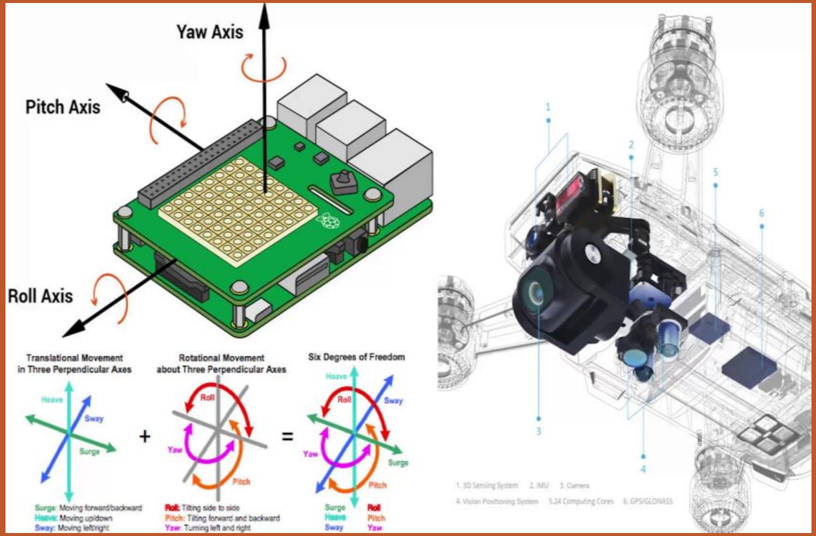
The raw measurements output by an IMU (angular rates, linear accelerations and magnetic field strengths) or AHRS (roll, pitch and yaw) can be fed into devices such as Inertial Navigation Systems (INS), which calculate relative position, orientation and velocity to aid navigation and control of UAVs.

IMUs are manufactured with a wide range of features, parameters, and specifications, so the most suitable choice will depend on the requirements for a particular UAV application.

The performance and accuracy of an IMU are influenced by a combination of factors, including the sensor technology, the thermal properties of the packaging, and the software used.

MEMS IMUs are ideal for smaller UAV platforms and high-volume production units, as they can generally be manufactured with much smaller size and weight, and at lower cost.

Higher bandwidth also makes FOG IMUs suitable for high-speed platform stabilization. Typically larger and more costly than MEMS-based IMUs, they are often used in larger UAV platforms.



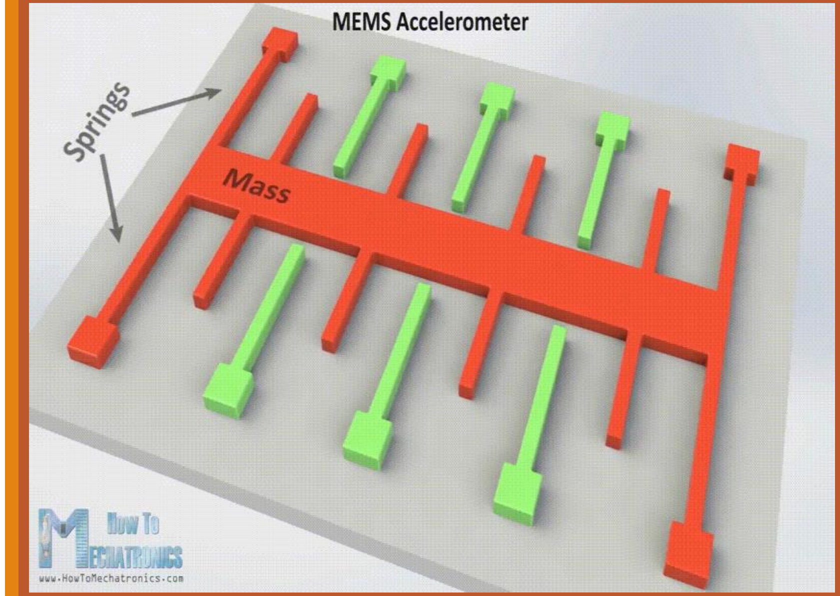
ACCELEROMETER

What is an Accelerometer ?

Accelerometers are *electromechanical devices that measure acceleration, the rate of change in velocity of an object.* MEMS accelerometers are designed for easy integration with Arduino or other microcontrollers With its miniaturized sensors, MEMS accelerometers are applicable for IoT usages, low-power, industrial and automotive applications, healthcare, etc.

How does an accelerometer work ?

- There are two types of MEMS accelerometers: variable capacitive and piezoresistive. The principle of operation in both types is measuring the inertia force on the proof mass and then find out acceleration (as mass is known).
- In Capacitive type, the proof mass is tethered to the frame by flexible strings as shown. Protrusions from the proof mass acts as capacitor plates forming a series of differential capacitor setup. The change in capacitance is directly associated with the force acting on the object.
- In case of piezoresistive MEMS accelerometers, the electricity output from the piezoelectric material is used to calculate the force and hence the acceleration.
- Generally, Capacitive accelerometers are used for low frequency applications such as to measure acceleration constantly (such as in UAVs and drones)whereas piezoresistive materials are used in high frequency applications such as shock testing.



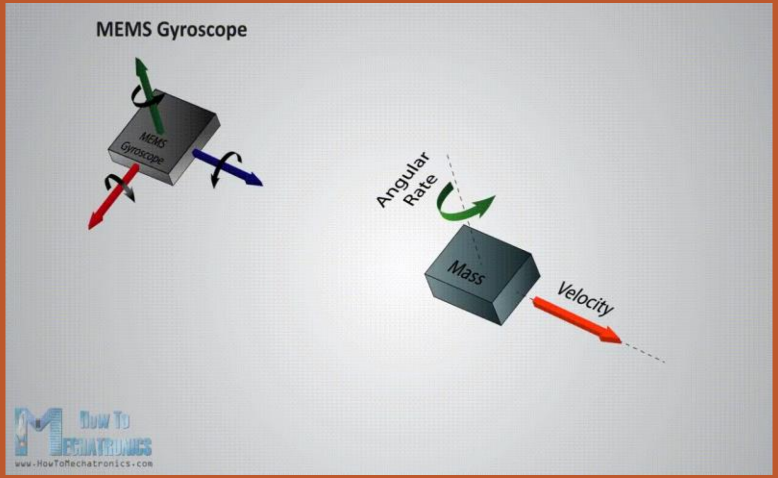
GYRO-SENSOR

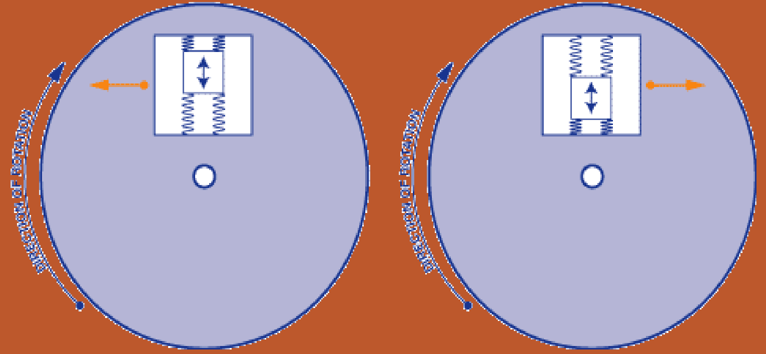
What is a Gyroscope ?

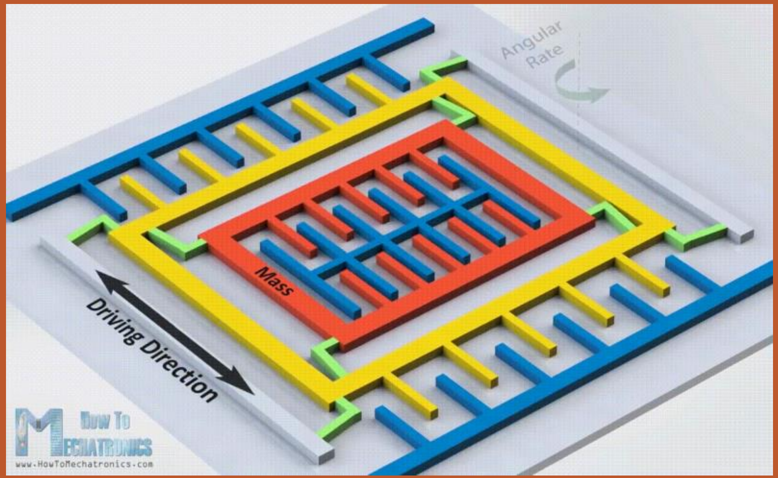
Gyroscopes, or gyros, are devices that measure or maintain rotational motion. MEMS (microelectromechanical system) gyros are small, inexpensive sensors that measure angular velocity.

How does a MEMS Gyro Works ?

- A gyroscope uses the Coriolis force to determine the angular orientation of a rotating body. The **Coriolis force** is an inertial or fictitious force that acts on objects that are in motion within a frame of reference that rotates w.r.t an inertial frame.
- The magnitude of the Coriolis force is directly proportional to the angular velocity of the rotating object. Measuring the Coriolis force is sufficient to determine the angular velocity (as the mass is already known).
- In a MEMS gyroscope this is achieved by using a vibrating mass system attached by springs. The proof mass is kept in constant vibration, so that when the body rotates, it moves sidewards due to Coriolis force and the magnitude can be easily calculated using a capacitive arrangement as shown.







MAGNETOMETER

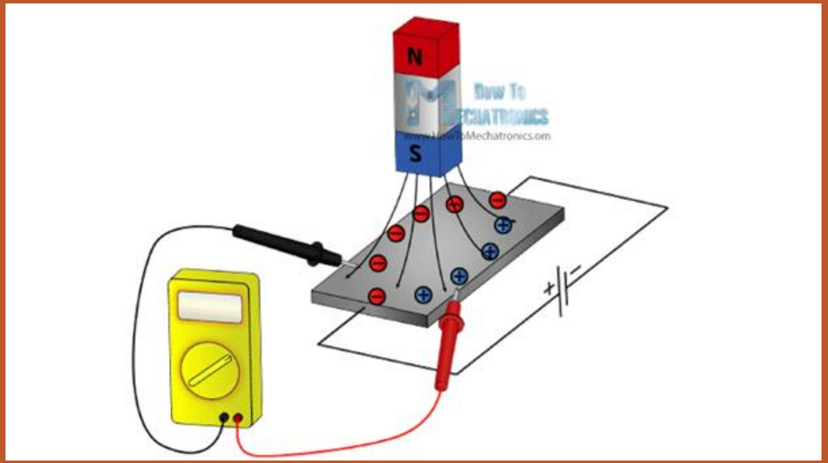
What is a Magnetometer?

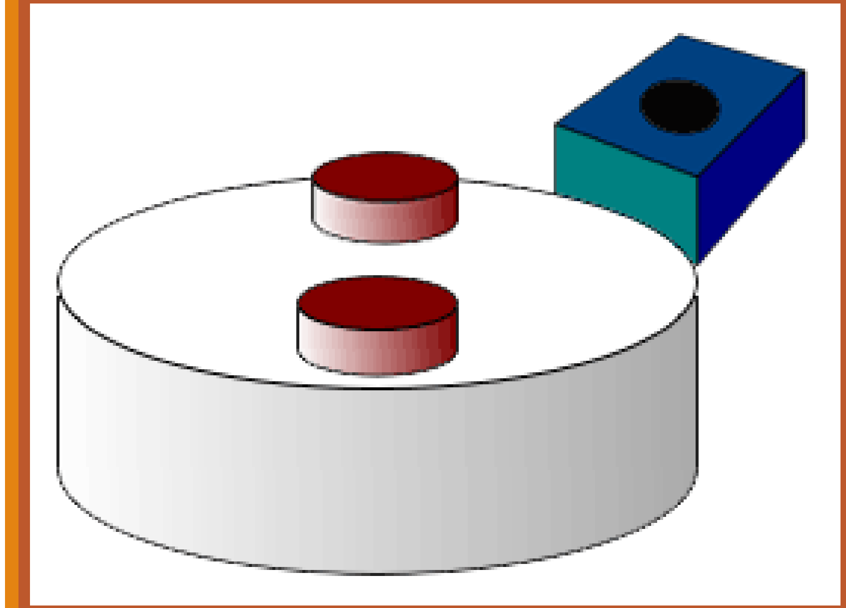
A magnetometer is a device that measures magnetic field or magnetic dipole moment. A MEMS magnetometer is a small-scale microelectromechanical system (MEMS) device for detecting and measuring magnetic fields.

How does a MEMS Magnetometer Work ?

- It measures the earth magnetic field by using Hall Effect or Magneto Resistive Effect. Almost 90% of the sensors on the market use the Hall Effect.
- If we have a conductive plate and we set current to flow through it, the electrons will flow straight from one to the other side of the plate.
  Now bringing a magnetic field near the plate would disturb the straight flow and the electrons would deflect to one side of the plate and the positive poles to the other side of the plate. That means if we put a meter now between these two sides, we will get some voltage which depends on the magnetic field strength and its direction.
- The other 10% of the sensors on the market use the Magneto-resistive Effect.

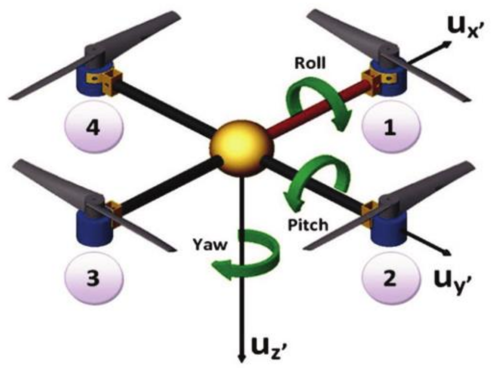
These sensors use materials that are sensitive to the magnetic field, usually composed of Iron (Fe) and Nickel (Ne). So, when these materials are exposed to magnetic field, they change their resistance.

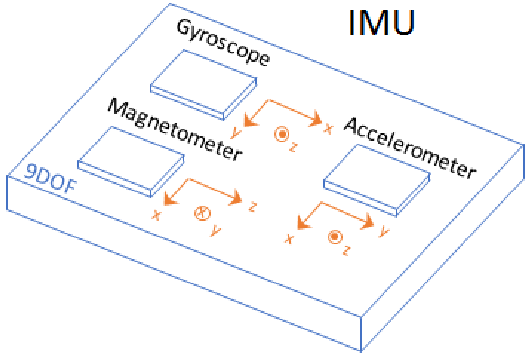


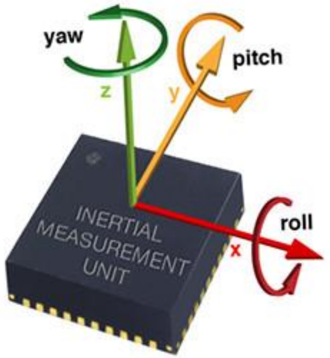


WORKING PRINCIPLE

- It works by detecting the current rate of acceleration using one or more accelerometers. The IMU detects changes in rotational attributes like pitch, roll and yaw using one or more gyroscopes. Some IMU on drones include a magnetometer, mostly to assist calibration against orientation drift.
- On board processors continually calculate the drone's current position. First, it integrates the sensed acceleration, together with an estimate of gravity, to calculate the current velocity. Then it integrates the velocity to calculate the current position.
- To fly in any direction, the flight controller gathers the IMU data on present positioning, then sends new data to the motor electronic speed controllers (ESC). These electronic speed controllers signal to the motors the level of thrust and speed required for the quadcopter to fly or hover.
- To control roll and pitch rpm of adjacent propellers are varied.
- To control yaw rpm of opposite propellers are varied.
- Selecting appropriate pair of adjacent and opposite propellers
- Depends on sign of roll,pitch,yaw and physical constraints (eg: maximum and minimum motor speed)



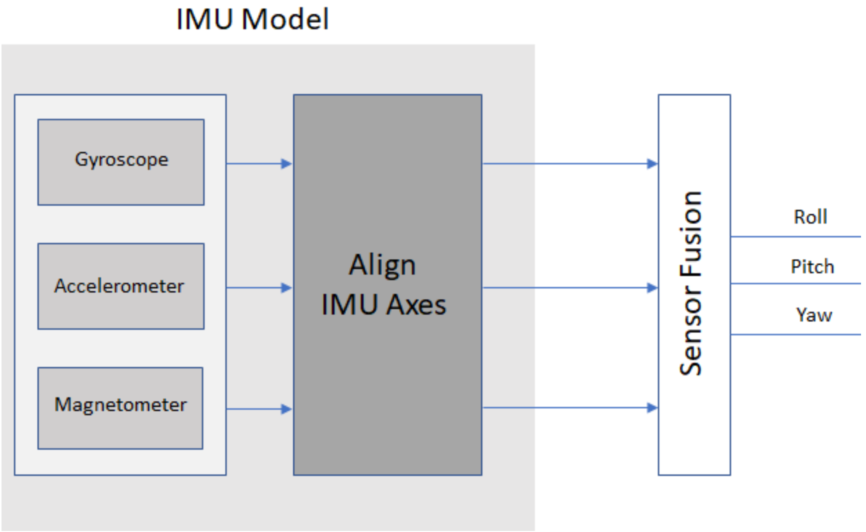




INTEGRATION & ASSEMBLY:

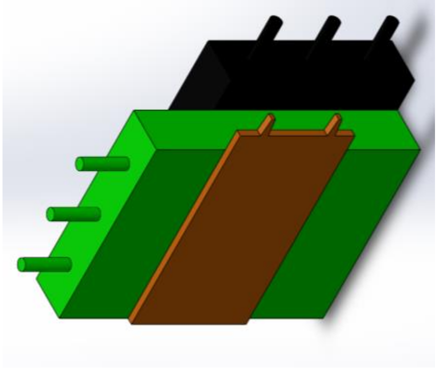
INTEGRATION

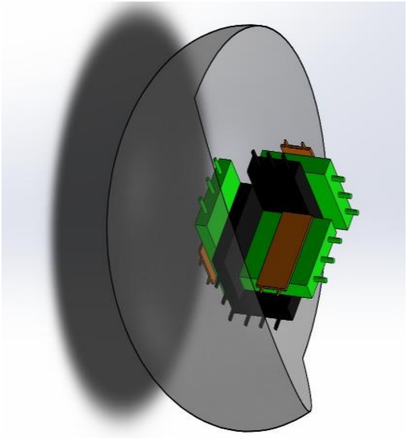
- An INS(**Inertial Navigation System)** fuses the inertial sensor data to calculate position, orientation, and velocity of a platform. An INS/GPS uses GPS data to correct the INS.
- Typically, the INS and GPS readings are fused with an extended Kalman filter, where the INS readings are used in the prediction step, and the GPS readings are used in the update step.



ASSEMBLY

- The basic structure of a uniaxial IMU consists of a set of three sensors such that the magnetometer and accelerometer face the same direction while the gyroscope remains perpendicular to the two.
- 3 sets of these in 3 orthogonal directions is responsible for velocity, angle and direction calculation in 3 mutually perpendicular directions.





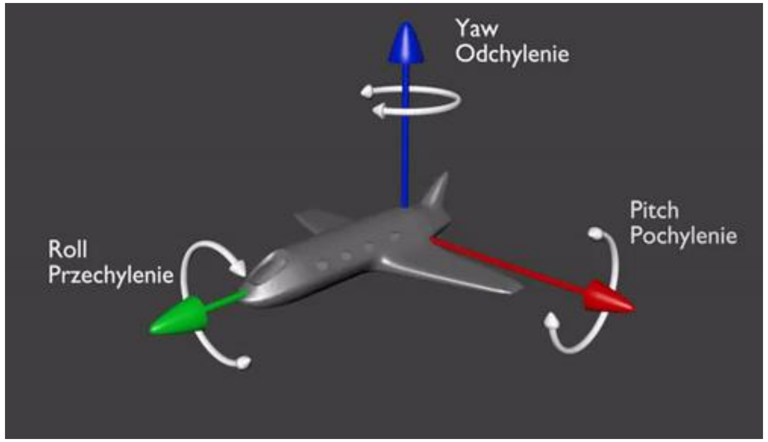
ACTUATION AND NAVIGATION

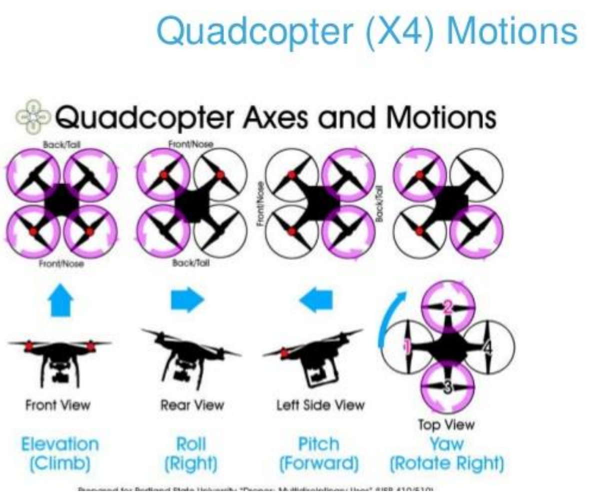
The data returned by IMUs is fused together and interpreted as roll, pitch, and yaw of the platform. Real-world IMU sensors have different axes for each of the individual sensors.

- In a situation a UAV loses balance during its operation due to a sudden engine ruggedness, the gyroscope along the axis to the rotation measures the angle and generates a voltage which is then send to ESC which controls the rotor mechanism ,allowing the vehicle to gain control over flight through pitching and rolling techniques.

- In another situation where the rotors and external forces tend to push the UAV or rotate it, the gyroscope and accelerometer measures the linear and rotational acceleration along with the lateral direction sending a signal to the ESC to yaw or translate the plane using rotor systems.

- Thirdly, if an embedded GPS/map is fed to the unit, the combination of rotation through gyroscopes, acceleration through accelerometer and locational details through magnetometer based on air's magnetic flux density, the heading direction of the drone can be found out. Further, the magnetic details also talks about the direction of the magnetic north pole and hence the UAV can be pitched, yawed and rolled to take the necessary path.





ADVANTAGES & DISADVANTAGES

Advantages

- An integrated INS/GNSS provides absolute position and attitude information to a platform. This information can be used to navigate vehicles autonomously, perform highly precise inspections, generate high-definition maps for location applications and many other purposes.
- An integrated INS/GNSS contains an IMU, a GNSS receiver and sensor fusion software to provide georeferenced information to the user.
- An integrated INS/GNSS contains software that fuses together inertial data along with other independent aiding sources (information from GNSS receiver, odometry, pressure, etc.) to generate accurate position and attitude information.

Disadvantages

- In some cases, absolute position and attitude information isn't required. In these cases, an IMU that provides changes in orientation and acceleration over short durations should meet the user's requirements.
- While an IMU doesn't contain a GNSS receiver, the user may want to use a GNSS receiver that is already being used on the platform. In this case, the user can integrate an IMU to enhance the position and attitude accuracy of the platform in areas where GNSS is unavailable.
- An IMU does not contain sensor fusion software; if aiding sources aren't present, then the user must rely on inertial data only and an IMU may be preferred to an integrated INS/GNSS.

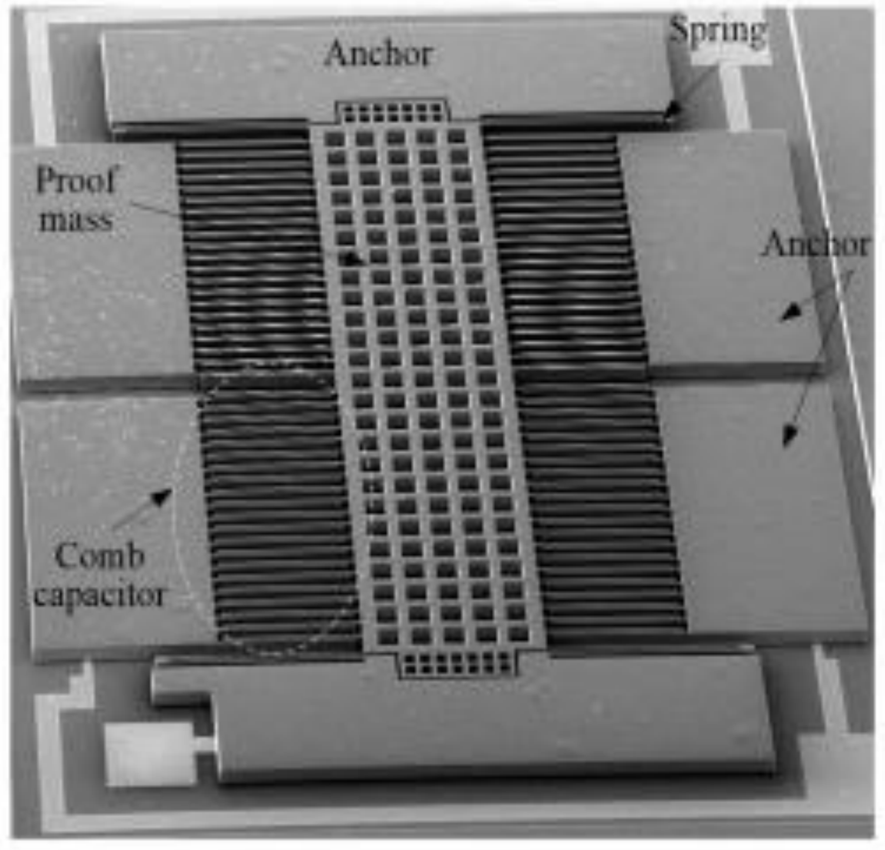
MATERIAL SELECTION

MATERIALS USED IN MEMS ACCELEROMETERS IN UAV's

- High-precision MEMS capacitive accelerometers are needed in applications like inertial navigation.

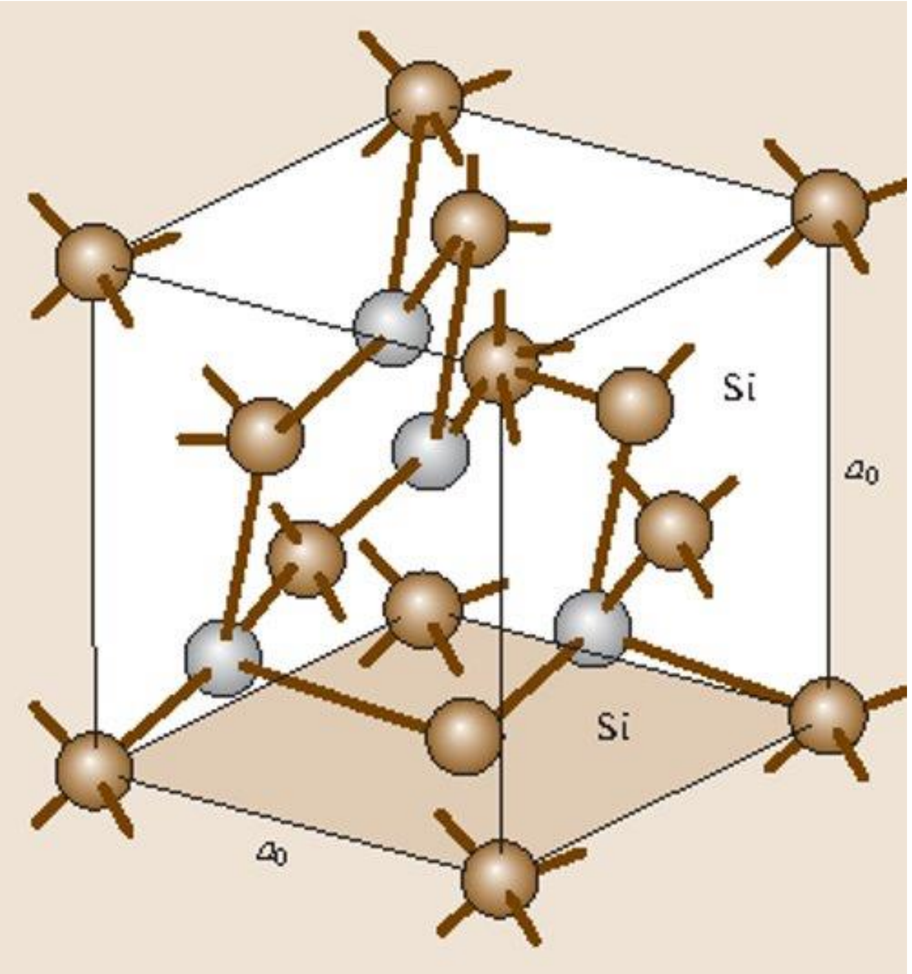
- Capacitive accelerometers have advantage as compared to other accelerometers in terms of high sensitivity, low power consumption and high resolution. Capacitive MEMS accelerometers are characterized using silicon and flexible polyamide substrates which provide higher sensitivities.

- The structure of the MEMS capacitive accelerometer is shown aside. Anchors and sensing elements (proof mass, comb capacitors, and springs) are made of single crystal silicon. The bottom substrate is made of Pyrex 7740 glass.



Single crystal silicon is the most widely used semiconductor material as a substrate material due to its excellent machinability, mechanical stability, and the potential to combine sensing elements and electronics on the same substrate. Circular wafers made of silicon are used as substrate in most MEMS sensors.

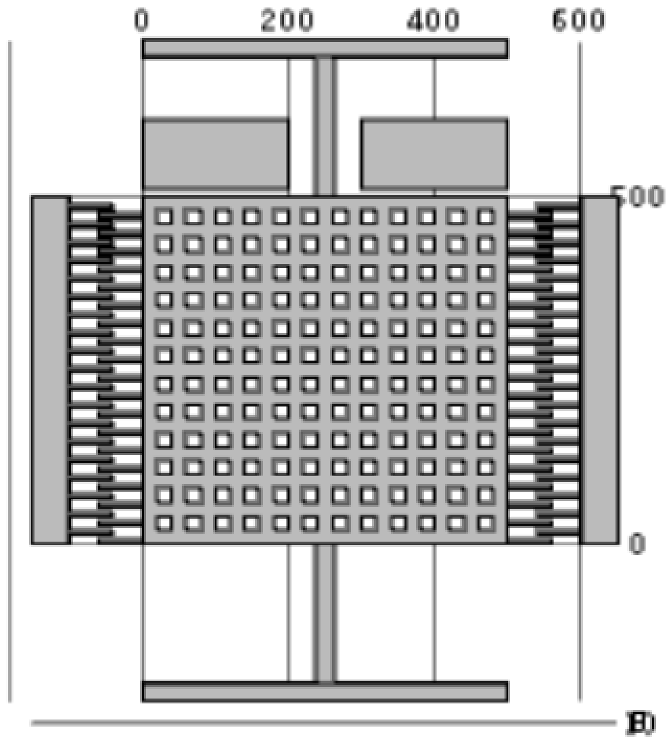
The crystal orientation should be known before manufacturing, since silicon has orientation-dependent properties such as piezo-resistivity coefficients and etching rates. The common orientation is (100) where the numbers represent Miller indices. It is an anisotropic material whose atoms are organized in a lattice having several axes of symmetry.



MATERIALS USED IN A MEMS GYROSCOPE

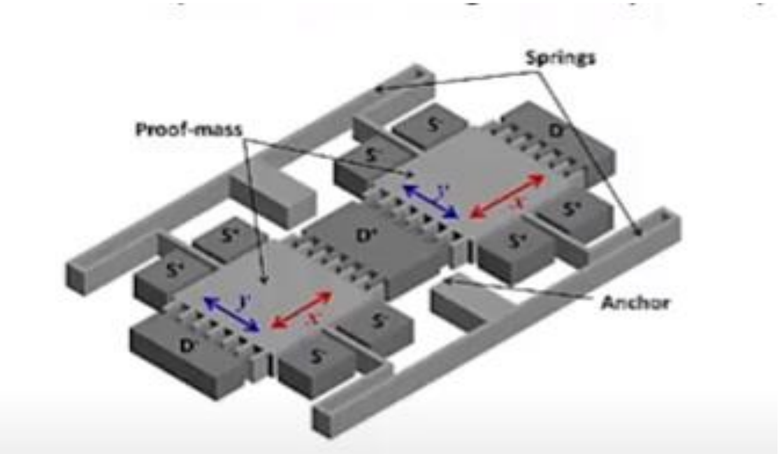
The structure on which the gyroscope is built is symmetrical with perforated proof mass. The substrate is made up of Silicon because of two main reasons:

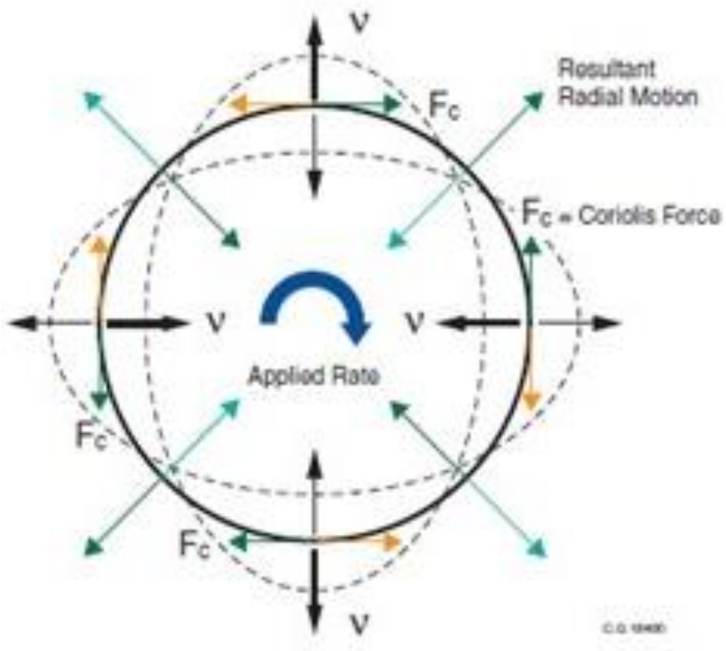
- It is mechanically stable, and it can be integrated into electronics on the one substrate. Electronics for signal transduction, such as a p- or n-type piezo-resistor, can be readily integrated with the Si substrate.
- Silicon is almost an ideal structural material. It has about the same Young's modulus as steel(about2x10^5 MPa),but is as light as aluminum, with a mass density of about 2.3g/cm3. Materials with a high Young's modulus can better maintain a linear relationship between applied load and the induced deformations.



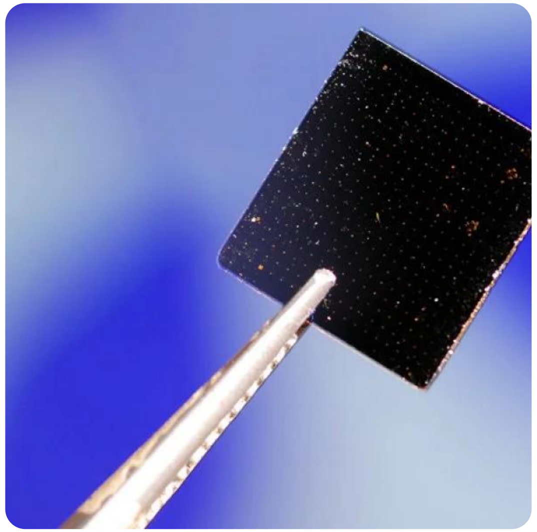
Perforated proof mass

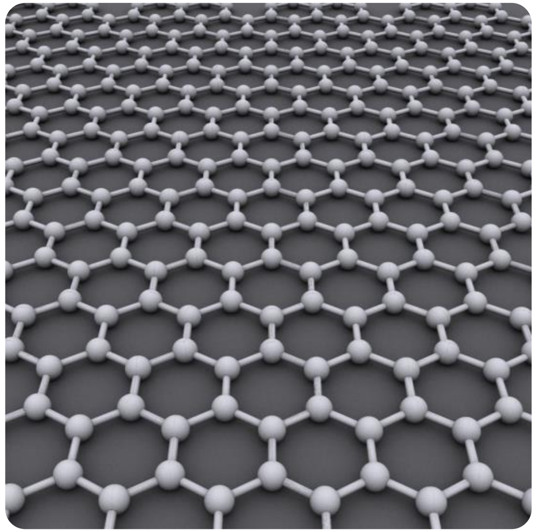
- The perforated proof mass generally made of calcium carbonate crystal enables in reducing the damping effect. The proof mass, which is suspended by flexible beams made of single crystal Silicon is of the order of one-fifth the width of a human hair.
- When ordinary proof mass is used, it increases the area of the proof mass and hence results in air-film damping. The moveable comb fingers are connected with the proof mass . The fixed comb fingers are used to drive the device. The structure is fixed at the anchors, while the rest of the structure including proof mass is free to move.
- The proof masses are electro statically actuated by applying voltage to comb drive. Proof masses vibrate in opposite directions in x- axis. The device uses the capacitance between each moving mass and each of the four electrodes to sense the rotation induced displacement. Ceramics are used as the dielectric material for the capacitors.





MATERIALS USED IN MEMS MAGNETOMETER





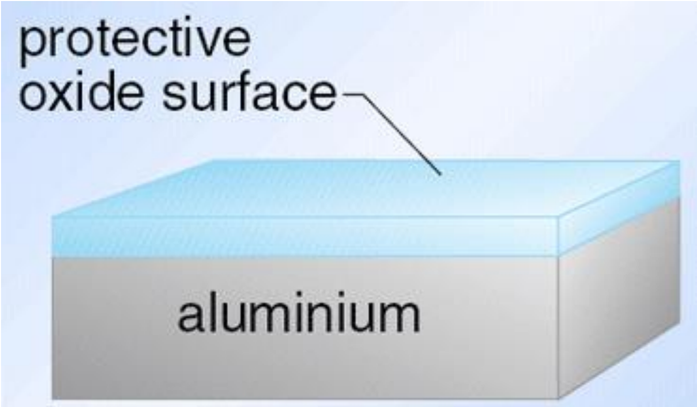
- Magnetometers have been used with inertial sensors (accelerometers and gyroscopes) to improve the attitude estimation performance. In addition to improving the attitude accuracy, a magnetometer also provides a slight improvement in the position accuracy.
- Hall devices which operate on the principle of Lorentz force are the most widely used magnetic sensor format due to their ease of fabrication and implementation, small size and high linearity.
- When considering the materials required for the fabrication of a magnetometer based on the hall effect, materials with high carrier mobility, low carrier concentration and narrow band gaps are desirable for Hall effect applications since these properties provide the exact characteristics for high sensitivity Hall devices. In addition, reducing the material thickness provides an exceptional advantage since the charge carriers are confined, which produces a stronger force. Considering these requirements, Graphene seems to be the best option. Possessing ultra-high carrier mobility and being one-atom thick makes graphene a specifically unique material for Hall effect type applications since charge carriers are constrained in a two-dimensional plane thus providing a higher sensitivity and an outstanding resolution. In addition, graphene is also an intrinsically low noise material.

An optical image of a graphene Hall effect device with Cr/Au contacts. Graphene layer is highlighted with red-dotted lines.

- Silicon or silicon dioxide is usually used as the substrate material due to its mechanical stability and it is feasibility to be integrated into electronics on the same substrate.

- The electrical contacts are the most critical part for the reliability . For this reason, the use of contact materials with higher hardness and low resistivity are desired. Gold is widely used as contact material but is a soft metal. Contact hardness can be improved preserving good conductivity and chemical inertness by alternating gold layers with thin layers of chromium.

ENCLOSURE AND COATINGS

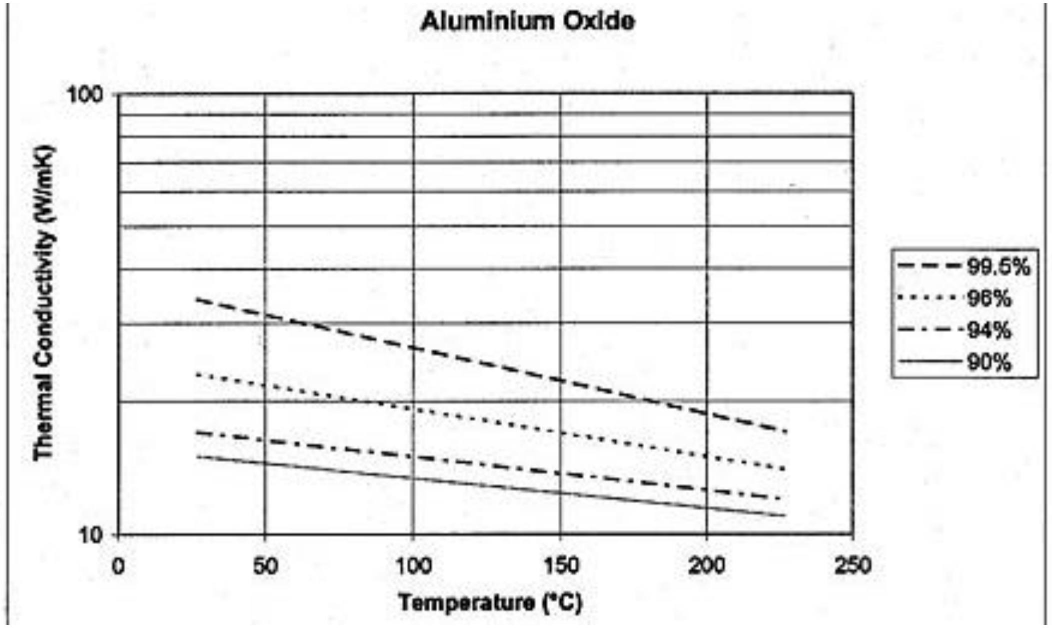


Accelerometer and Gyroscopes:

The accelerometers and gyroscopes contain capacitive elements which are to be electrically insulated from the housing and the external environment.

Furthermore, the capacitance of the two sensors might be affected through temperature changes in the surroundings.

In order to account for these effects, the housing for these sensors is generally made of aluminium with the layer of aluminium Oxide on one side.



- For a general diagonal size of the sensors of around 250 to 300 microns, it is essential to add a 100 microns thick Aluminium layer at minimum with a 40 microns oxide layer which prevents electric leakage and thermal loss while at the same time ensuring minimum measurement loss due to the high flexural rigidity of Aluminium.
- In certain cases, titanium can be used as the housing material. In this case, a thin coating of zinc or chrome on the inner side allows thermal stability and electric insulation.
- Titanium has the advantage of higher strength to weight ratio allowing lesser noise in readings due to less weight.

ABS

<u>Plastics used to enclose Mechanical Sensors:</u>

Wide range of plastics and polymers are used for the purpose of enclosing mechanical sensors. Depending on the requirement of mechanical and chemical properties any one of the below mentioned polymers can be used.

1. ABS (Acrylonitrile Butadiene Styrene)
2. PA (Polyamide)
3. PC (Polycarbonate)
4. PC+ABS Blend (Polycarbonate + Acrylonitrile Butadiene Styrene) (Suitable for our application as it has high temperature resistance, impact strength and suitable for permanent outdoor operation.

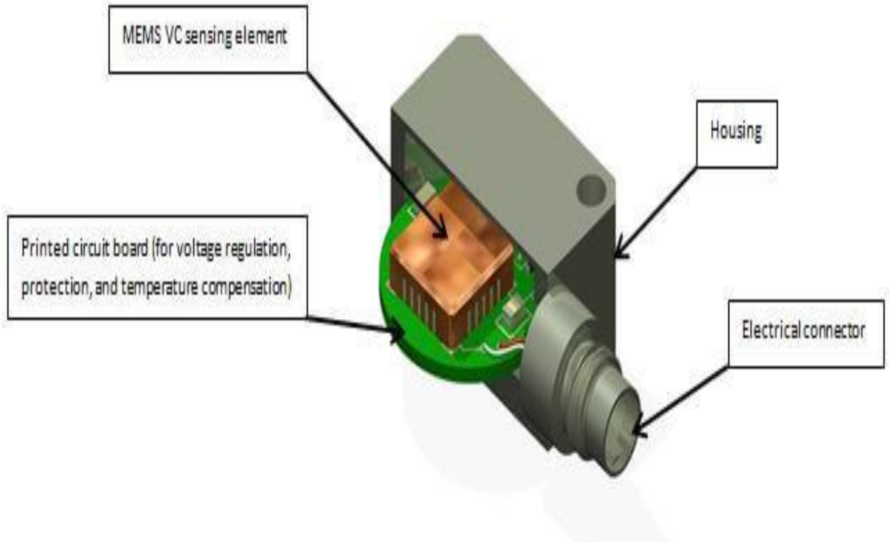
Polyamide

PCB:

- PCBs are usually a flat laminated composite made from non-conductive substrate materials with layers of copper circuitry buried internally or on the external surfaces.
- They can be as simple as one or two layers of copper, or in high density applications they can have fifty layers or more. The flat composite surface is ideal for supporting the components that are soldered and attached to the PCB, while the copper conductors connect the components to one another electronically.

Epoxy resins to seal the mechanical sensor package:

- 1. High strength
- 2. Low Shrinkage
- 3. Excellent adhesion to various substrates
- 4. Effective electrical insulation
- 5. Chemical and solvent resistance
- 6. Low cost and low toxicity



Internal structure and housing of a capacitive accelerometer

- Epoxies are easily cured, and they are also compatible with most substrates.
- They tend to wet surfaces easily, making them especially suitable for composite applications.

FORCE CALCULATIONS

CALCULATIONS INVOLVING ACCELEROMETER

For the initial case,

$$C_1 = C_2 = \frac{A\varepsilon_0}{d} = \frac{A\varepsilon_0\,(d)}{d^2}$$

Any acceleration can cause the mass to move in the opposite direction by a distance Δx.

$$C_1 = \frac{\varepsilon_0 A(d+\Delta x)}{(d+\Delta x)^2} \qquad C_2 = \frac{\varepsilon_0 A(d-\Delta x)}{(d-\Delta x)^2}$$

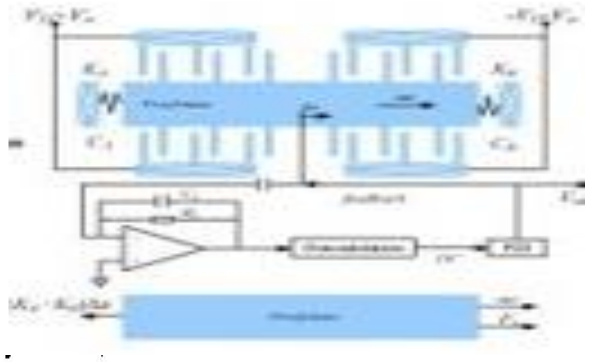
Here, d, Δx<< 1µm, which implies dΔx, (Δx)2 are approx. equal to zero.

$$\Delta C = C_1 - C_2 = \frac{2\varepsilon_0 A \Delta x}{d^2}$$

This capacitance change can be measured through an op-amp circuit connected to a digital display. Now, both springs provide resistive force in the same direction

$$K_s = 2K$$

$\therefore F_R = 2K\Delta x$, which resists the accelerative force $F_R = ma$ $\quad a = \frac{2K\Delta x}{m}$



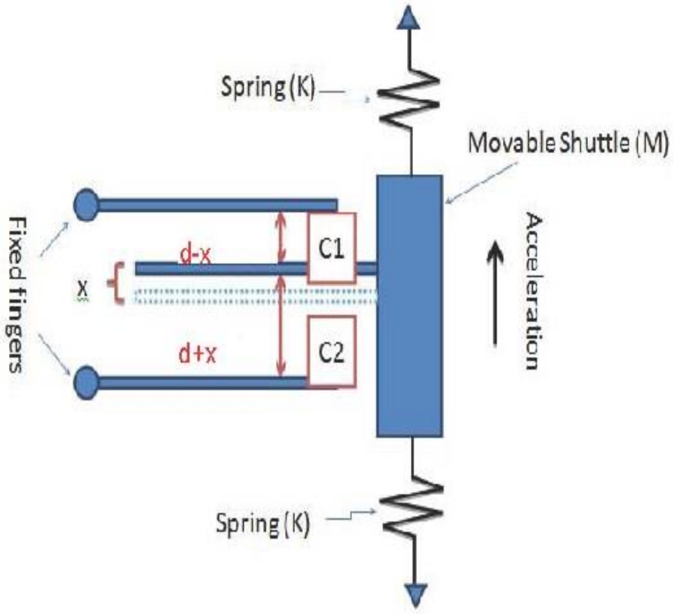


Figure 1: Spring-Mass Capacitive Accelerometer Structure

The usual mass is a polysilicon bar of force m = 20 µg, soft steel spring, k = 5 N/m. Therefore,

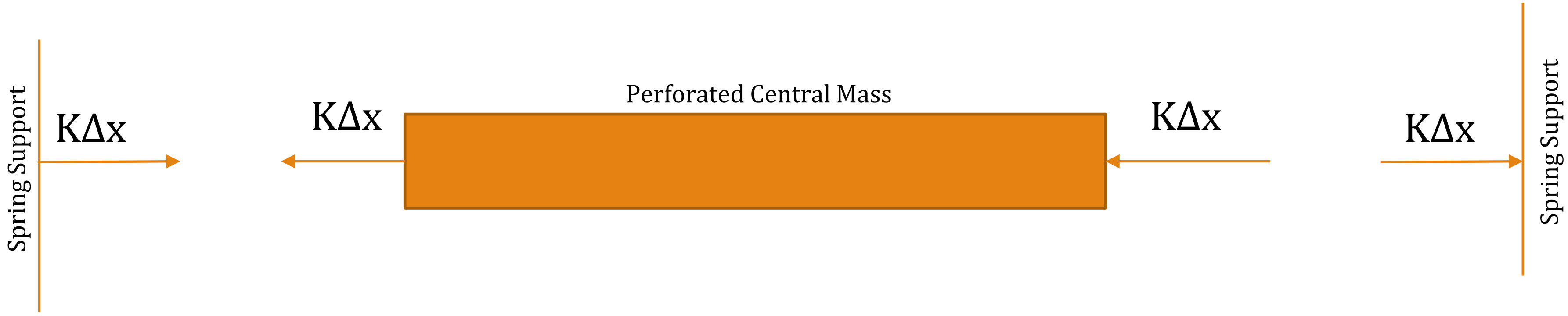
$$a = 0.5x \times 10^{6}\ m/s$$

Measurement range: 50 µg to 50 mg = 490.5 µN to 490.5 mN

Or from $49.05 \times 10^{-6} m$ to $49.05 \times 10^{-3} m$

Therefore, applicable accelerometer dimensions is 52 mm.

The system can be represented as a bar element as shown below.



CALCULATIONS INVOLVING GYROSCOPE

$$C_1 = \frac{\varepsilon 0 A}{d + x} \qquad C_2 = \frac{\varepsilon 0 A}{d - x}$$

$$C_2 - C_1 = \Delta C = \varepsilon 0 A\left(\frac{1}{d - x} - \frac{1}{d + x}\right)$$

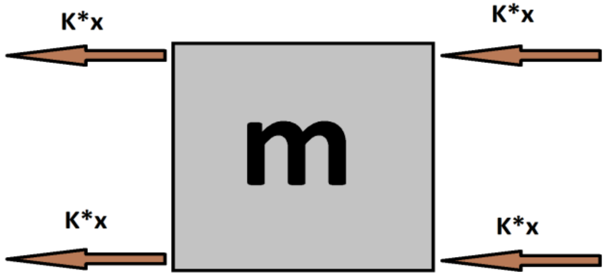
$$\frac{2\varepsilon 0 A x}{d^2} \qquad x \ll d$$

$$\Delta C = \frac{2\varepsilon 0 A x}{d^2}$$

where,C1,C2 are the values of capacitance between two fixed plates and the movable central plate rigidly attached to the proof mass

$$F_c = 4kx$$

Where Fc is the Coriolis force

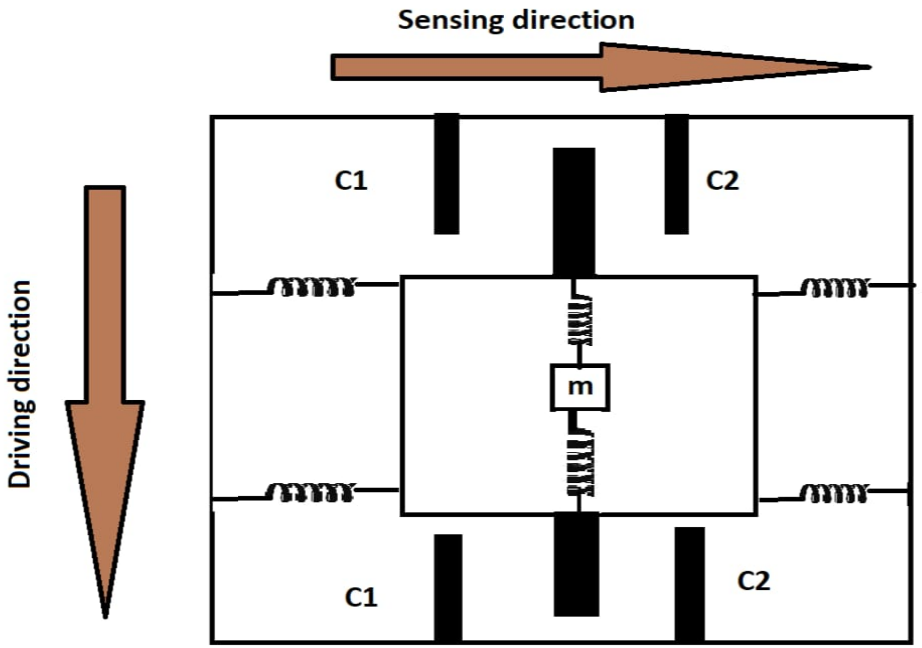


$$F_c = 2mV_x w$$

$$2mV_x w = 4kx$$

$$W = \frac{2kx}{mV_x}$$

Reduced free body diagram



where Vx is the velocity of proof mass along the driven direction and where w is the angular velocity of the UAV perpendicular to the plane of gyroscope.

Assume angular velocity of UAV to be 30 deg/s which is equal to π/6 rad/s.

Wy=Angular velocity of proof mass along driven direction=sqrt(k/m).

For MEMS devices, spring constant ranges from 5-250 N/m. Proof mass value is in micrograms.

Let's assume value of k to be 10N/m and mass to be 100 μg.

$Y = y_o Sin(wt)$,where y_o is the amplitude of oscillation

∴ $Vy=y_o\, w\, Cos(wt)$

∴ $Vy(max)=y_o.w$

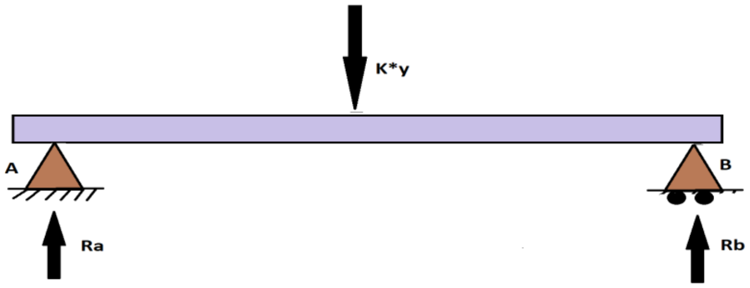
Let's assume y_o=10 μm

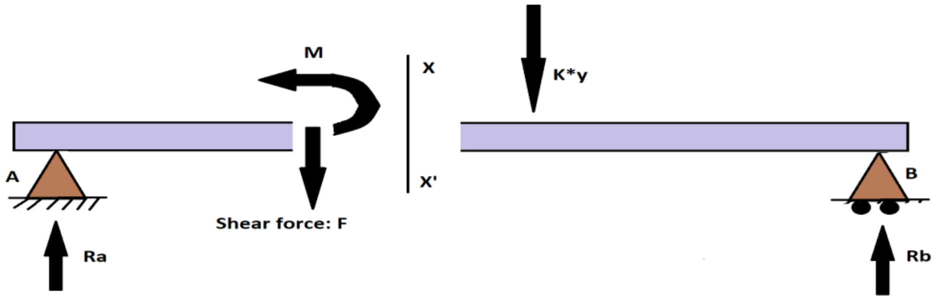
Area of cross section of enclosure of proof mass 'm' is 5 μm X 5 μm

$$F_c = 2mV_x w$$

$$w = \frac{\Delta C k d^2}{mVA\varepsilon 0}$$ Relation between w and ΔC

Free body diagram of simply supported beam





Edges of enclosure containing proof mass m is assumed to be a simply supported beam with a point load at the centre.
Ra and Rb are reaction forces at points A and B respectively.

$R_a = R_b = ky/2$

Along any arbitrary plane X-X',

Shear force $F = R_a = ky/2$

Bending Moment $M = R_a x \; = kyl/4$

Substituting the values assumed in the previous slide,
F=(10*10^-6)/2=50 μN
Shear stress is uniform along the rod and maximum shear stress occurs when y=yo=50/(5*5*(10^-12))=2MPa
Maximum bending moment=10*(10*10^-6)*(100*10^-6)/4=2.5*(10^-9)Nm

Silicon is used as substrate in MEMS Gyroscope and the yield point of silicon is 24 MPa.

As calculated earlier, maximum shear stress endured by the MEMS Gyroscope is 2 MPa but the yield strength is 24Mpa.Hence,the chosen material, i.e. Silicon can be used to fabricate the MEMS Gyroscope and is able to withstand the stress.

CALCULATIONS INVOLVING MAGNETOMETER

Hall Effect Sensors are devices which are activated by an external magnetic field. We know that a magnetic field has two important characteristics flux density, (B) and polarity (North and South Poles). The output signal from a Hall effect sensor is the function of magnetic field density around the device. When the magnetic flux density around the sensor exceeds a certain pre-set threshold, the sensor detects it and generates an output voltage called the Hall Voltage, VH.

This Hall voltage, (VH) of the basic Hall Element is directly proportional to the strength of the magnetic field passing through the semiconductor material (output $\propto$ H). It is quite small, only a few microvolts even when subjected to strong magnetic fields so most commercially available Hall effect devices are manufactured with built-in DC amplifiers, logic switching circuits and voltage regulators to improve the sensors sensitivity, hysteresis and output voltage. This also allows the Hall effect sensor to operate over a wider range of power supplies and magnetic field conditions.

Hall Effect Sensors are available with either linear or digital outputs. The output signal for linear (analogue) sensors is taken directly from the output of the operational amplifier with the output voltage being directly proportional to the magnetic field passing through the Hall sensor. This output Hall voltage is given as:

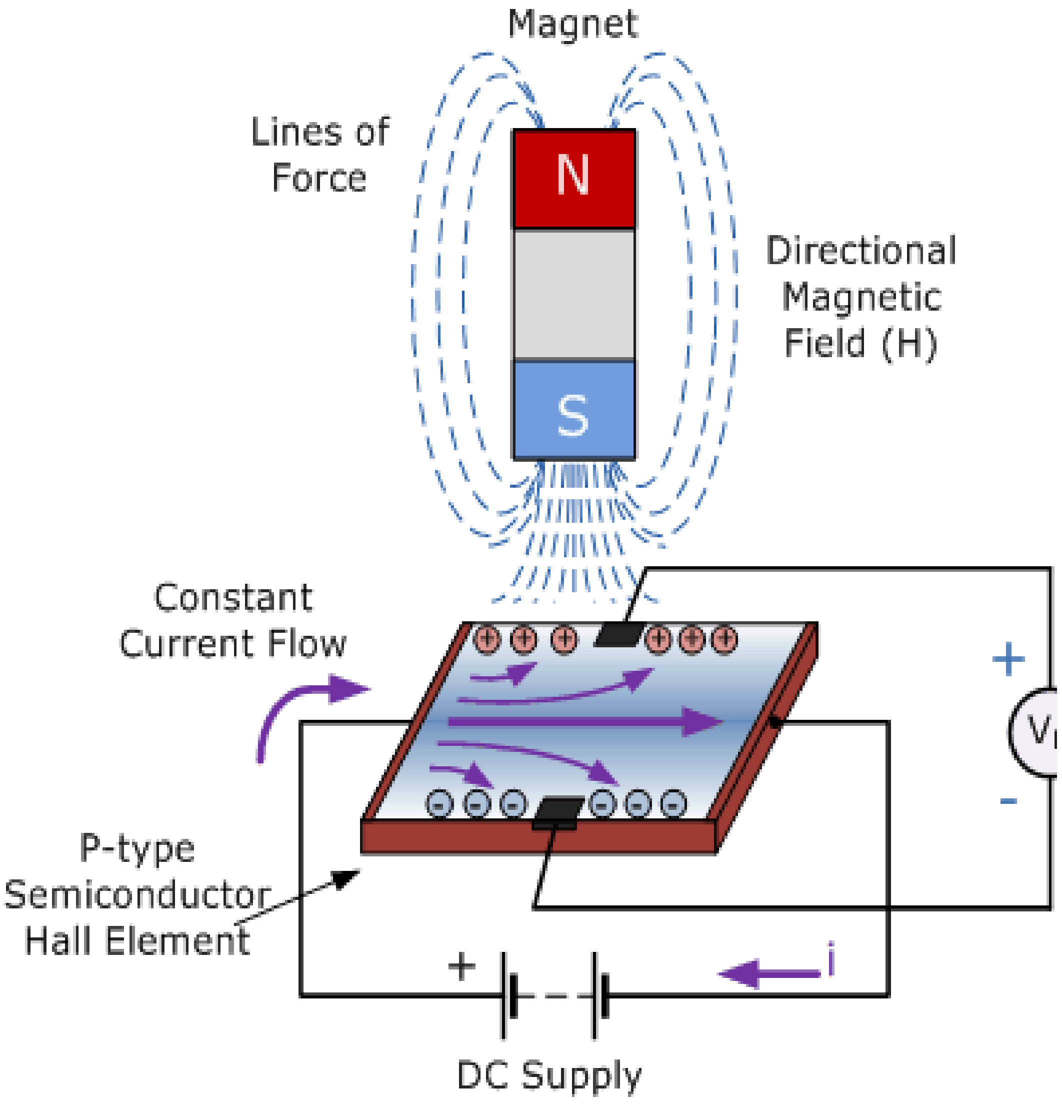
$$V_H = R_H\left(\frac{I}{t} \times B\right)$$

Where:

VH is the Hall Voltage in volts; RH is the Hall Effect co-efficient; I is the current flow through the sensor in amps; t is the thickness of the sensor in mm; B is the Magnetic Flux density in Teslas

Magnetometers used in IMUs are to be highly sensitive to detect the Earth's magnetic field and determine position. To increase sensitivity, we can choose materials with high carrier mobility, low carrier concentration, and narrow bandgaps. Other than these physical properties of a material, the dimension of the magnetometer plays a major role in determining sensitivity. The lesser the thickness of the material, the higher will be the sensitivity of the magnetometer.
For this reason, Graphene is used as the ideal magnetometer sensing material. It is a P-Type material which can be fabricated to one atom layer thickness (and intrinsically a low noise material).

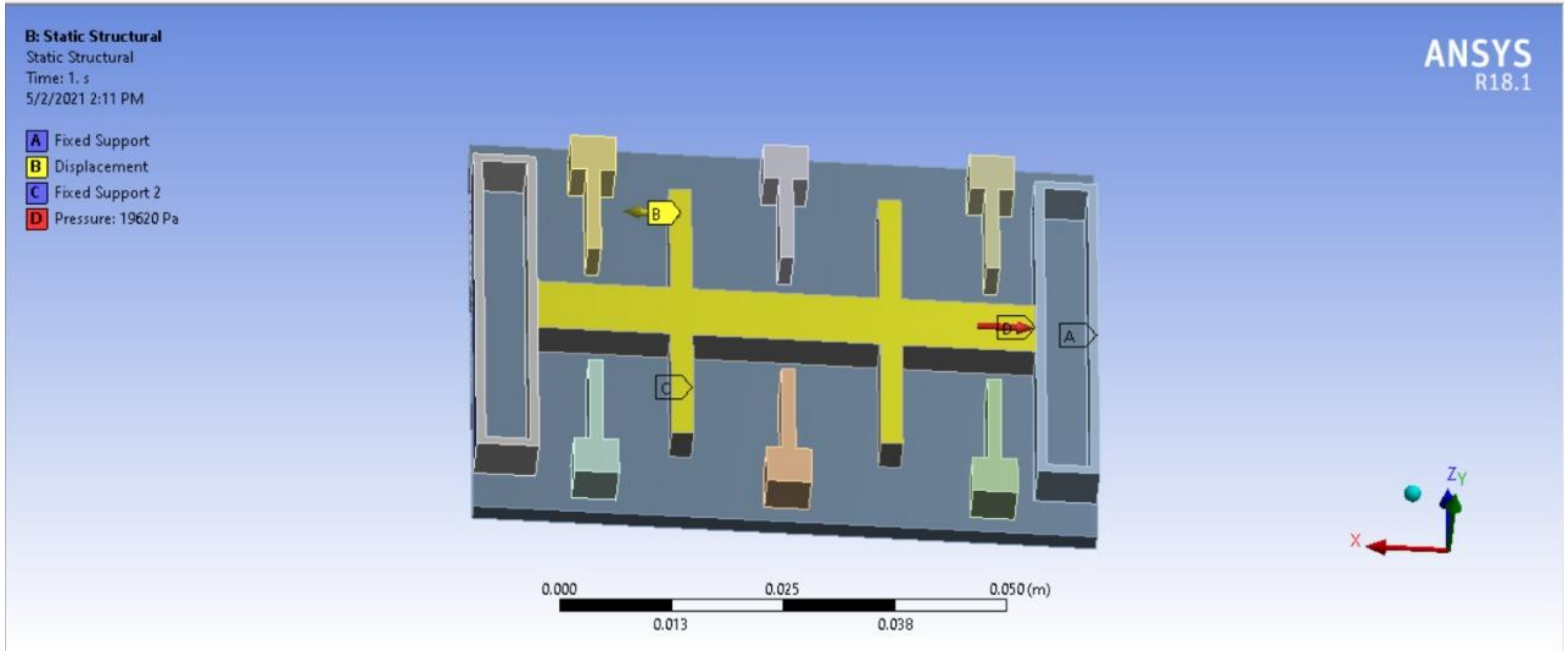
- The **thickness of monolayer graphene is 0.335 nm**.
- Assuming **earth's magnetic field as B as 45 µT** and current used in the sensor as **1 mA**. The Hall-effect coefficient value of graphene is 7 X 10^-7 m3/C.
- The Hall Voltage for the above configuration by substituting in the formula is **94 µV concluding the advantage of graphene**.
- Also, the carrier concentration of graphene is **10.52 X 10^24 m-3 that is fifteen orders of magnitude bigger than silicon**.



ANSYS MODELLING

ACCELEROMETER MODEL

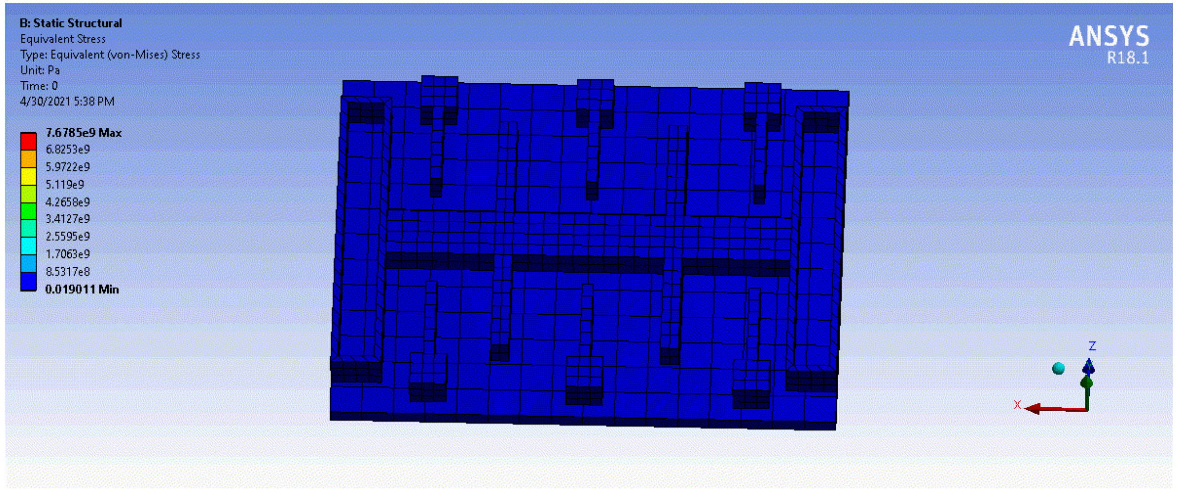
Forces Involved and components on which the force acts:



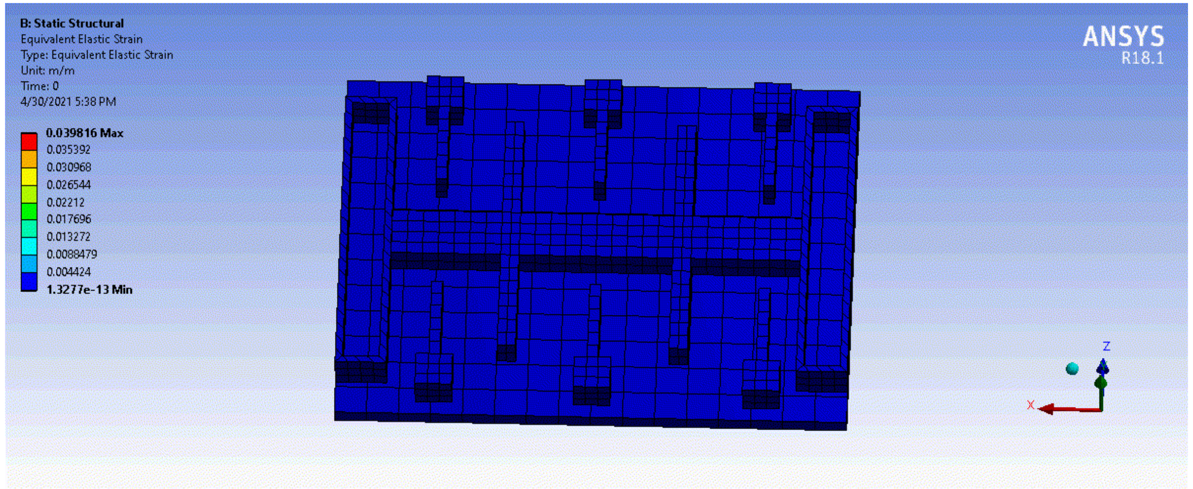
Materials:

Base – polymide | Young's Modulus : 1850 MPa
Mass – silicon | Young's Modulus : 140 GPa
Constraint spring - stainless steel | Young's Modulus : 190 GPa
Electrode- structural iron

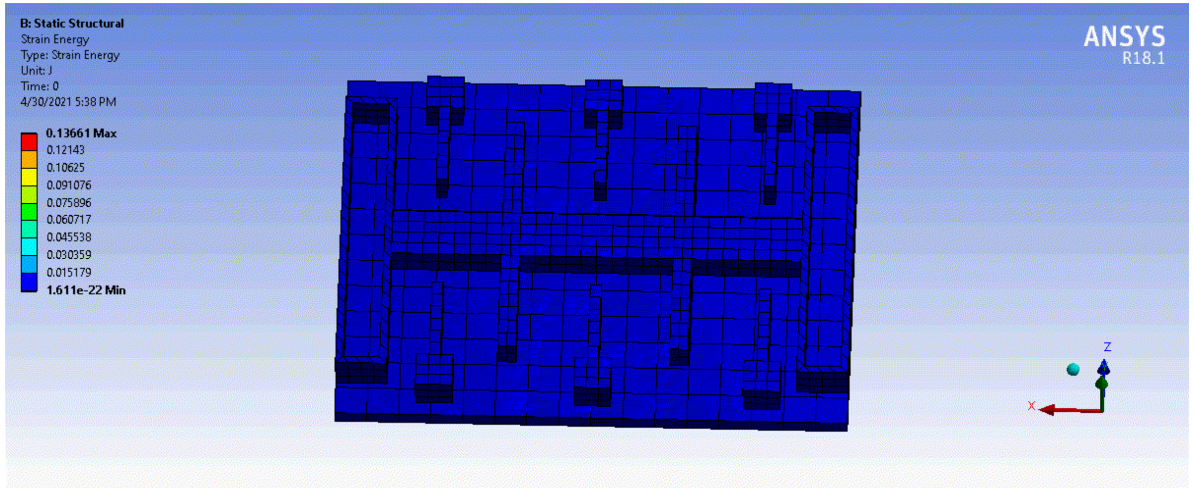
STRESS, STRAIN & ENERGY ANALYSIS



Stress Analysis | Double springs attached



Strain Analysis | Double springs attached



Strain Energy Analysis | Double springs attached

Maximum Stress
7.6785×10^9 Pa

Minimum Stress
0.019011 Pa

Maximum Strain
0.039816

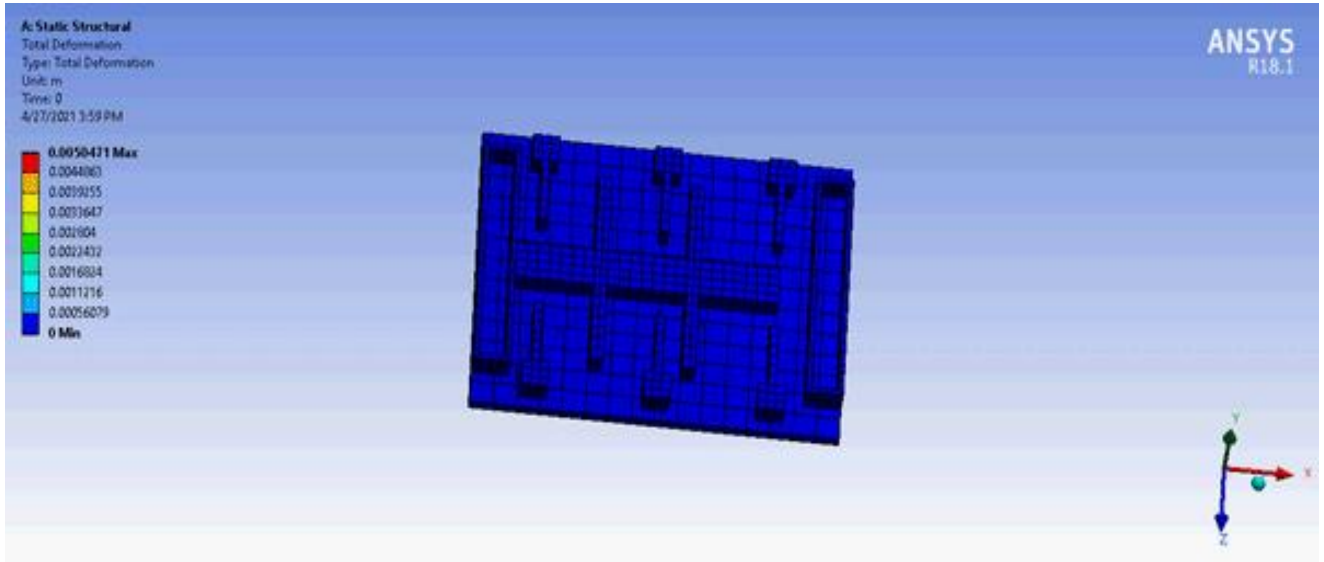
Minimum Strain
1.3277×10^{-13}

Maximum Strain Energy
0.13661 J

Minimum Strain Energy
1.611×10^{-22} J

DEFORMATION

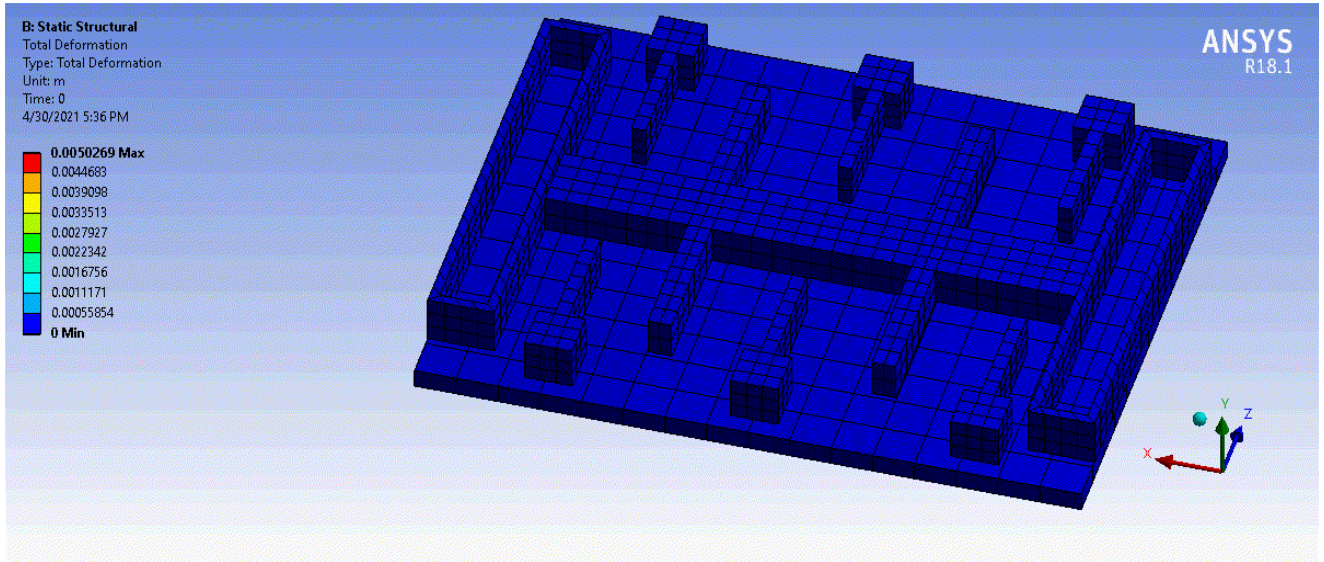
<u>Deformation Analysis</u>
Single spring attached



<u>Maximum Deformation</u>
0.0050471 m

<u>Minimum Deformation</u>
0 m

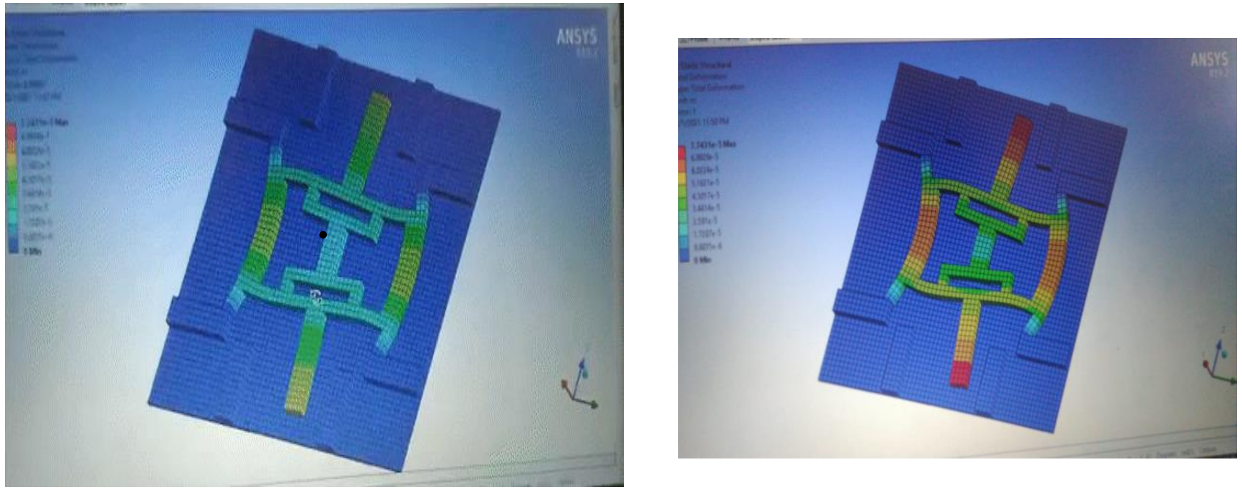
<u>Deformation Analysis</u>
Double spring attached



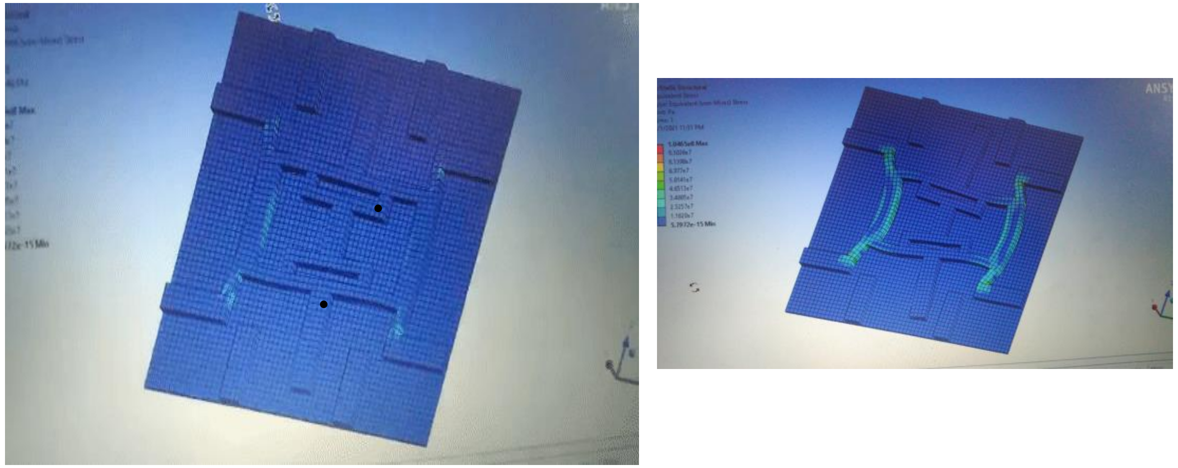
<u>Maximum Deformation</u>
0.0050269 m

<u>Minimum Deformation</u>
0 m

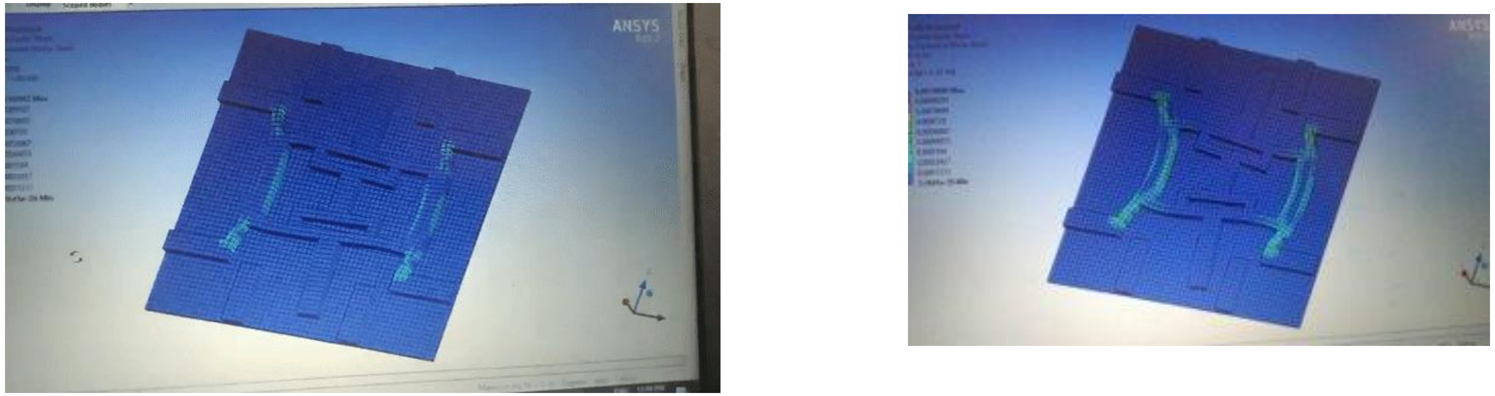
DESIGN AND MODELLING OF MEMS GYROSCOPE:



Total deformation in gyroscope(ANSYS)



Total stress simulation in ANSYS



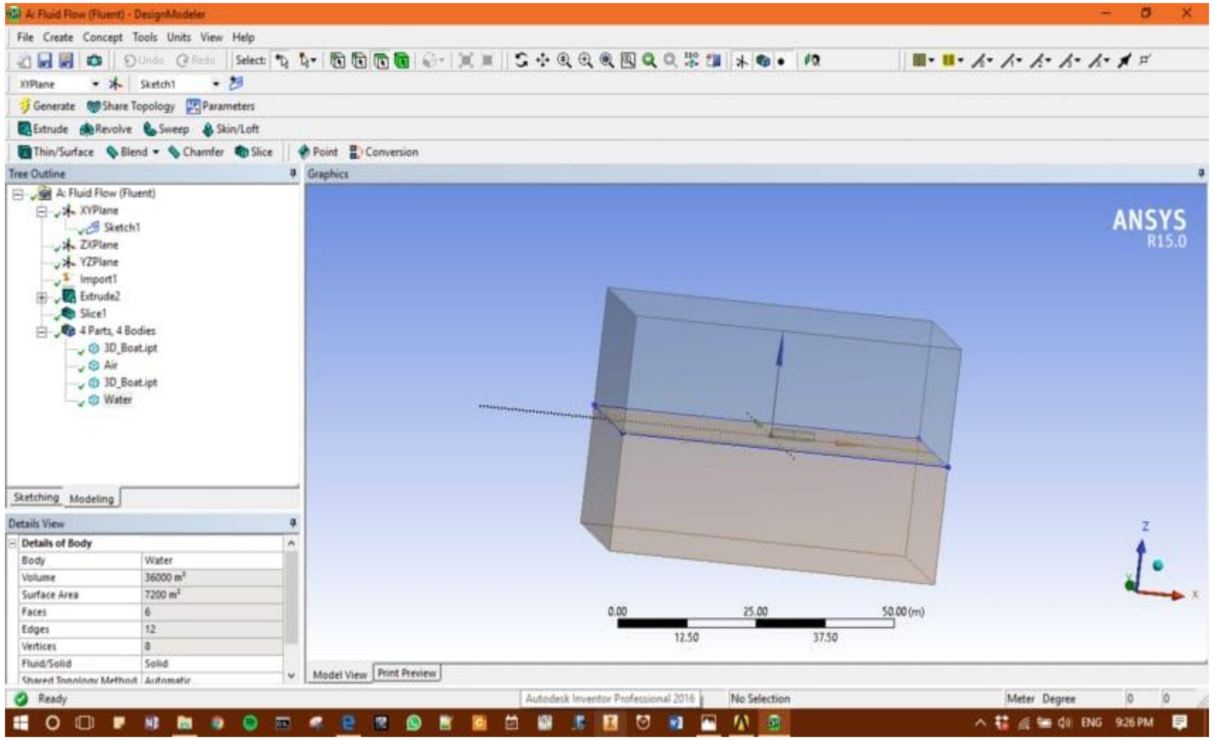
Total Strain simulation in ANSYS

Boundary conditions:

Y=yo Sin(wt)
V=yo w Cos(wt)
A=-yo w^2 Sin(wt)

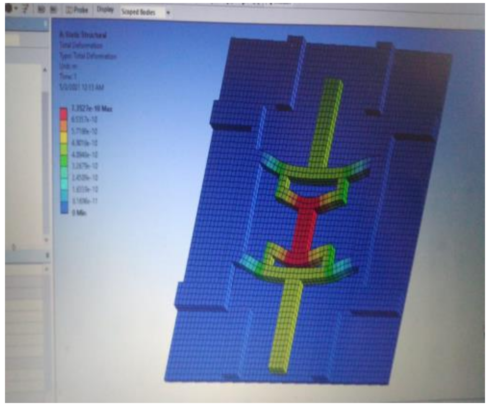
Therefore,
Spring force=Fs=ma=-m(yo w^2 Sin(wt))
Coriolis force=Fc=2mv(Wg)
=2m yo w(Wg)Cos(wt)

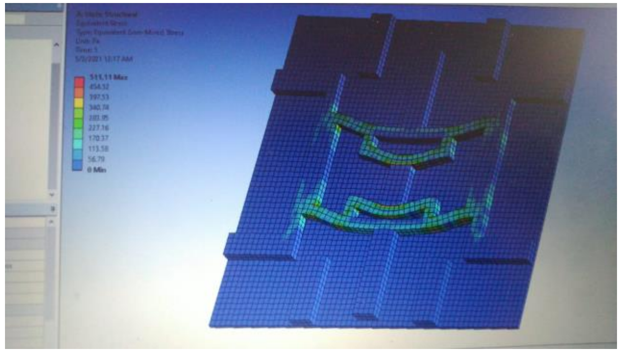
Where,
Yo=Amplitude of oscillation of proof mass
w=Angular velocity of oscillating mass
Wg=Angular velocity of aircraft
Fs and Fc are out of phase by 90 degrees

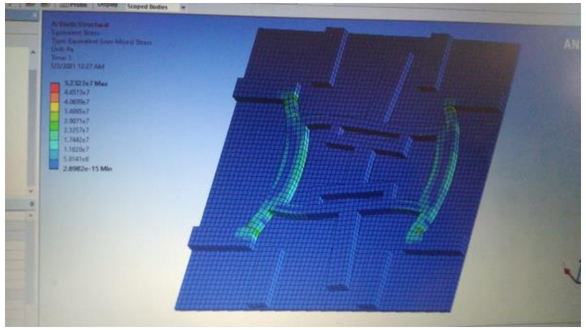


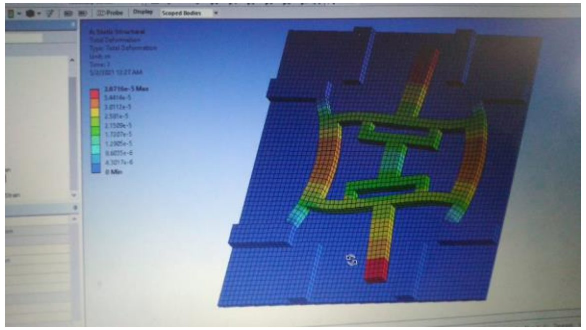
Constraints in contact surfaces

Our analysis containing 0,30,45,60,90 degrees are shown in the subsequent slides





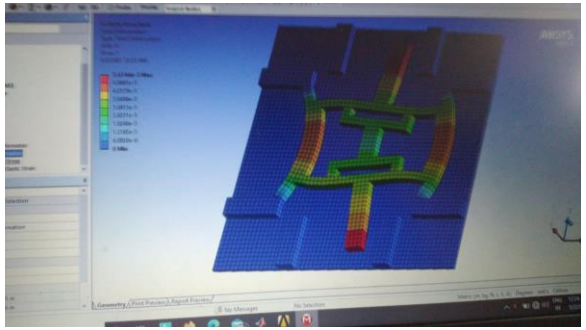


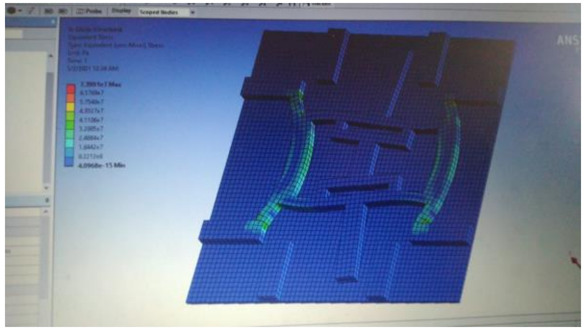


30 degrees

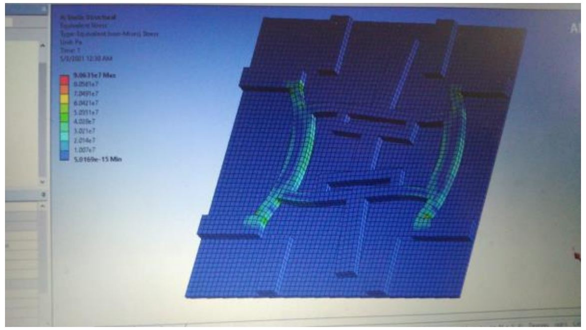
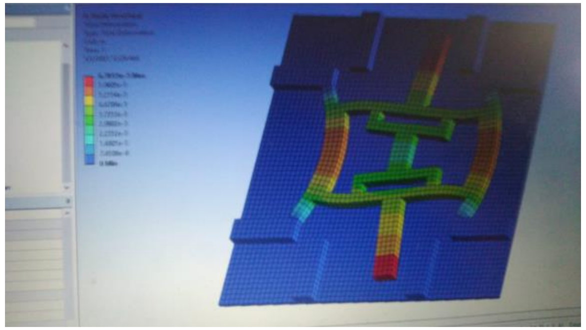
0 degrees

In the analysis,four lateral edges of silicon wafers are set as fixed support
Maximum force of 1N along each face along driving direction to represent spring force.
Maximum pressure of 2MPa on enclosure containing proof mass along sensing direction

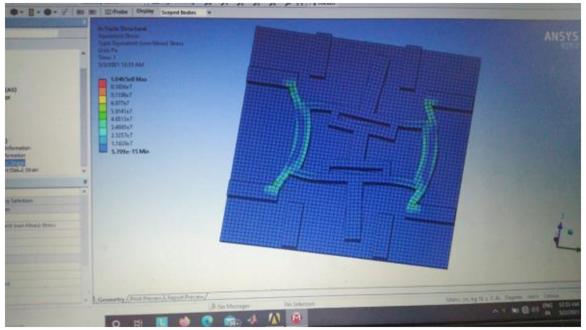
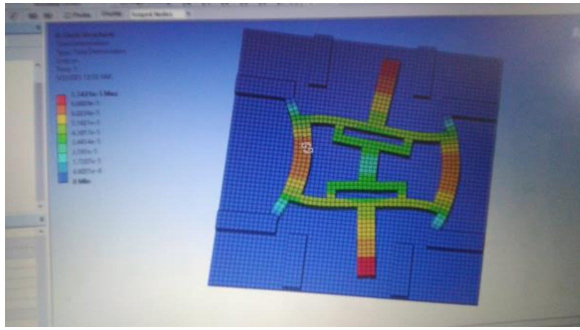




45 degrees

60 degrees

90 degrees

Interaction of all surfaces in contact are made as bonded or frictional with a suitable coefficient of friction depending on the design requirements

Materials used:

Limestone for proofmass

Youngs modulus:25MPa

Shear modulus:64MPa

Poisson's ratio:0.22

Anisotropic silicon for other structures

Youngs modulus:140GPa

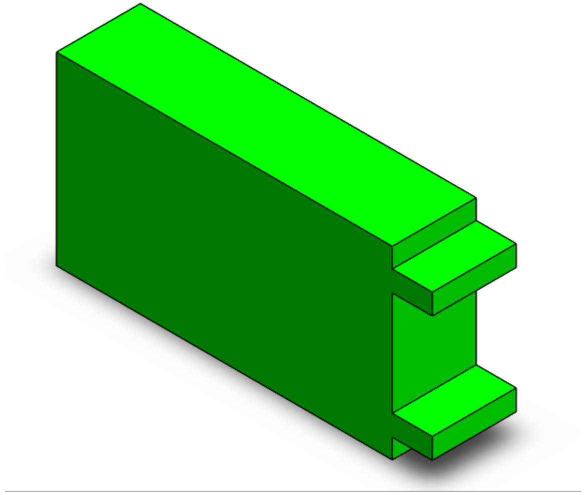
Shear modulus:60Gpa

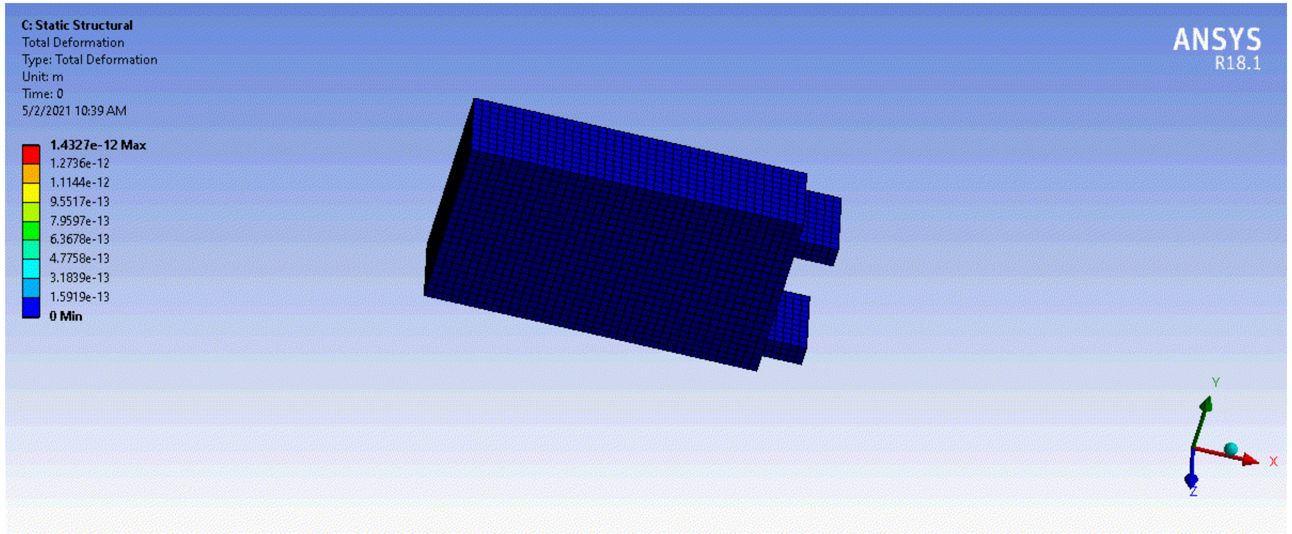
Poisson's ratio:0.265

MAGNETOMETER MODEL

MATERIALS USED

Graphene	Modulus of Elasticity: 1.02 TPa Poisson's ratio: 0.184
Copper(rods)	Modulus of Elasticity: 115 GPa Poisson's ratio: 0.34

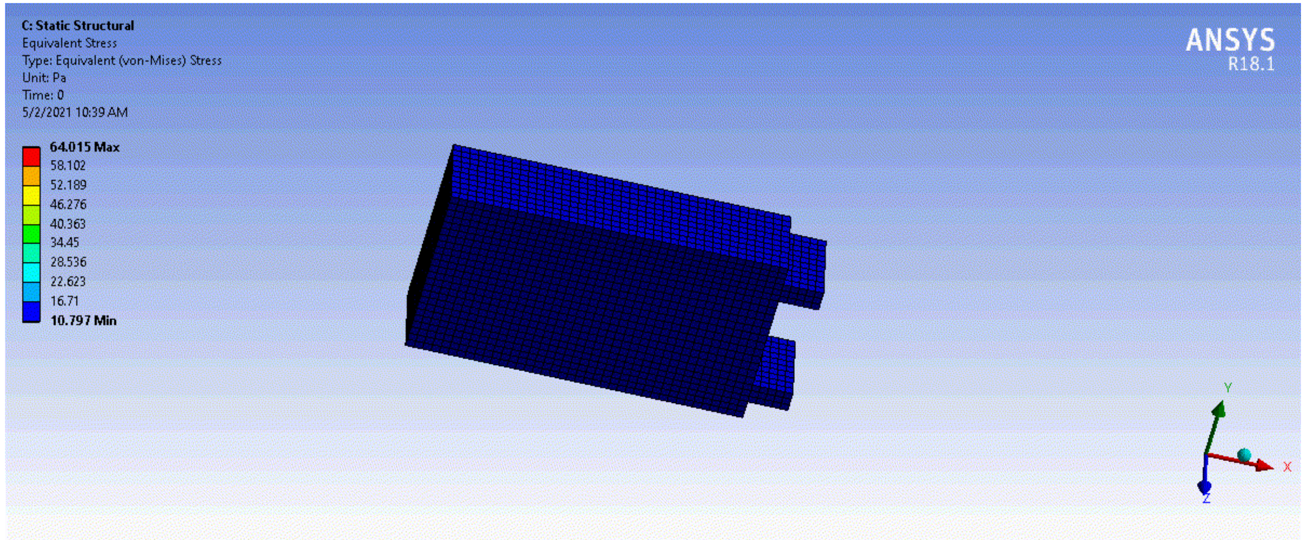




Total Deformation in Magnetometer(Ansys)

<u>Force applied:</u> 300 mN

STRESS STRAIN ANALYSIS



Stress Analysis (Ansys)

<u>Maximum stress:</u> 64 Pa

Strain Analysis (Ansys)

<u>Maximum strain:</u> 3.2 x 10^-10