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COMSOL Simulations:
Piezo Electric Rate Gyroscope

Introduction

This model shows a way to analyze a MEMS device tuning fork based piezoelectric rate gyroscope using COMSOL 5.6 software. The effect of the reverse piezoelectric is used to drive an in-plane tuning fork mode. The Coriolis force couples this mode to an out-of-plane mode and the direct piezoelectric effect sense the resulting out of plane motion. The design of the geometry of the tuning forks is based on that the eigenfrequencies of the nearby modes are separated in frequency space,then the frequency response of the system is computed and the rotation rate sensitivity is evaluated.[1]

Note that the model focuses on the performance of the sensor in a uniformly rotating reference frame.

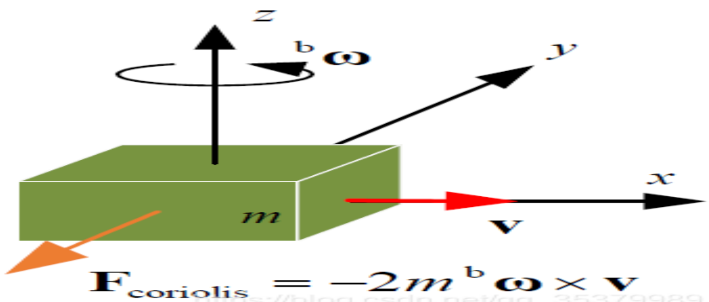

Figure 1: coriolis effect

Model Definition

The gyroscope can be thought of as two tuning forks, coupled together by a suspension structure. The suspension is anchored to the package of the device which is in turn attached to the rotating object. The drive tines are driven close to their resonance in an in-plane mode. The sense tines are designed to have a resonance at a nearby, but distinct, frequency with a significant out of plane component to their motion.

The tines are fabricated from single crystal quartz wafers with the crystallographic Z-axis aligned parallel to the normal of the wafer plane.[2]

In general, for resonant structures like this model, a very fine mesh is required to achieve accurate frequency response results.

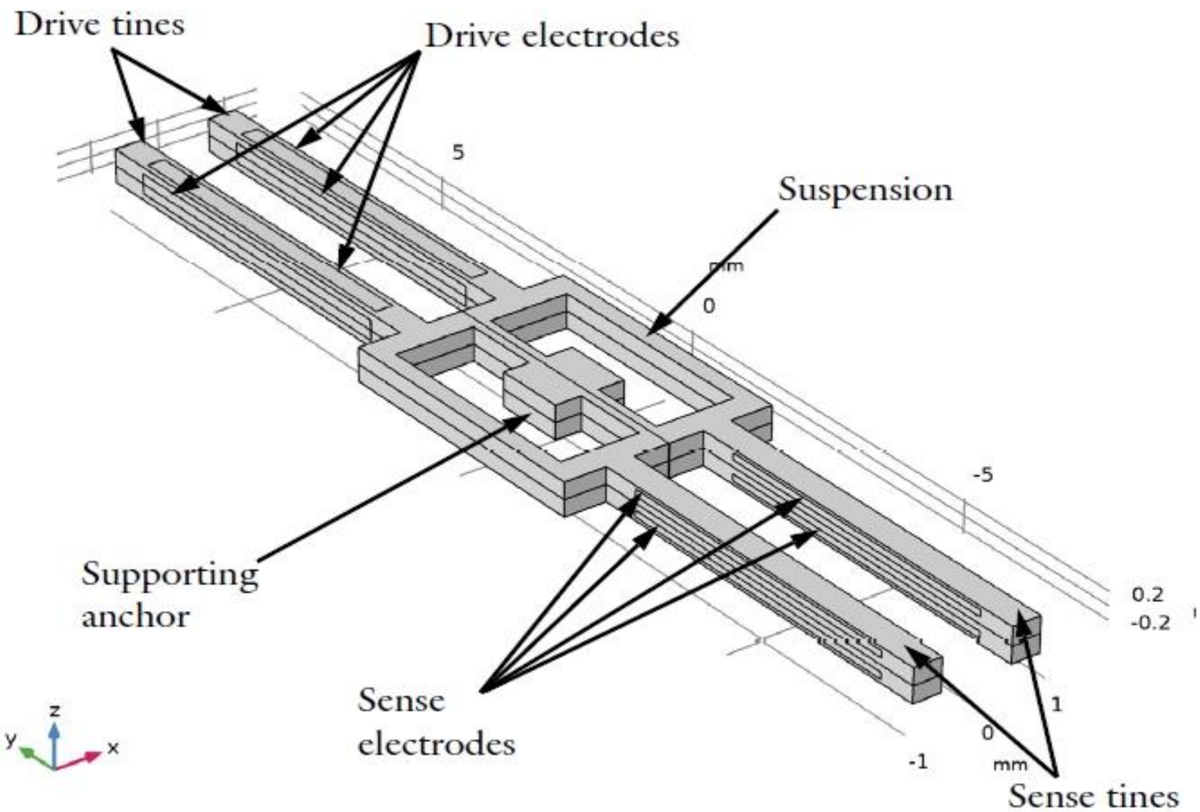

Figure 2: Double tuning fork gyroscope stracture

Model Operation

A rate gyroscope senses the rotational motion and angular velocity of a system. In this piezoelectric rate gyroscope, the tuning forks' resonant modes are used to produce the measurement signal.

Two resonant modes are used:

- **<u>Drive mode:</u>** The reverse piezoelectric effect is used to drive the in-plane mode, while the out-of-plane motion is sensed by the direct piezoelectric effect.
- **<u>Sense mode:</u>** The out-of-plane sense mode movement is caused by the effect of the Coriolis force as the gyroscope rotates around the y-axis.

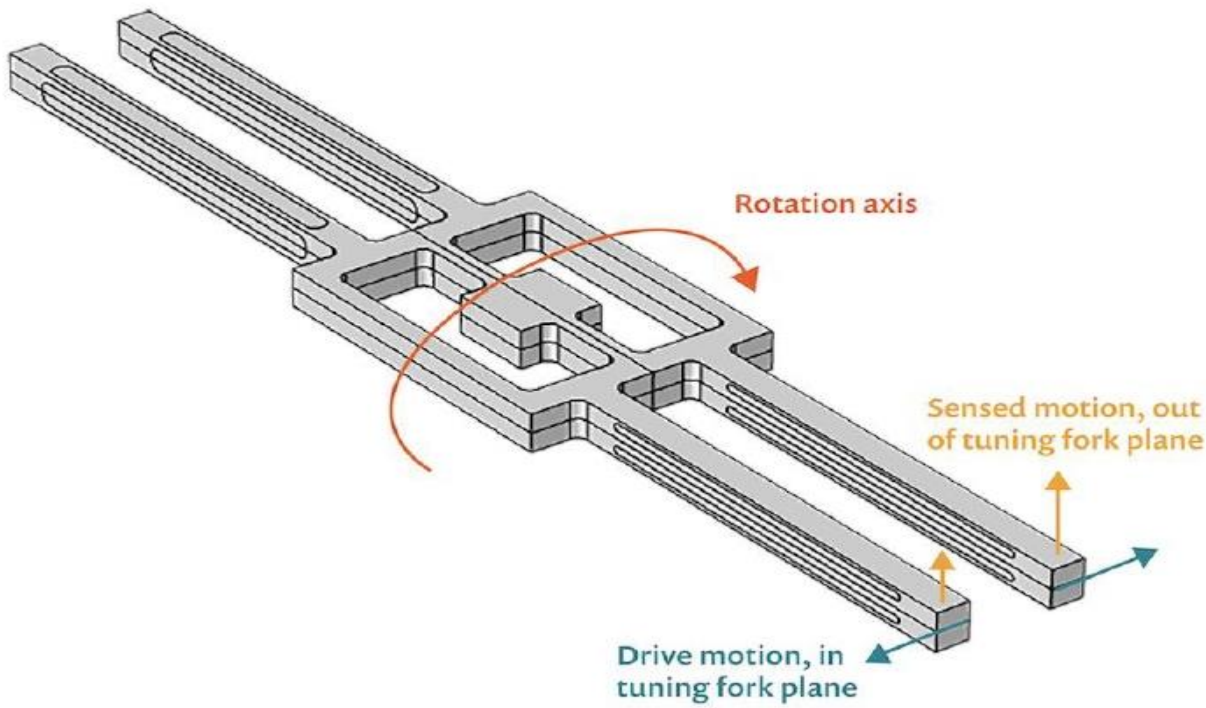

Figure 3: Gyroscope Operation

These two modes serve as the driving and sensing aspects of the gyroscope. In operation, the tuning fork is driven at the resonant frequency of the drive mode through an electric field applied by electrodes deposited on the surfaces of the drive tines. The drive tines vibrate in the tuning fork plane, the *xy* plane. In the sense mode, the sense tines vibrate out of the tuning fork plane and along the *z*-axis instead.[3]

Geometry

As shown in figure 2,the model consists of:

- Sense tines
- Drive tines
- sense electrodes
- drive electrodes
- supporting anchor
- suspension

We used the open source geometry from COMSOL site then calculated the parameters and the required specs.

The dimensions from different planes are shown in figures from figure 4 to figure 8, the model has length of 15.5 mm, width of 2.5 mm and the thickness is 0.4 mm.

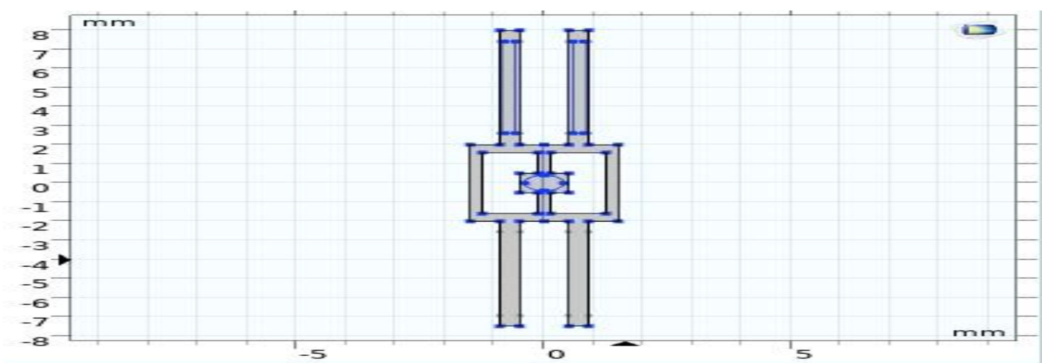

Figure 4: Dimensions of the model

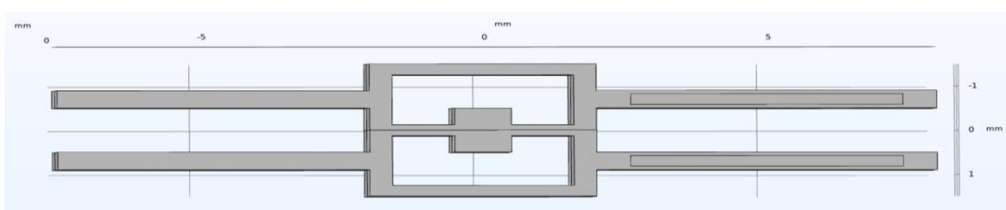

Figure 5: X-Y plane of the model

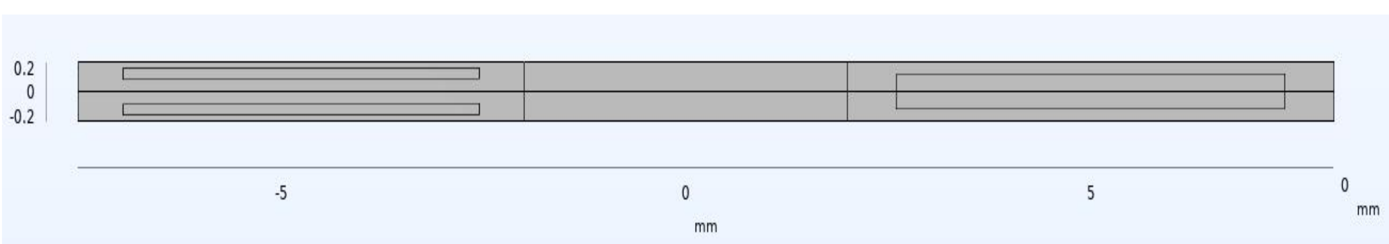

Figure 6:X-Z plane of the model

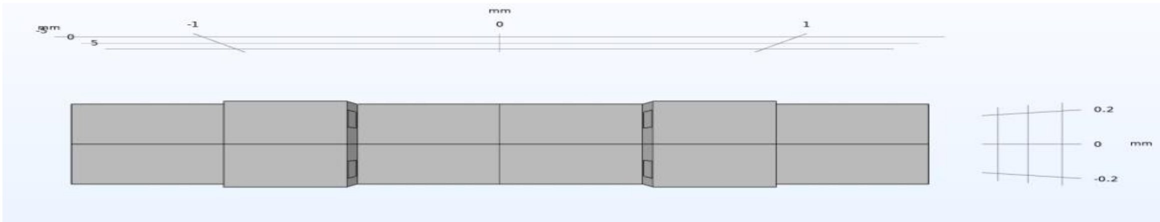

Figure 7:Y-Z plane of the model

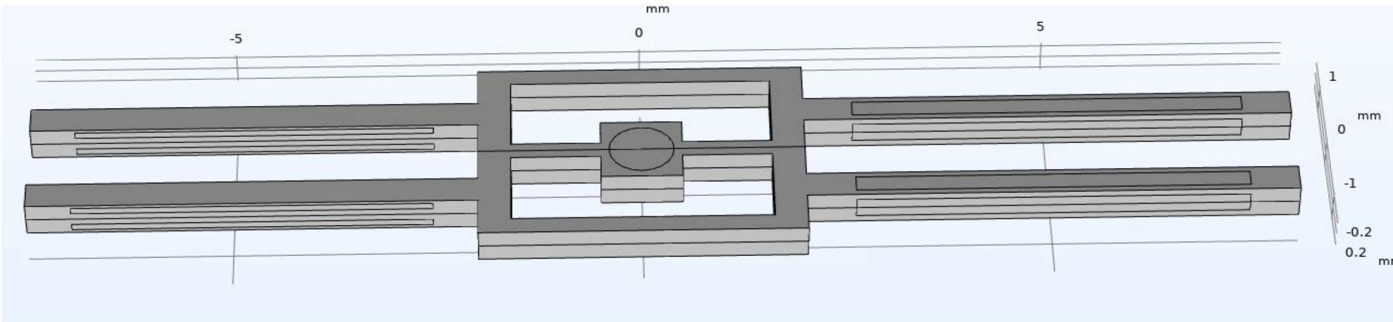

Figure 8: The Isometric view of the Piezo Electric Rate Gyroscope

Materials

We used Quartz LH (1978 IEEE) Piezoelectric with Rotating Frame for the all domains in the model.

Electrostatics(Es)

We applied voltage source with voltage of +1,-1 Volt to the drive terminals : Drive tines and Drive electrode

Mesh

Then we used symmetric mesh for this model so that the numerical result for no rotation will be very close to the expected.

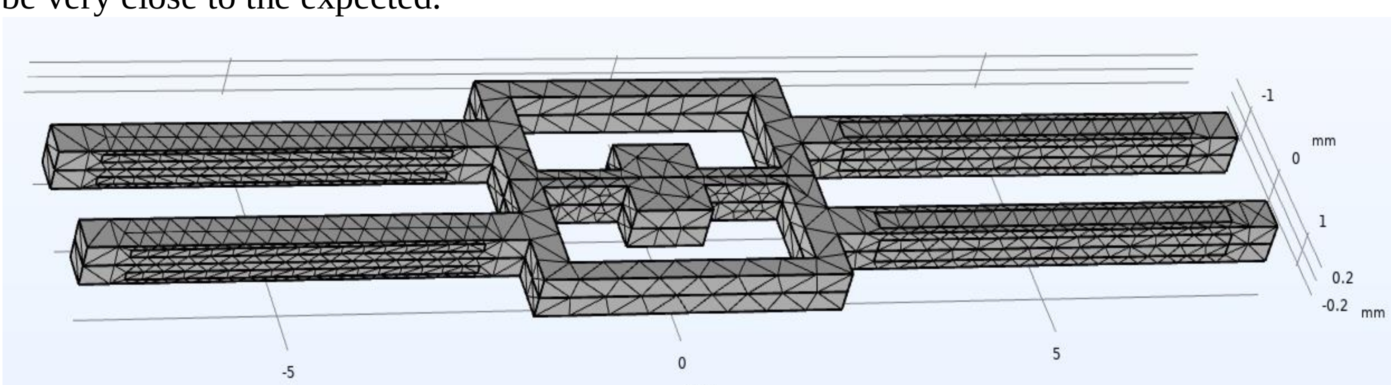

Figure 9: fine symmetric mesh for the model

Simulation Results

1- Mode Shape Plot

The default mode shape plot shows a surface plot of the displacement magnitude.

The eigenmode corresponding to the drive mode is done with a frequency of 8352.9+j0.20751 Hz , and the eigenmode corresponding to the sense mode is done with a frequency of 10630+j0.26346 Hz.Both the in-plane and out-of-plane motions of these modes are shown separately in the figures.

a) Drive mode, showing both in-plane motion (right) and out-of-plane motion (left):

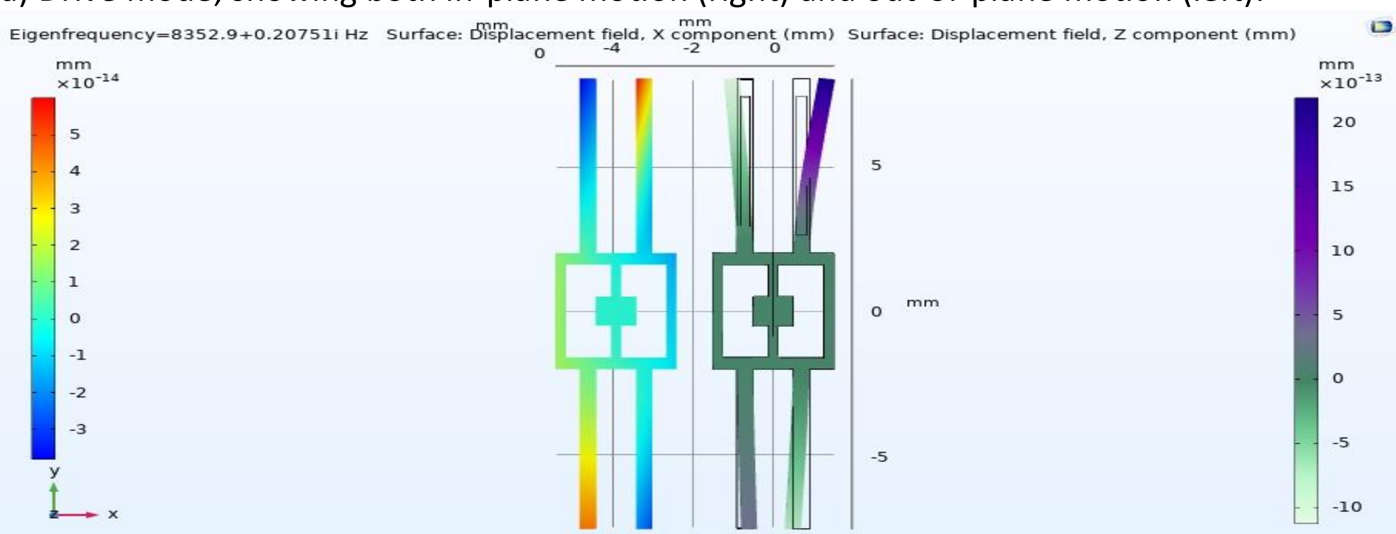

Figure 10: Drive mode top view

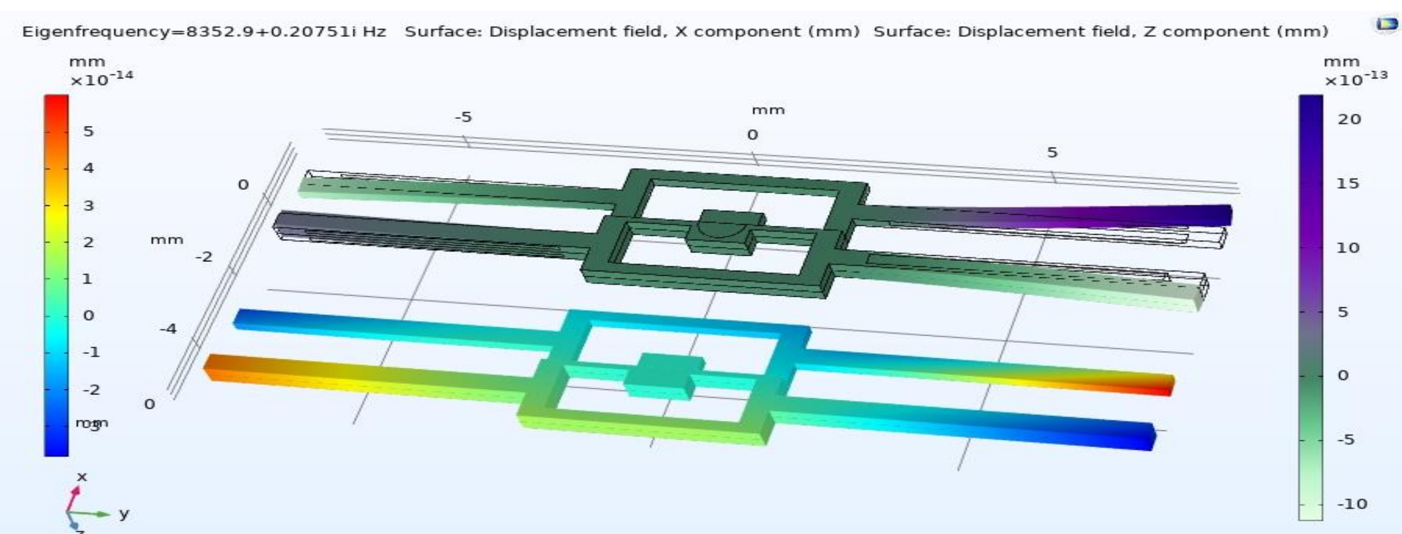

Figure 11: Drive mode

b) Sense mode, showing out-of-plane motion (left) and in-plane motion (right):

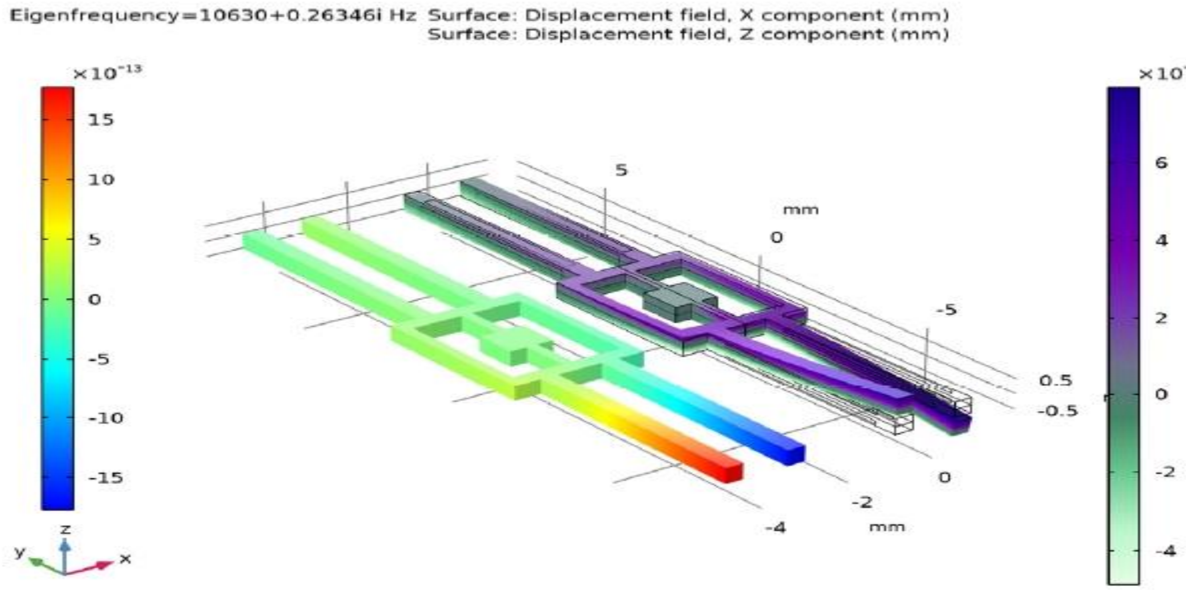

Figure 12:Sense mode

2-Sense Voltage Vs. Drive Frequency

The results are calculated with when applied sinusoidal drive voltage of amplitude 2 V (Peak-to-Peak)and an angular acceleration of 64 deg/s.

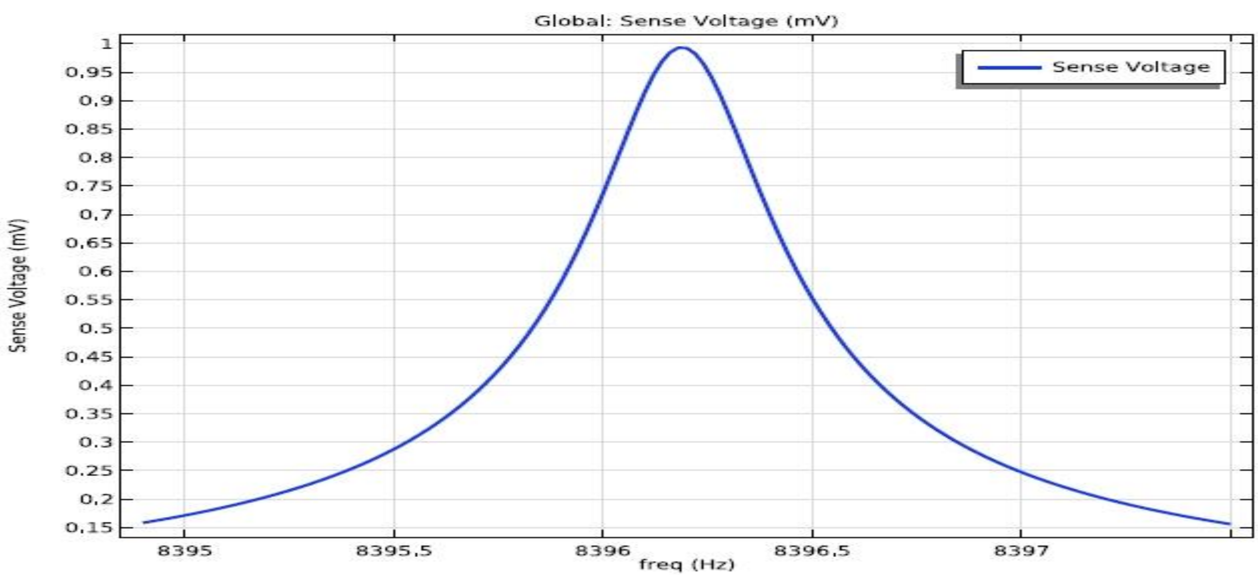

Figure 13: Sense Voltage Vs. Drive Frequency

The results show that a a peak appears at a drive frequency equal to 8396 Hz approxmetly which means it’s the optimum drive frequency for the device.

3-Sense Voltage Vs. Angular Acceleration

The results are calculated with when applied a drive voltage of amplitude 2 V (Peak-to-Peak) and a frequency of 8396 Hz(Calculated in previous part) which is the peak in the response close to the drive frequency.

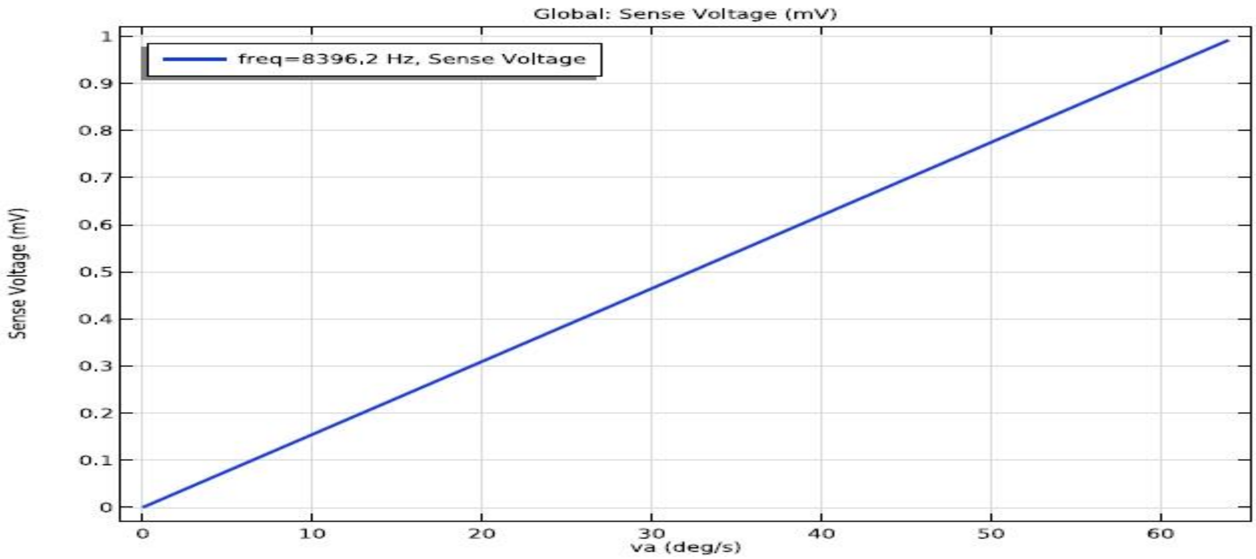

Figure 14: Sense Voltage Vs. Angular Acceleration

The figure shows that the sense voltage against the angular acceleration with a 2 V drive voltage at a frequency close to this optimum. As expected the response of the sensor is linear, with a sensitivity(the slope of the linear response)of approximately 0.015mV /(deg/s).

References :

[1] S.D. Senturia, “A Piezoelectric Rate Gyroscope,” Microsystem Design, chapter 21,Springer, 2000.

[2] COMSOL Site,Application Gallery,” Piezoelectric Rate Gyroscope”. Application ID: 21471. [Avaliable online]

[3] Emily Ediger, ” Modeling a Double-Tuning-Fork MEMS Gyroscope”, COMSOL Blog, October, 2019.