Project Report on

# Piezoelectric Rate Gyroscope

***Submitted by***

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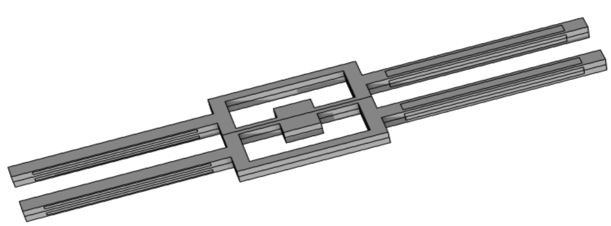
As per the requirement for the course on

**Micro Sensors and Actuators**

# Tuning fork based Piezoelectric Rate Gyroscope


## Abstract:

Piezoelectric rate gyroscopes are devices used for measuring angular velocity or rate of rotation, and they find various applications in navigation, robotics, and aerospace industries. In this study, we developed a piezoelectric rate gyroscope using quartz as the sensing element and simulated its performance using COMSOL software. The gyroscope design, which undergoes bending due to the Coriolis effect when subjected to angular velocity. The piezoelectric effect in quartz generates electrical charges proportional to the applied mechanical strain, which can be measured to determine the rate of rotation. The simulation in COMSOL software involved modeling the gyroscope's mechanical and electrical behavior. The mechanical analysis included studying the deformation of gyroscope under rotation and its effect on the output voltage. The electrical analysis involved evaluating the generated electrical charges and their distribution on the electrodes, as well as calculating the output voltage and sensitivity of the gyroscope. The simulation results demonstrated the feasibility of the piezoelectric rate gyroscope using quartz as the sensing element. The gyroscope exhibited high sensitivity and linearity in its output voltage, indicating its potential for accurate rate measurement. Furthermore, the simulation allowed for optimization of the gyroscope design by analyzing the effects of various parameters, such as thickness, electrode placement, and applied angular velocity. Overall, the simulation study using COMSOL software provided valuable insights into the performance of the piezoelectric rate gyroscope using quartz, and it serves as a basis for further experimental validation and optimization of the gyroscope design.

## Introduction:

Gyroscope sensor is a device that can measure and maintain the orientation and angular velocity of an object. These are more advanced than accelerometers. These can measure the tilt and lateral orientation of the object whereas an accelerometer can only measure the linear motion.

## Reference Paper 1:

- Gyroscope is an instrument used to measure angular velocity and importantly for navigation.Two Modes exists in a gyroscope they are
    - Driving Mode
    - Sensing Mode
- There are three basic types of gyroscopes:
    - Rotary
    - vibrating structure
    - optical gyroscope.

## Reference Paper 2:

- Piezoelectric gyroscopes make use of two vibration modes of a vibratory piezoelectric body in which material particles move in two perpendicular directions, respectively.
- When a piezoelectric gyroscope is excited into vibration in one of the two modes by an applied alternating voltage and attached to a rotating body,Coriolis Force will excite the other mode through which the rotation rate of the body can be detected.

## Reference Paper 3:

- This model shows how to analyze a tuning fork based piezoelectric rate gyroscope.
- 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 eigen frequencies of the nearby modes are separated in frequency space.The frequency response of the system is computed and the rotation rate sensitivity is evaluated.

## Reference Paper 4:

- **Working Principle:**
  - ➔ The concept of Coriolis force is used in Gyroscope sensors. In this sensor to measure the angular rate, the rotation rate of the sensor is converted into an electrical signal.
  - ➔ The concept of Coriolis force is used in Gyroscope sensors. In this sensor to measure the angular rate, the rotation rate of the sensor is converted into an electrical signal. The Coriolis force (Fcor) is given by:

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

$F_c$ = Coriolis Force

$\Omega$ = Angular Velocity

P = Momentum or Density

$(\partial u/\partial t)$ = Change in Velocity

## Reference Paper 5:

Design and Simulation :

Piezoelectric Material is commonly used for electromechanical transducers,and the requirements for the performance of piezoelectric ceramic vary for different regions of applications.

As for the solid-state gyroscopes we used ,the Piezoelectric material serves as the excitation source and sensing element simultaneously, so the piezoelectric material should have larger piezoelectric constant and electromechanical coupling constants.

## Problem Statement:

The objective of this project is to model and simulate the behavior of a piezoelectric rate gyroscope using COMSOL Multiphysics software. A piezoelectric rate gyroscope is a type of inertial sensor that measures the angular velocity or rate of rotation in a system. It typically consists of a thin, piezoelectric material sandwiched between two electrodes, with additional mechanical structures to provide the necessary sensitivity and stability. The piezoelectric material generates an electric charge proportional to the angular velocity applied to it, which can be measured and used to determine the rate of rotation.

## Objectives:

- ❖ Designing a Piezoelectric Gyroscope structure.
- ❖ Simulate the design using COMSOL software.
- ❖ Compute angular velocity and plot graphs of sense voltage vs angular frequency and sense voltage vs frequency.
- ❖ Compare results of 2 materials.

## Methodology and New Findings:

The methodology for simulating a piezoelectric rate gyroscope using COMSOL Multiphysics has several steps:

1. Geometry Creation: Create a geometric model of the piezoelectric rate gyroscope in COMSOL Multiphysics using the built-in geometry modeling tools.
2. Material Properties: Define the material properties of the piezoelectric material, including its piezoelectric coefficients, permittivity, and mechanical properties.
3. Electrode Modeling: Model the electrodes that are attached to the piezoelectric material. Define their geometry, material properties, and boundary conditions. These electrodes are responsible for applying the excitation voltage and measuring the generated charge.
4. Boundary Conditions: Define the boundary conditions for the gyroscope model.
5. Physics Settings: Select the relevant physics settings in COMSOL. This may include the Solid Mechanics module for mechanical behavior, the Electrostatics module for electric field calculations, and the Piezoelectric Devices interface for coupling between electrical and mechanical behaviors.
6. Meshing: Generate a suitable mesh for the gyroscope model. The mesh should be fine enough to capture the complex behavior of the piezoelectric material and its interaction with the electrodes and structures.
7. Simulation: Run the simulation in COMSOL Multiphysics and analyze the simulation results to understand the gyroscope's behavior, including its sensitivity, stability, and performance under different conditions.
8. Sensitivity Analysis: Perform sensitivity analysis by changing material and eigen frequency frequencies.

9. Optimization: Based on the sensitivity analysis results, optimize the gyroscope design by adjusting the design parameters and material to achieve the desired performance.
10. Validation: Validate the simulation results by comparing them with experimental data or theoretical predictions. Adjust the model parameters, if necessary, to improve the accuracy of the simulation results.

Overall, the methodology for simulating a piezoelectric rate gyroscope in COMSOL Multiphysics involves creating a geometric model, defining material properties, modeling electrodes, setting boundary conditions, choosing appropriate physics settings and meshing, running simulations, performing sensitivity analysis, optimizing the design, validating the results.

## Experimental Details:

**Mesh profile:**

Sequence type: User-controlled mesh.

Element size: Finer.

Element Size Parameters:

Maximum element size = tQz/4 = 0.125mm.

Minimum element size = tQz/12 = 0.0416mm.

1. Mesh consists of 15630 domain elements, 5220 boundary elements, and 1139 edge elements.
2. Complete mesh consists of 62520 domain elements, 17926 boundary elements, and 3726 edge elements.

**Material**: Quartz LH (1978 IEEE) and PZT-5A.

**Parameters:**

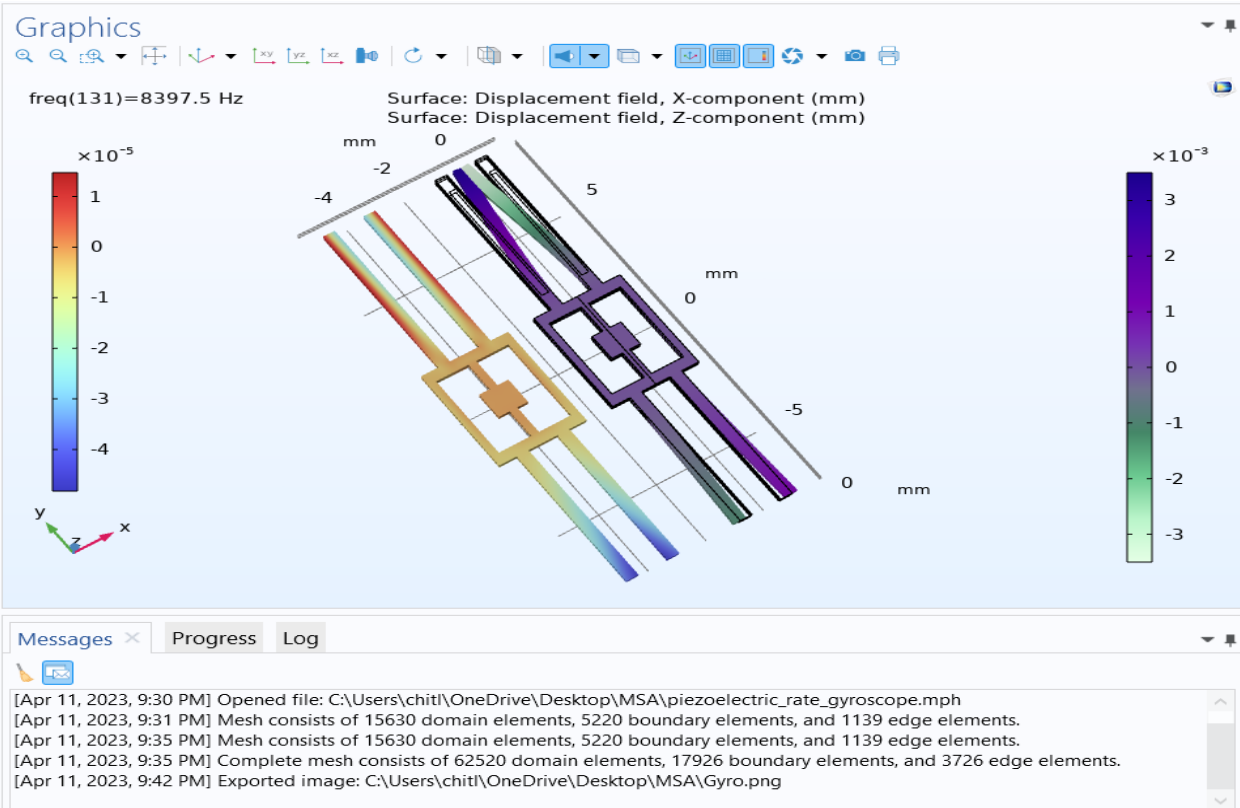
| Name | Expression | Value | Description |
|---|---|---|---|
| va | 64[deg/s] | 1.117 rad/s | Rotation angular velocity |
| tQz | 0.5[mm] | 5E-4 m | Quartz thickness |
| w_m | 1[mm] | 0.001 m | Mount width |
| l_w | (l_f-w_m)/2-w_tbf | 0.0011 m | Wing length |
| w_w | 0.25[mm] | 2.5E-4 m | Wing width |
| l_f | 4[mm] | 0.004 m | Frame length |
| w_f | 3[mm] | 0.003 m | Frame width |
| w_tbf | 0.4[mm] | 4E-4 m | Frame top/bottom thickn |
| w_sf | 0.25[mm] | 2.5E-4 m | Frame side thickness |
| l_d | 6[mm] | 0.006 m | Drive tine length |
| w_d | 0.4[mm] | 4E-4 m | Drive tine width |
| l_s | 5.5[mm] | 0.0055 m | Sense tine length |
| w_s | 0.4[mm] | 4E-4 m | Sense tine width |
| gap | 1[mm] | 0.001 m | Gap between tines |

**Eigen Frequencies:**

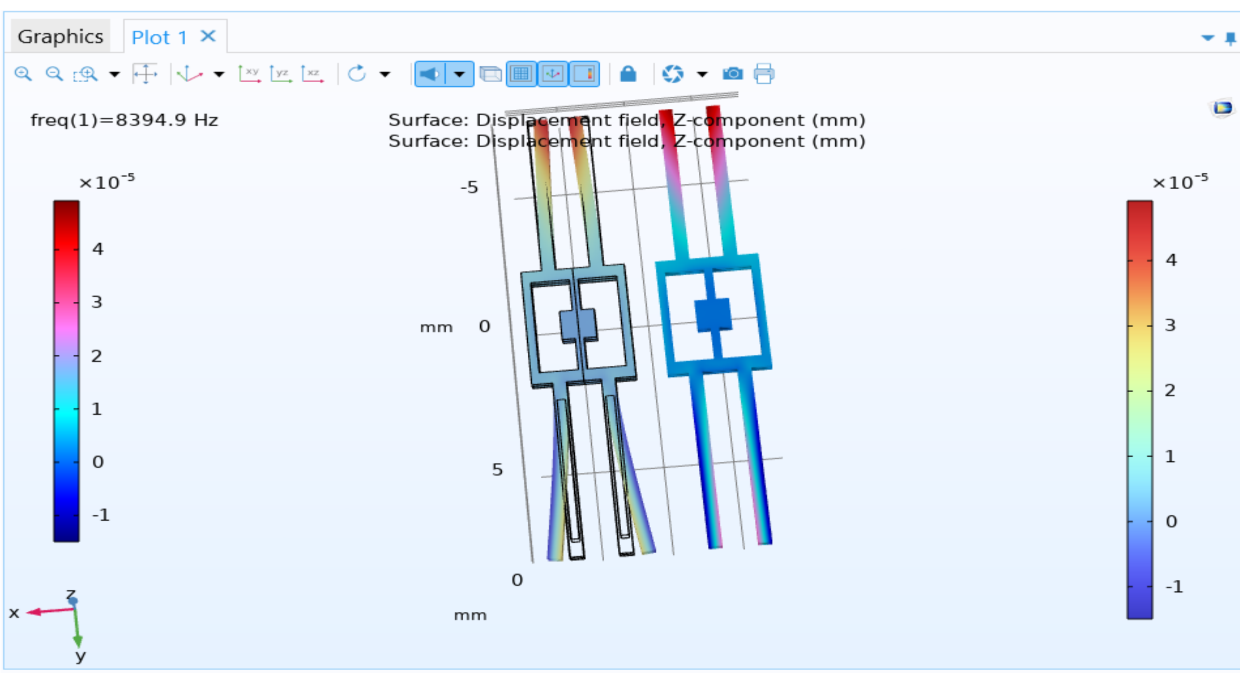
Eigenfrequencies, also known as natural frequencies or characteristic frequencies, are the frequencies at which a system vibrates or oscillates when it is excited by an external force or disturbance and allowed to freely oscillate.

| Eigenfrequency (Hz) | Angular frequency (rad/s) | Damping ratio (1) | Quality factor (1) |
|---|---|---|---|
| 3910.5+0.096934i | 24571+0.60905i | 2.4788E-5 | 20171 |
| 6173.8+0.15362i | 38791+0.96521i | 2.4882E-5 | 20095 |
| 7472.7+0.18584i | 46952+1.1677i | 2.4869E-5 | 20105 |
| 8396.2+0.20848i | 52755+1.3099i | 2.4830E-5 | 20137 |
| 9225.9+0.22990i | 57968+1.4445i | 2.4919E-5 | 20065 |

**Study:**




**Model shape:**



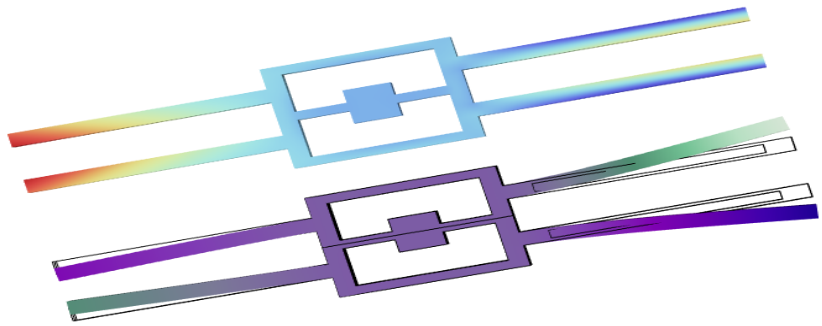
## Results and Discussion:

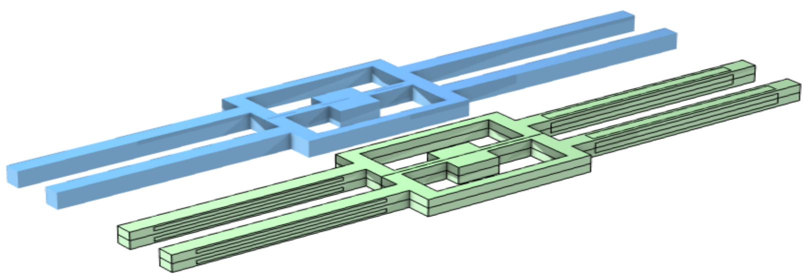
To determine which is better we performed simulations for both Quartz and PZT-5A materials in a piezoelectric rate gyroscope. The selection between quartz and PZT-5A for a gyroscope depends on several characteristics, like the specifications for the specific use, performance behaviors, and cost considerations. Quartz and PZT-5A are both typical piezoelectric materials used in gyroscope applications, but they have different features that might affect how well suitable they are for specific uses.

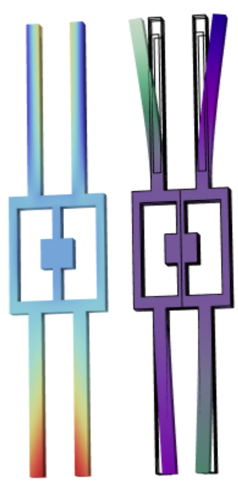
1. **Sensitivity:** Quartz has a higher sensitivity compared to PZT-5A, meaning it generates a larger output signal for a given input.
2. **Stability:** Quartz is known for its excellent long-term stability.
3. **Frequency Range:** PZT-5A has a broader frequency range compared to quartz, which makes it suitable for applications that require a wider operating frequency range
4. **Size and Weight:** Quartz is generally lighter and smaller in size compared to PZT-5A, which can be advantageous in applications where space and weight are critical, such as in portable or miniaturized devices.
5. **Cost:** PZT-5A is generally less expensive than quartz, which may make it more attractive for applications with cost constraints. Quartz, being a naturally occurring crystal, can be more expensive to produce and process.

In summary, while quartz and PZT-5A are both commonly used piezoelectric materials in gyroscope applications, they have different properties that can impact their suitability for a specific application. Quartz is known for its high sensitivity, stability, and smaller size, but it may have a narrower frequency range and can be more expensive. On the other hand, PZT-5A has a broader frequency range and is generally less expensive, but it may have lower sensitivity and stability compared to quartz. The choice between quartz and PZT-5A for a gyroscope will depend on the specific requirements of the application and the trade-offs between these properties.

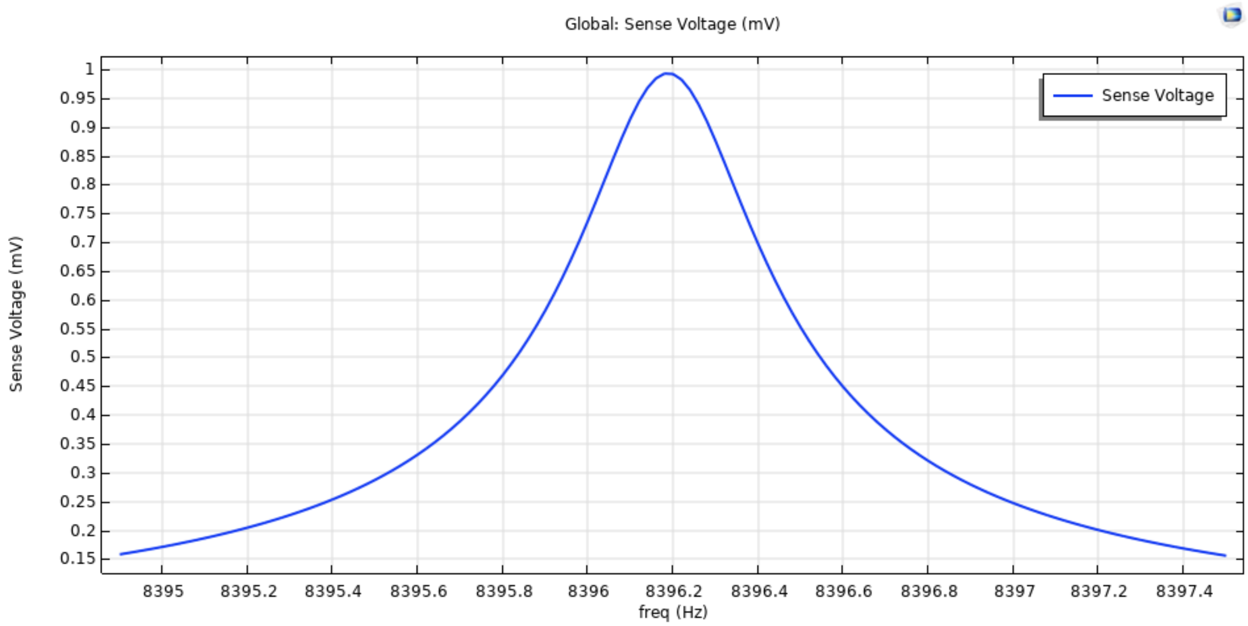
**The snapshots of the model from the COMSOL while simulating:**



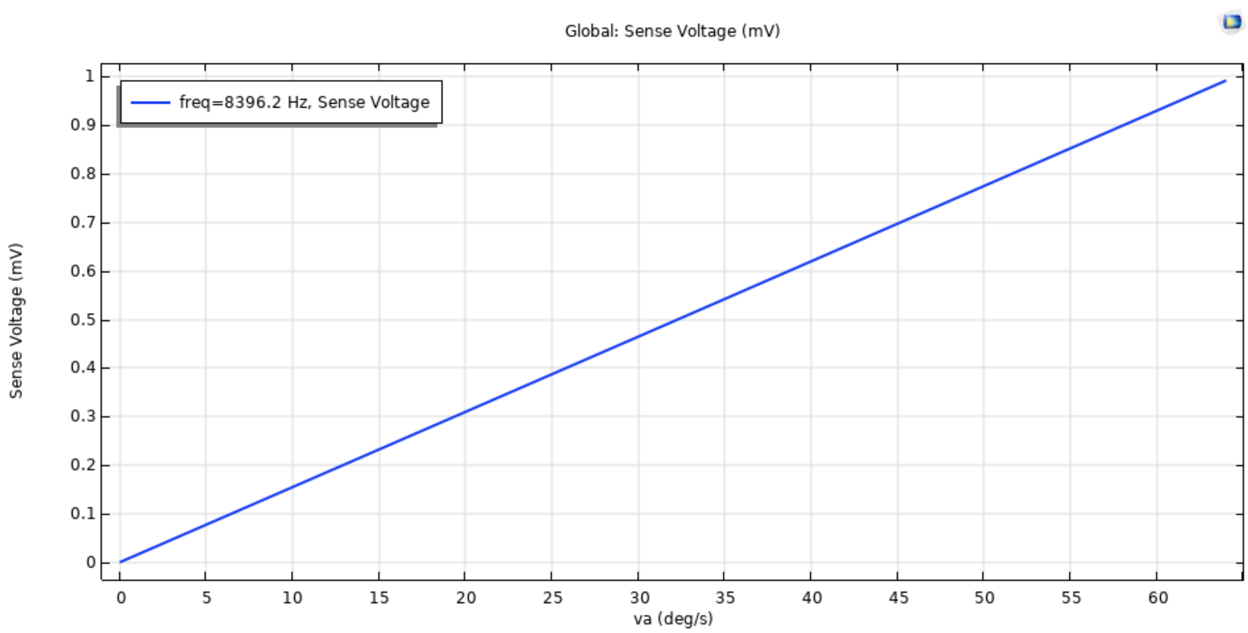




**Sense voltage vs frequency of Quartz.**




**Sense voltage vs angular frequency of Quartz.**




The curve is linear for Quartz, but slight bending for PZT-5A. From this we can conclude Quartz has better sensitivity and also high output voltage. Therefore Quartz is better.

## Applications:

Piezoelectric rate gyroscopes are used in a wide range of applications where accurate measurement of angular velocity or rotational rate is required.Some of the common applications Of piezoelectric rate gyros include:

1.Robotics and Autonomous Vehicles
2.Navigation and Guidance Systems
3.Stabilization Systems
4.Virtual reality and Augmented reality
5.Industrial and Structural Monitoring
6.Sports and Fitness
7.Consumer Electronics.

## Future Work:

We can study the materials in-detail and parameters which are best to use for specific purposes.

## Challenges Faced:

1. Knowing all the COMSOL features is a really big task.
2. Defining parameters for material selected is very difficult.
3. To choose Model Complexities, Meshing and Boundary conditions.

## Conclusion:

This model shows how to analyze a tuning fork based piezoelectric rate gyroscope. 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 frequency space. The frequency response of the system is computed and the rotation rate sensitivity is evaluated.

## References: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[2].Sato, Kenji, Atsushi Ono, and Yoshiro Tomikawa. "Experimental study of gyro sensor using double-ended tuning fork quartz resonator." *Proceedings of the 2004 IEEE International Frequency Control Symposium and Exposition, 2004.*. IEEE, 2004.

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[4]. Lee, Sang Woo, et al. “A micro rate gyroscope based on the SAW gyroscopic effect.” Journal of Micromechanics and Microengineering 17.11 (2007) ; 2272.

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## Contributions:

T.V.S.Kalyan : Simulation of Gyroscope with Quartz and PZT-5A.

C.V.Bhanu Prakash : Verifying properties of Gyroscope for different Eigen frequencies.

S.Sai Anirudh : Meshing and referring to base papers.