A Project Report

On

Modelling and Simulation of Piezoelectric Rate Gyroscopes For Satellite Rotation Control

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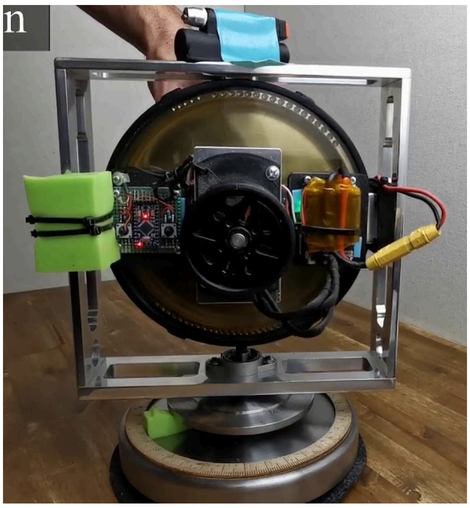
Introduction

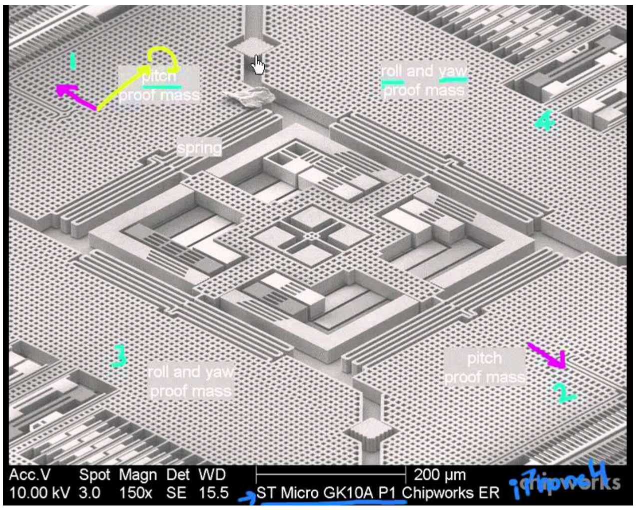
The project is based on modelling and simulating the piezoelectric rate gyroscope. Piezoelectric materials are active materials that can produce electricity in response to mechanical strains. They are used in a variety of applications, including sensors, actuators, and energy harvesting devices. In this project we are using the piezoelectric material to make a Rate Gyroscope. This project is focused on selecting the best material for piezoelectric gyroscope by simulating them in COMSOL and finding out their characteristics.

A gyroscope is a device that measures or maintains orientation and angular velocity. Mechanical gyroscopes are devices made up of a spinning wheel or disk that can rotate freely around an axis, whereas electronic gyroscopes (or MEMS-based gyroscopes) are devices made of piezoelectric materials that produce voltage signals when the orientation of the device changes. In this project, we are simulating the MEMS-based electronic rate gyroscope.

There are many types of gyroscopes, one of which is the rate gyroscope. The term "rate" in a gyroscope refers to the measurement of angular velocity. In this project, we simulate a rate gyroscope with different motions, such as constant angular velocity and a path in the XYZ direction, and determine the produced voltage.



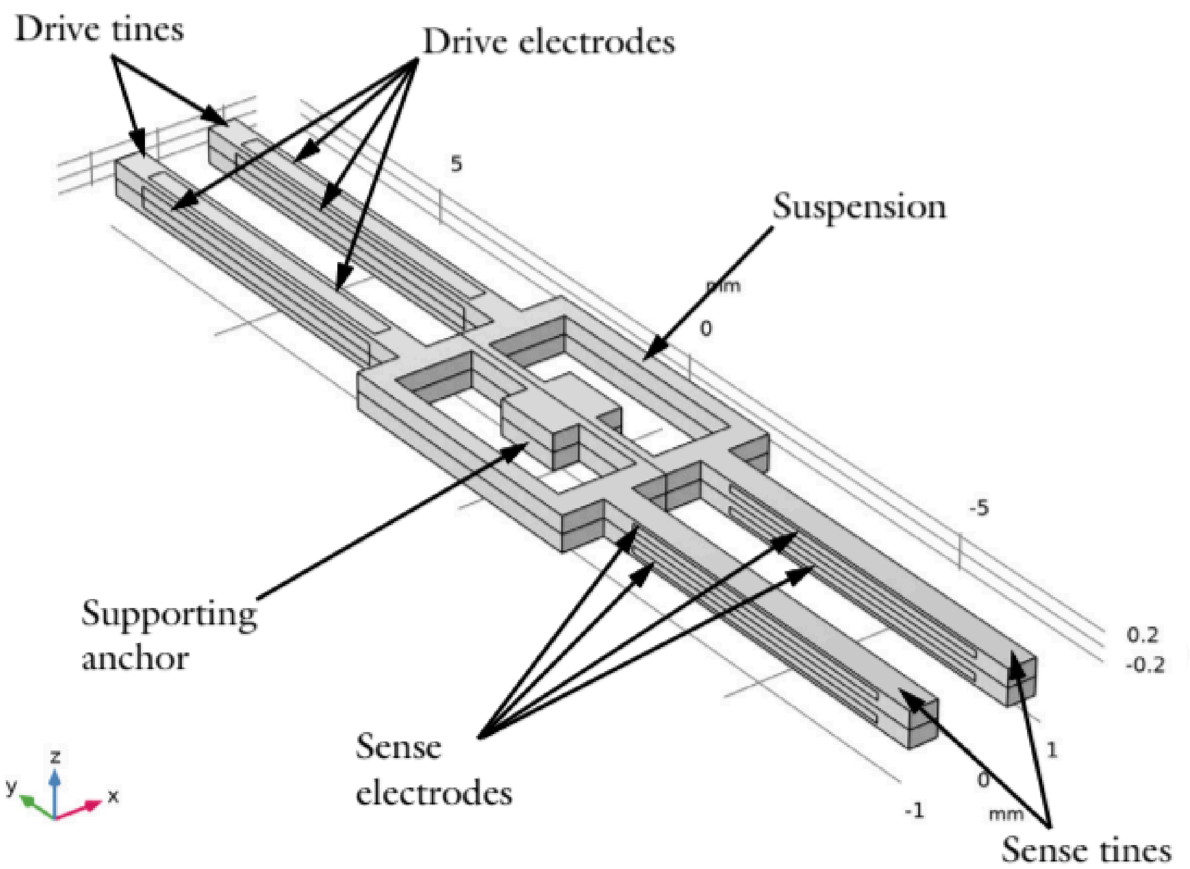
MECHANICAL GYROSCOPE



MEMS GYROSCOPE

Design and Working Principle

In this simulation we are designing a tuning fork shaped rate gyroscope made of some piezoelectric material. The design consists of 4 tuning forks separated into 2 categories called drive tines and sense tines. Inside these drive tines and sense tines we have drive electrodes and sense electrodes. Suspension and Supporting anchor is built for holding the tuning fork together. Suspension is also responsible for transporting mechanical stress from drive tines to sense tines.



Drive tines are designed to oscillate in the in-plane mode, whereas sense tines are designed to oscillate in the out-of-plane mode with respect to the substrate. The in-plane mode involves oscillation parallel to the plane of the substrate, while the out-of-plane mode involves oscillation perpendicular to the substrate.

Coming to the working principle of this model. There are two types of effects in the piezoelectric material they are:

1) Reverse piezoelectric effect: the phenomenon where a piezoelectric material deforms mechanically when an electric field is applied to it.
2) Direct piezoelectric effect: The direct piezoelectric effect converts mechanical energy into electrical energy, while the inverse piezoelectric effect converts electrical energy into mechanical energy.

The reverse piezoelectric effect is used to drive an in-plane tuning fork mode. This mode is coupled to an out-of-plane mode by the Coriolis force, and the resulting out-of-plane motion is sensed by the direct piezoelectric effect. The geometry of the tuning forks is designed so that the eigenfrequencies of the nearby modes are separated in the frequency space. The frequency response of the system is computed, and the rotation rate sensitivity is evaluated.

The voltage is applied to the drive electrodes (called drive voltage), which then start to vibrate in the in-plane mode. When an angular impulse is applied, a force called the Coriolis force is generated, adding out-of-plane oscillation in the forks. This out-of-plane oscillation is transferred to the sense tines via suspension in the form of mechanical stress. These oscillations induce out-of-plane mode oscillations in the sense tines and generate a voltage called sense voltage. This voltage is used to identify the angular frequency/ oscillation.

An effect whereby a mass moving in a rotating system experiences a force called Coriolis acting perpendicular to the direction of motion and to the axis of rotation. It is given as

$$\mathbf{F_{cor} = -2\rho\Omega \times (\partial u/\partial t)}$$

Fcor = Coriolis force

ρ = Density of the material

Ω = angular velocity of rotating frame

u = the local displacement of the structure

Simulation and Parameters

Piezoelectric Rate gyroscope:

We have modelled our Piezoelectric Rate Gyroscope using the COMSOL Multiphysics 6.2.

The dimensions and parameters of gyroscope are as follows:

tQz 0.5[mm] "Quartz thickness"

w_m 1[mm] "Mount width"

l_w (l_f-w_m)/2-w_tbf "Wing length"

w_w 0.25[mm] "Wing width"

l_f 4[mm] "Frame length"

w_f 3[mm] "Frame width"

w_tbf 0.4[mm] "Frame top/bottom thickness"

w_sf 0.25[mm] "Frame side thickness"

l_d 6[mm] "Drive tine length"

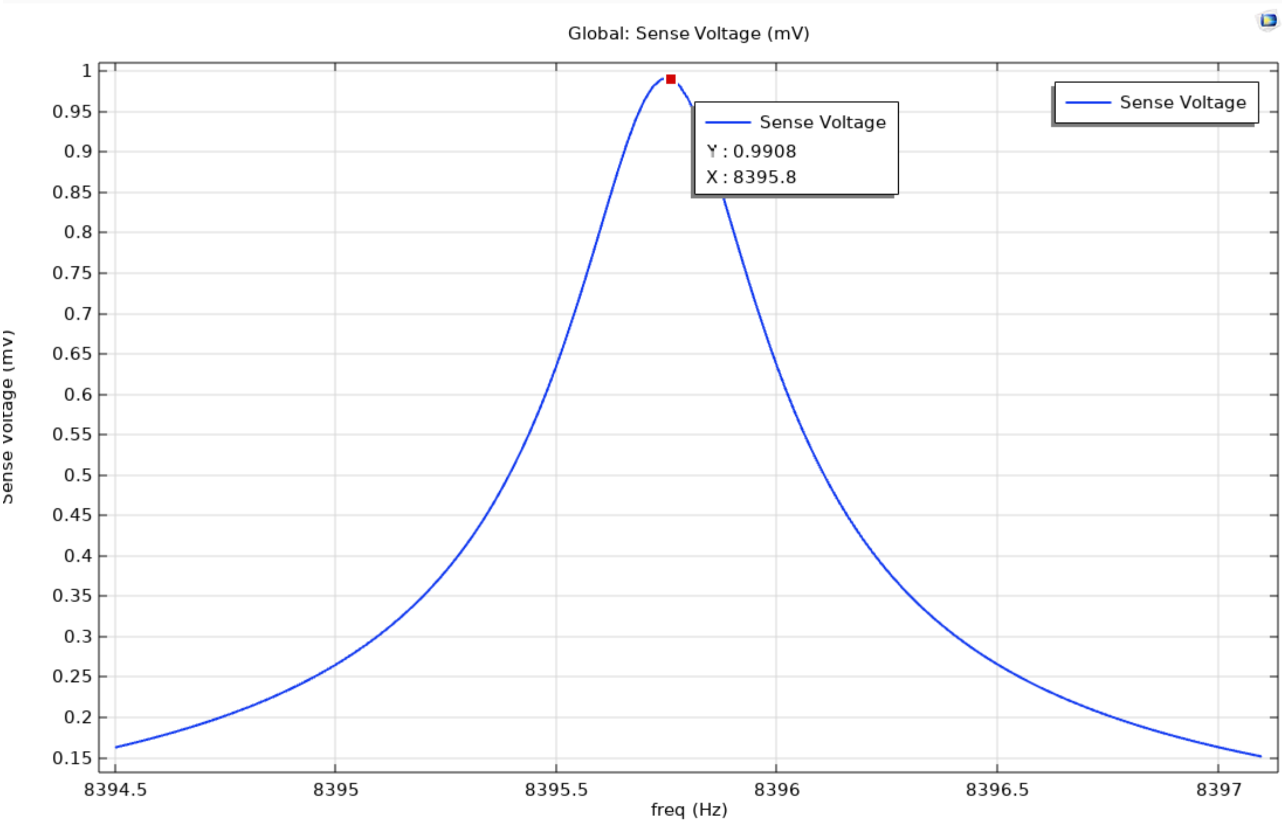
w_d 0.4[mm] "Drive tine width"

l_s 5.5[mm] "Sense tine length"

w_s 0.4[mm] "Sense tine width"

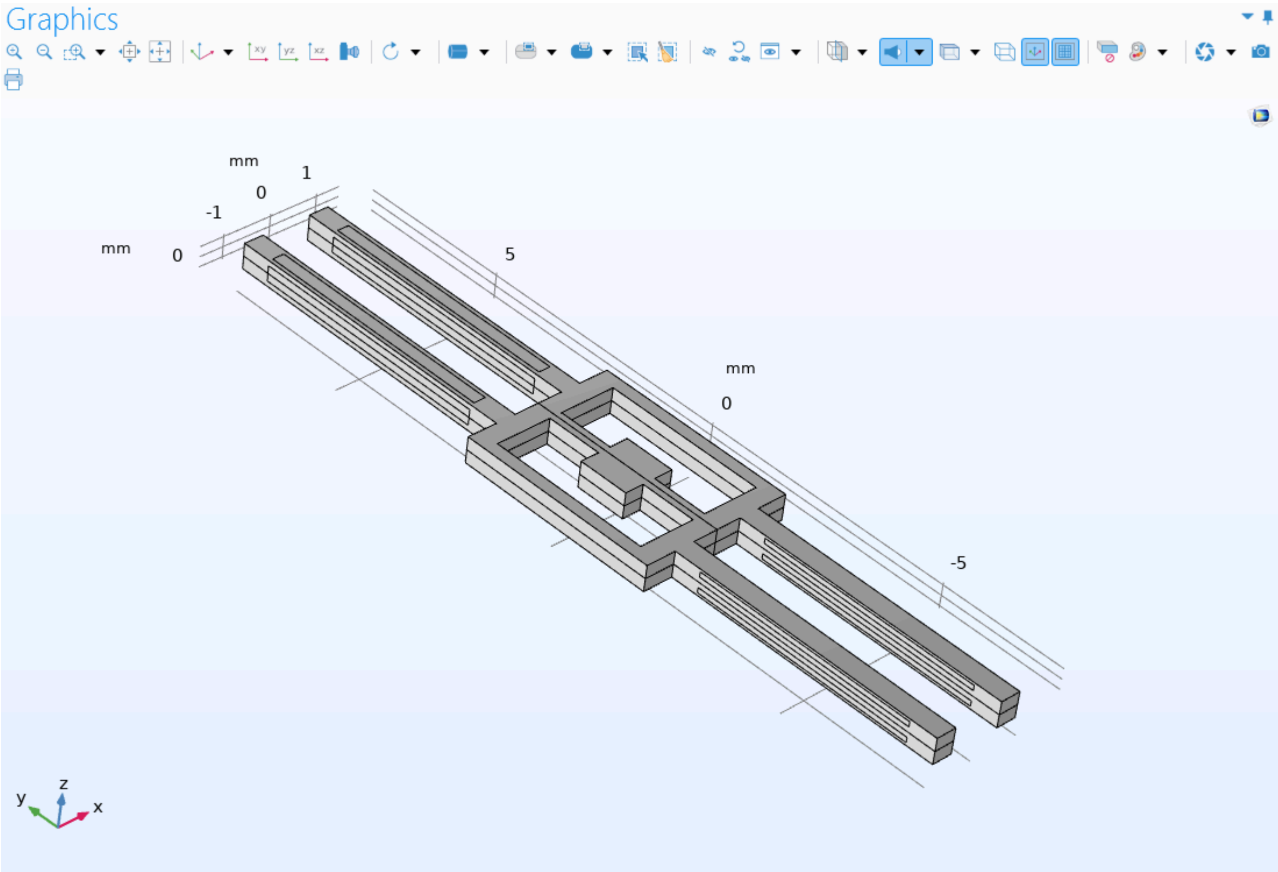
gap 1[mm] "Gap between tines"

As discussed earlier, Coriolis force is maximal when the angular velocity of the frame is parallel to the long in-plane axis of the gyroscope structure. In this case the resulting force is in the out of plane direction and produces a corresponding out of plane motion of the drive tines. This motion causes reaction moments in the supporting suspension which in turn transfers these moments to the sense tines — driving the sense mode. Note that in this model the angular velocity vector is assumed to be parallel to the long axis of the device.

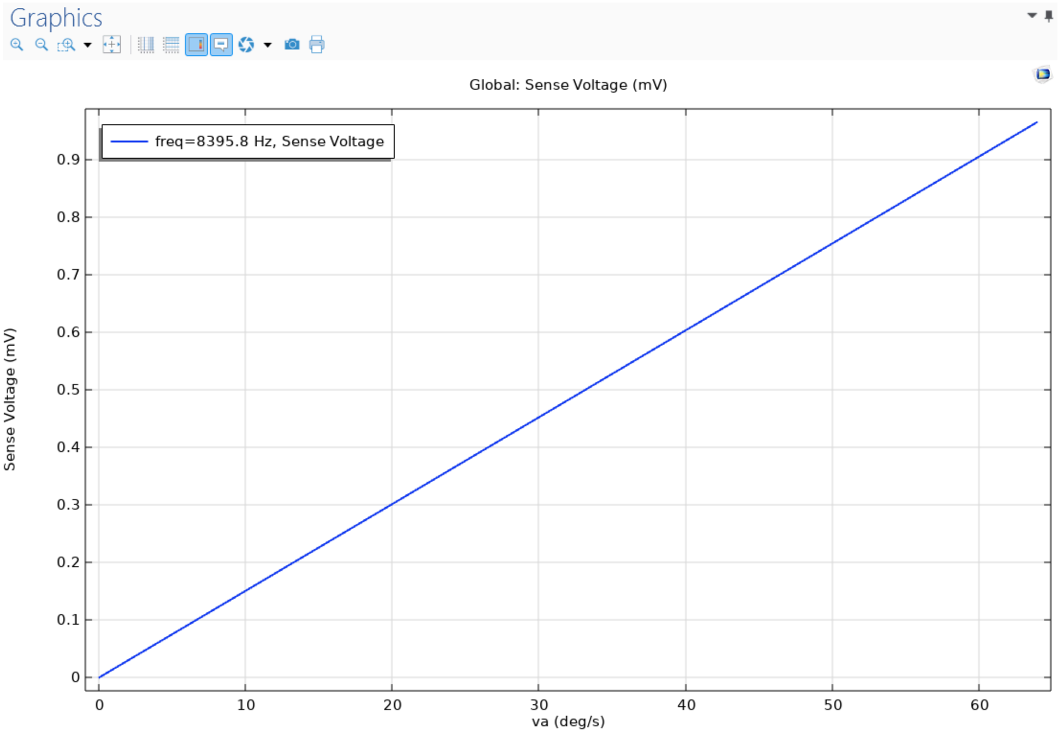


(Sense voltage vs. drive frequency with an applied sinusoidal drive voltage of amplitude 2 V and an angular velocity of 64 deg/s.)

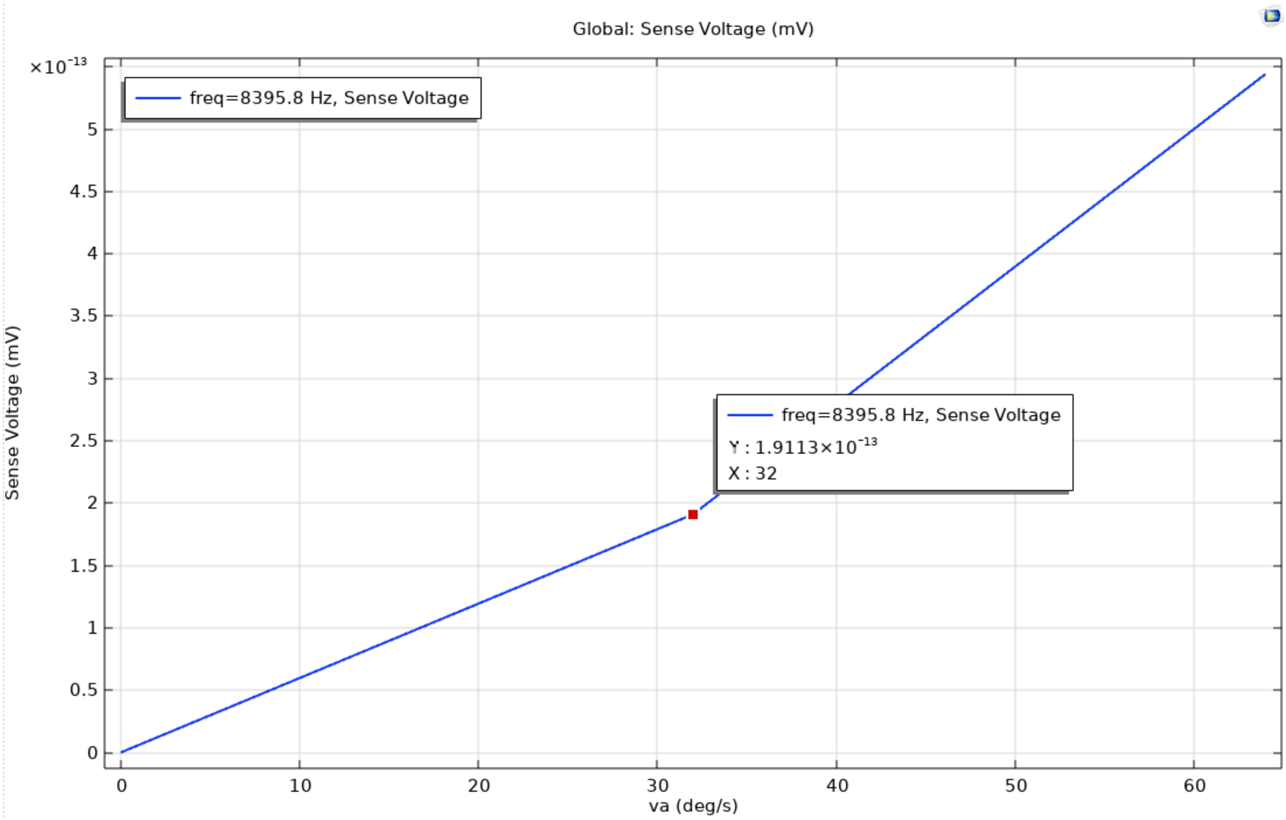
The sense voltage shows a clear peak near the drive frequency of 8396 Hz. This indicates that the gyroscope is most sensitive at this frequency, which corresponds to its resonance. Away from the resonance frequency, the voltage decreases significantly, showing less sensitivity to angular velocity changes. The peak at 8396 Hz suggests that this is the optimal drive frequency for operating the gyroscope to maximize its sensitivity to angular velocity. We have selected 3 materials for testing the characteristics. The materials are Zinc sulfide, Gallium Arsenide and Quartz LH.



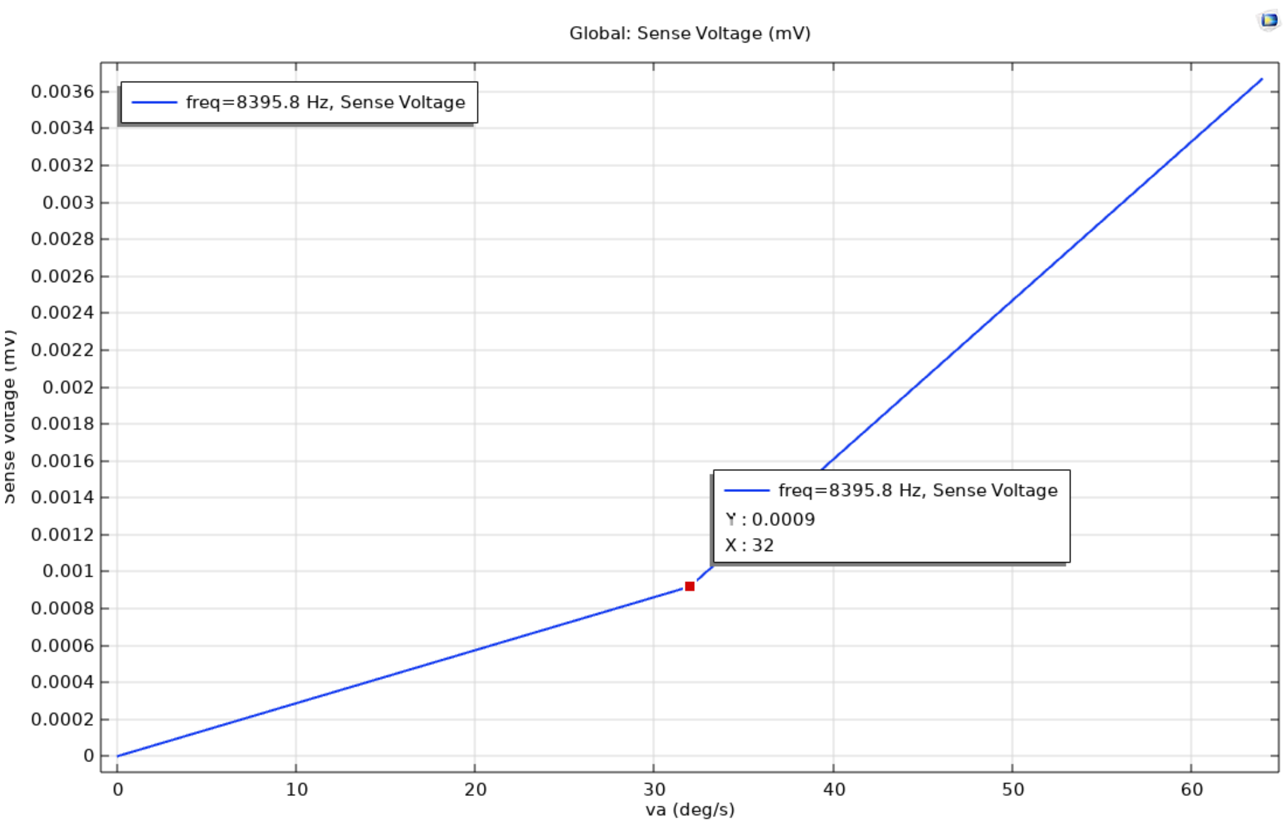
The following is the model we have made in COMSOL. The sensor has an overall length of 20mm. These are the graphs between sense voltage and angular velocity for three different materials



For Quartz LH(IEEE 1978)



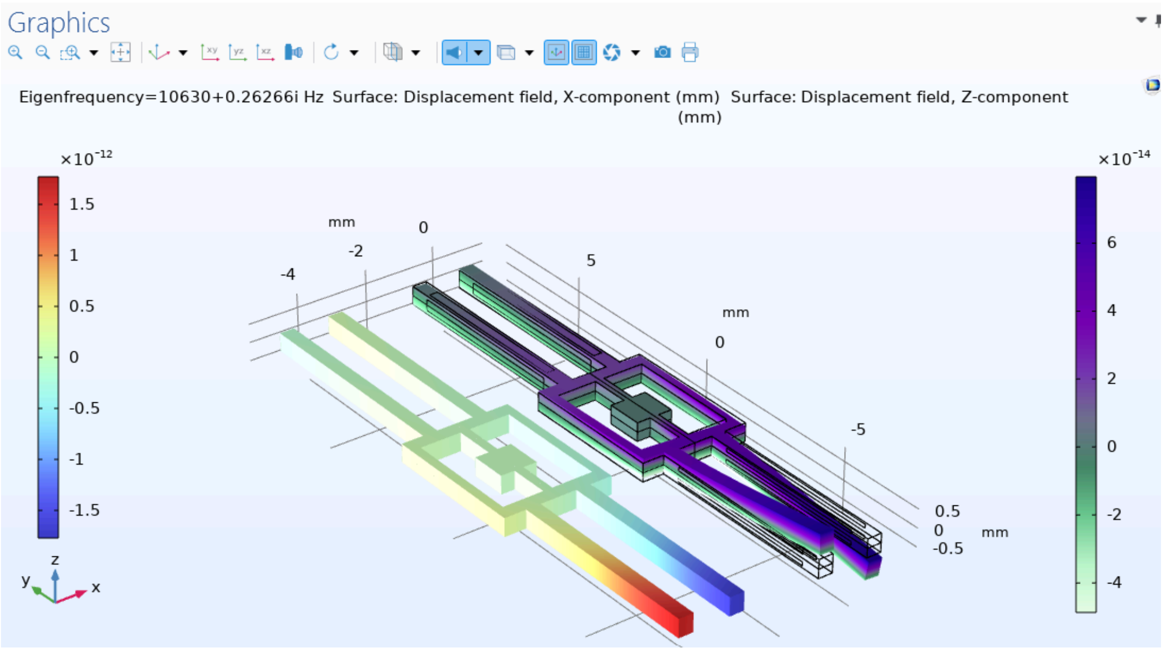
For Gallium Arsenide



For Zinc Sulphide

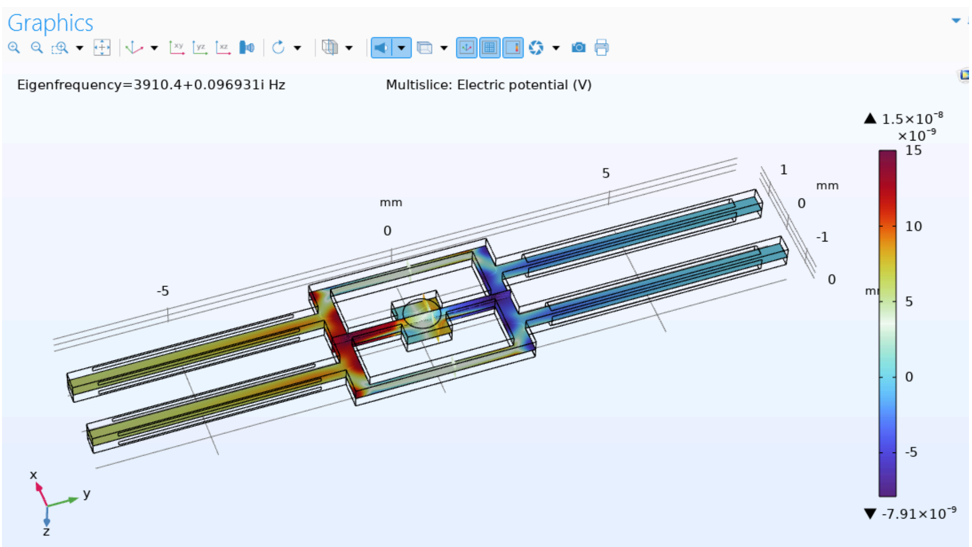
From the figures above we can see that Quartz has better characteristics. It has a linear relationship between the angular velocity and sense voltage and not only that it also has better sense voltage output(around mV). The other materials are not providing reasonable sense voltage output. So, we have selected Quartz material for our further experiment.

- **<u>Mode Shape:</u>**



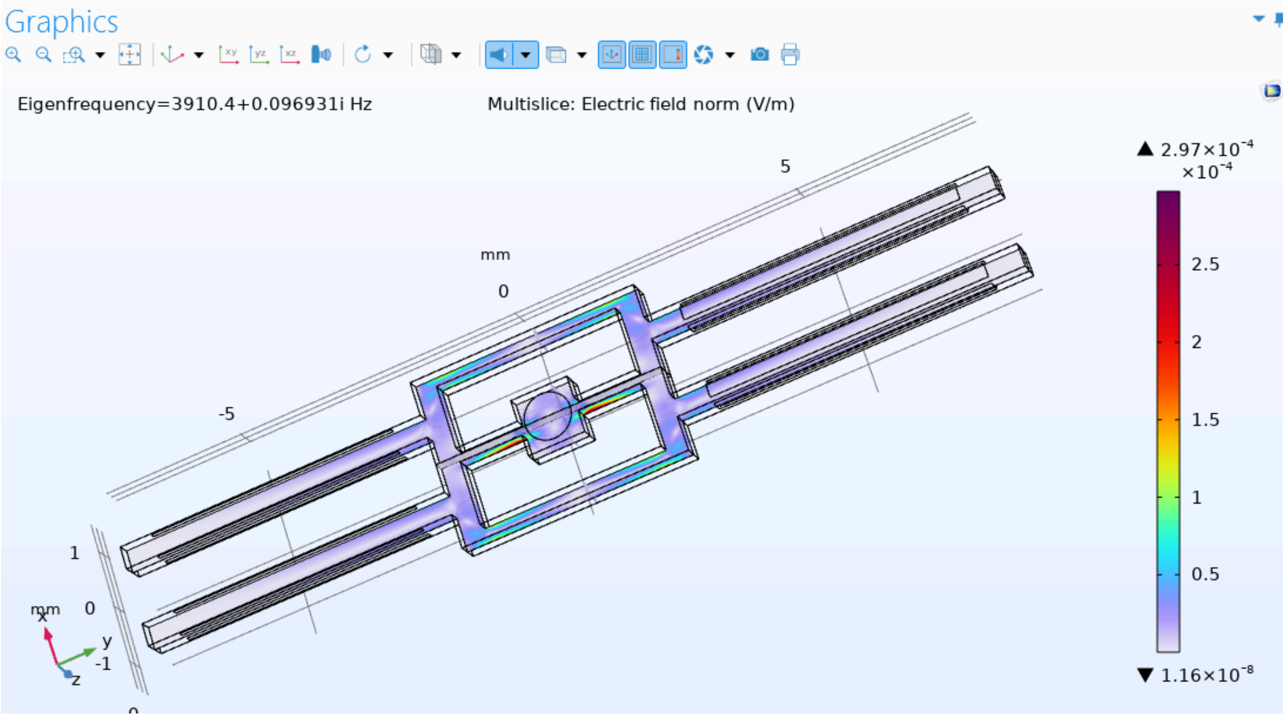
<u>(Surface: Displacement field, X-component (mm) Surface: Displacement field, Z-component (mm))</u>

- **<u>Electrostatic Potential</u>**



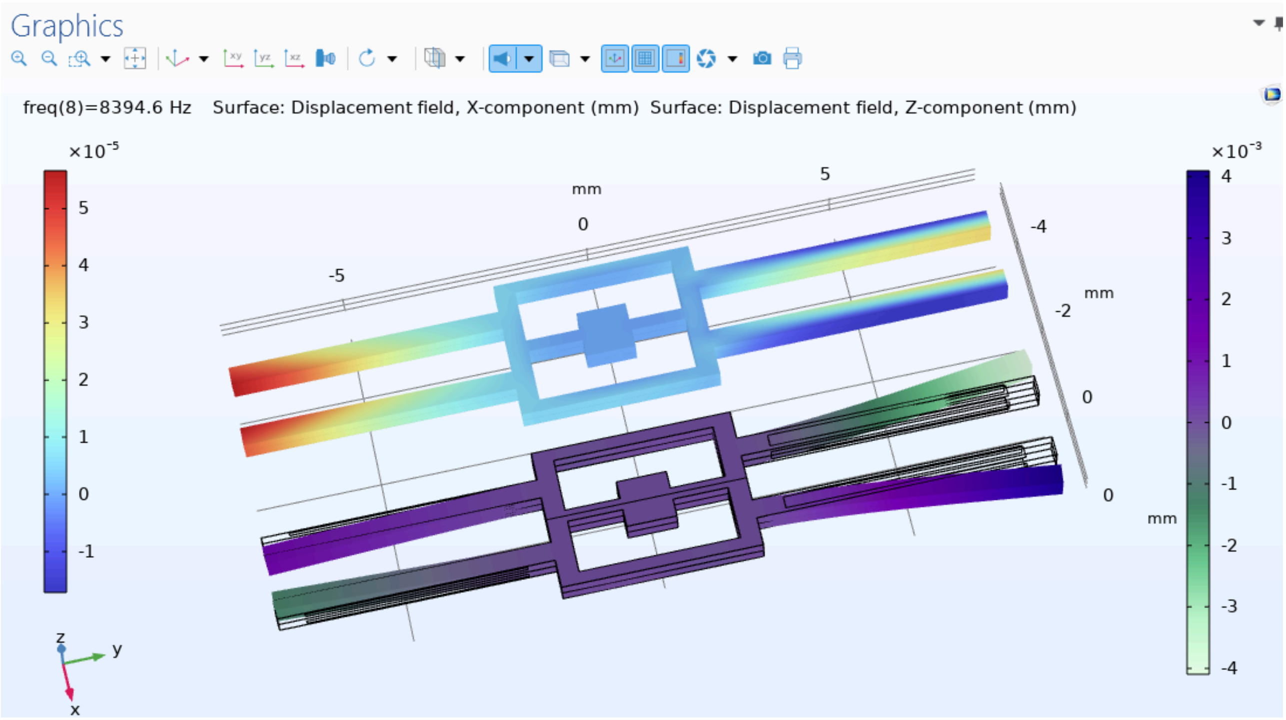
<u>Multislice: Electric potential (V)</u>

- **<u>Electrostatic Potential</u>**



<u>(Multislice: Electric field norm (V/m))</u>

- **<u>Frequency Response Displacement:</u>**

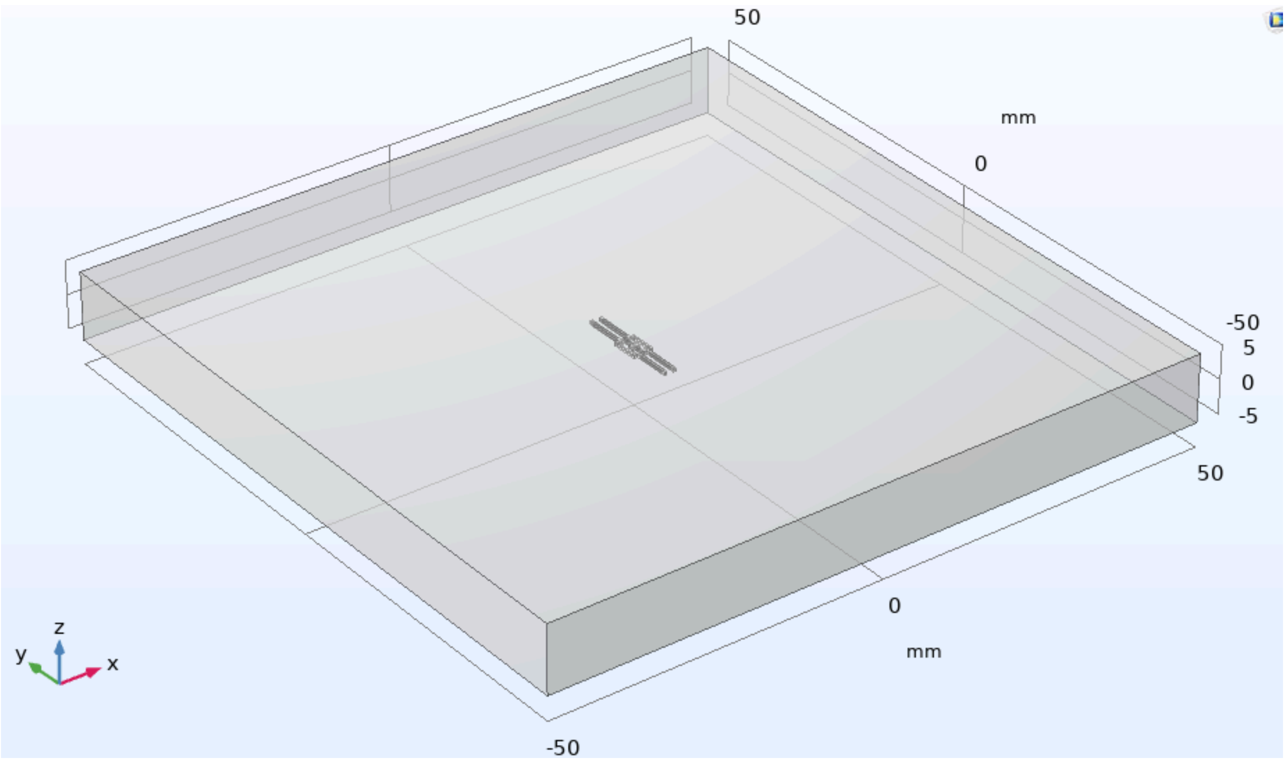


<u>Surface: Displacement field, X-component (mm) Surface: Displacement field, Z-component (mm)</u>

Modelling the satellite and its physics

Satellites use attitude control to maintain their orientation for various functions like communication, navigation, and imaging. Gyroscope can help the satellites in maintaining a orbit or altitude with the help of Coriolis effect and Piezoelectric principles.This part focuses on understanding the gyroscope's response to sinusoidal angular velocity input which corresponds to oscillatory rotational motion of satellite dynamics.

To simulate a satellite we have taken a small cube of 50mm*50mm*10mm.The gyroscope is placed inside the cube.

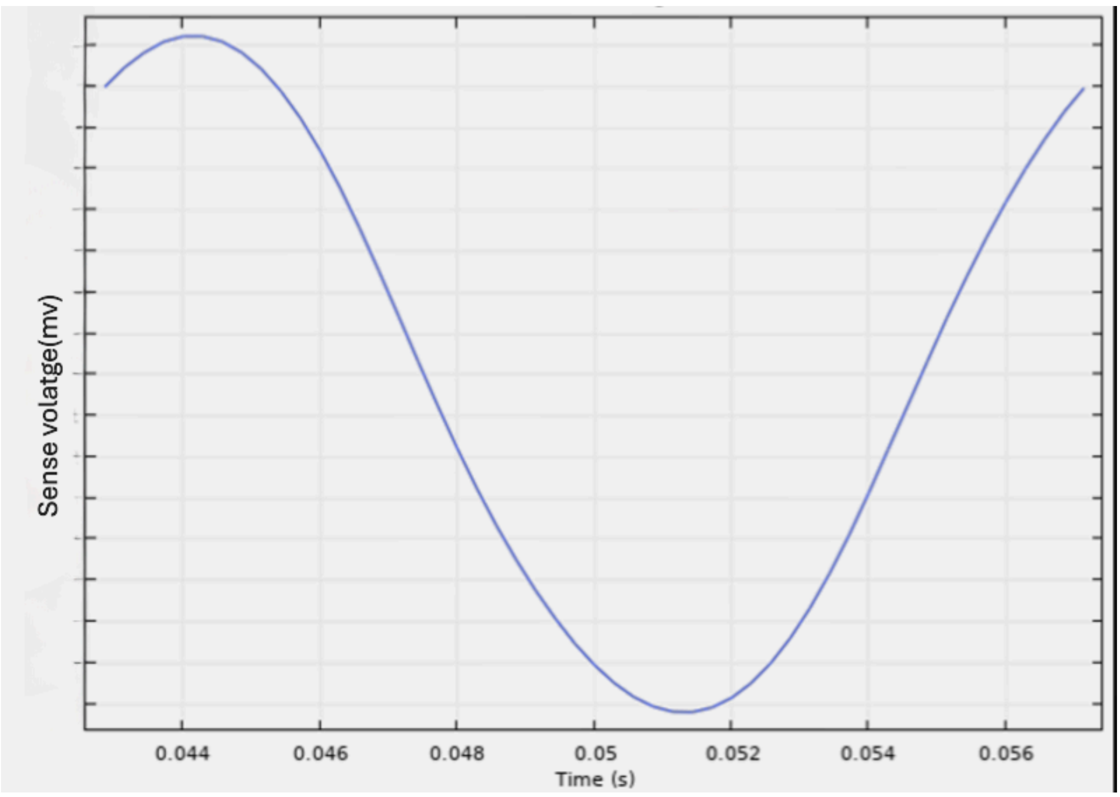


The satellite model uses multiple physics like mechanical and piezoelectric physics to get the interaction between rotational motion and the gyroscope's piezoelectric functions.The gyroscope’s functioning is based on the Coriolis force, which comes into play when the satellite undergoes angular velocity. This force causes displacement in the vibrating element of the gyroscope, which is transformed into an electric voltage by the piezoelectric effect. The output of the gyroscope, which is the sense voltage, is used to monitor the rotation and position of the satellite.Generally the sense voltage is directly proportional to angular velocity given to the gyroscope.

To simulate these dynamics, a sinusoidal angular velocity input is applied to the satellite, defined by parameters such as amplitude (ω0) and frequency (*f*). This input induces oscillatory motion, vibrating the gyroscope and thus getting a corresponding output. The simulation is done on COMSOL Multiphysics. A time-dependent study is used to see the transient effects and observe the gyroscope's response over time.

The Coriolis force generated by the sinusoidal angular velocity excites the piezoelectric material, producing a voltage output. This voltage, plotted as a function of time, exhibits sinusoidal behavior with the same frequency as the input angular velocity but includes a phase shift due to system dynamics.

The output of the gyroscope when given a sinusoidal angular velocity is as follows:



The simulation results also include structural responses in the gyroscope, including stress and strain distributions which are caused by the oscillatory motion. Resonance conditions were not included by having input angular velocity frequency not the same as the natural frequency of the gyroscope. This is important as resonance could increase vibrations and affect the sensing accuracy.

Future uses of this study can include simulations with more complex systems like multiple axis angular velocities or irregular motion caused by some external disturbances. Another improvement can be analyzing the effect of temperature variations on the piezoelectric material as satellites operate in extreme thermal environments.

Feedback system

A feedback loop is an important component in the attitude control system of satellites. It ensures that the satellite's orientation is continuously monitored and adjusted thus allowing for precise control of its attitude in space. The feedback loop works by taking real-time measurements of the satellite's rotational state and comparing them to a desired fixed setpoint and adjusting to correct any deviations.

The feedback loop operates in the following manner:

1. Sensing: The piezoelectric gyroscope continuously monitors the satellite's rotation taking real-time data on its angular velocity.
2. Processing: The sensed angular velocity is compared to a desired reference value (setpoint) within the control algorithm. This comparison forms the core of the feedback process.
3. Actuation: If any deviation is detected, the control system sends corrective signals to the satellite's actuators (e.g., reaction wheels, control moment gyroscopes, or magnetorquers) which adjust the spacecraft's orientation to return it to the desired state.

4. Correction: The actuation causes changes in the satellite's position which is again measured by the gyroscope, completing the loop.

Problems such as noise in the sensor signals and errors in the feedback loop must be taken care of. The control algorithm must be designed to filter out unwanted noise and smooth the system's response. Also temperature variations can affect the gyroscope's accuracy thus requiring regular calibration of the system.

To include a negative feedback loop we use matlab script and link it to our Comsol file.

Modelling the Feedback System

We define a PID controller which adjusts the angular velocity to minimize the error between actual and required orientation of the satellite.

```
Kp = 1;  % Proportional gain
Ki = 0.1; % Integral gain
Kd = 0.01; % Derivative gain

% Error calculation
error = desired_angle - current_angle;
error_integral = integral(error);
error_derivative = derivative(error);

% Control output
control_signal = Kp * error + Ki * error_integral + Kd * error_derivative;
```

This control signal will be used to adjust the rotational velocity in COMSOL.

Now we can send control signals to COMSOL and update the angular velocity of the satellite.

Example of sending the control signal to COMSOL in MATLAB:

```
omega_control = control_signal;  % The output from your PID controller

model.param.set('omega_control', omega_control);   % Set the angular velocity in
COMSOL
```

Now we can include a feedback mechanism to constantly check and update the angular velocity of the satellite.

Example in MATLAB (pseudo-feedback loop):

```
while time < total_time
       current_angle = model.result('sol1').getData('angle');   % Get angle from
COMSOL
      error = desired_angle - current_angle;
          control_signal = PID_algorithm(error);

           model.param.set('omega_control', control_signal);   % Set new angular
      velocity in COMSOL
          model.study('std1').run();  % Run the COMSOL simulation
end
```

By integrating a satellite control algorithm (like a PID controller) with COMSOL through LiveLink for MATLAB we can control the satellite's attitude in real-time. The external software will send commands to COMSOL which simulates the satellite's rotation and allows us to analyze and adjust the control algorithm based on real-time feedback from the simulation.

Conclusion

This project focuses on modeling a satellite's attitude control system using a piezoelectric gyroscope. The satellite's rotational motion is simulated with a sinusoidal angular velocity input which represents oscillatory motion in satellite systems. The piezoelectric gyroscope which is placed within the satellite detects angular velocity by converting mechanical motion into an electrical voltage using the piezoelectric effect. The system uses a feedback loop, where the gyroscope’s voltage output is monitored and compared with a desired set orientation and adjustments are made through actuators to correct deviations. The simulation is performed in COMSOL Multiphysics, models both mechanical dynamics and piezoelectric effects, ensuring realistic representation of gyroscope behavior. The sense voltage, which is sinusoidal in nature, is analyzed to determine the system's sensitivity and performance. This project highlights the importance of using piezoelectric gyroscopes in satellites for controlling its orientation for space missions.

References

We have taken references from:

1) Comsol Application library
2) S.D. Senturia, “A Piezoelectric Rate Gyroscope,” Microsystem Design, chapter 21, Springer, 2000.
3) Resources from YouTube.