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Simulation Studies on Tuning Fork MEMS Gyroscope for Mode Matched Analysis

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Abstract

Micro-Electro-Mechanical-System (MEMS) based gyroscopes are very familiar in the current era of cutting-edge technology. The benefits greatly compensate for the costs when the MEMS-based devices are very lightweight and compact in design in the trend of miniaturization technology. MEMS-based inertia devices are used for guidance and navigation purposes in military applications. More recently, commercial industries have adopted such devices in many applications like; airbag sensors, smart mobiles, toys, etc., which have also made MEMS inertia devices smaller and cheaper. The sensitivity of a sensor plays a significant role in high accuracy measurement. The sensitivity of a MEMS gyroscope can be improved by minimizing the resonant frequency mismatch between the drive and sense mode.

In this work, a tuning fork gyroscope is designed using IntelliSuite 8.9 MEMS utility software through device-level analysis to macro model extraction. In this, an element-based model of a tuning fork gyroscope is created and further optimized the structure using parametric analysis in order to match the resonant frequency in drive and sense mode. Then, a mask layout is extracted from the element-based model and used to create a 3D meshed model for analysis automatically. The natural frequencies of the tuning fork gyroscope are determined, examining the device response in a static and dynamic case.

Keywords: *MEMS; Tuning fork Gyro; Drive & Sense Mode; Coriolis force*

1. Introduction

A gyroscope's application depends significantly on its design. The Micro-Electro-Mechanical System (MEMS) tuning fork vibratory gyroscope [1] is the most used type. This gyroscope has a symmetrical tuning fork structure in its design. Two proof masses are used in this design. The proof masses are free to move since the construction is made of long, thin beams anchored in the middle. All dimensions must be adjusted to achieve the correct frequency range for the data to be captured and analyzed without too much background noise interference. Many diverse industries, both modern and old, employ gyroscopes. They are utilized for wireless sensing [2] communication gadgets like the iPhone 4 and gaming systems like the Wii Motion Plus accessory.

In addition to being utilized in shipbuilding and space exploration, gyroscopes are also employed in the automobile and aircraft sector for health monitoring [3] applications.

Gyroscopes are appealing due to their compact design, minimal power consumption, and inexpensive manufacturing costs. Today, layered silicon wafers [4-5] are used to create the majority of gyroscopes. These wafers have been micro-machined so that the form of the gyroscope is visible from the middle of the wafer.

Gyroscopes are made to detect rotation, and they achieve this by utilizing the Coriolis effect [6]. The acceleration a moving body appears to undergo within a rotating reference frame is known as the Coriolis effect. A person standing still on the x-axis and a particle moving along the positive y-axis can be used to demonstrate the Coriolis effect. The particle seems to travel in the direction of the observer who is standing in the rotating reference frame once a rotation about the z axis is introduced. The Coriolis effect allows the angular velocity measurement by employing two vibration modes in a gyroscope. The drive mode is the first vibrational mode. This mode is purposefully added to the system to benefit from the Coriolis effect by having two proof masses move apart from one another horizontally. Adding angular velocity to the moving object results in the second mode of vibration. The proof masses travel differently from the first mode due to the Coriolis effect. The proof masses then move vertically in oppositional directions.

The proof masses have sense electrodes above them that can measure how far the mass is moving. These sense electrodes can determine through capacitance transduction technique [7], a quantity that depends on distance. Because of this capacitance's direct relationship to angular velocity, it is possible to quantify angular velocity accurately in terms of capacitance.

2. MEMS Tuning Fork Gyroscope: Mechanical Structure and Operation Principle

MEMS tuning-fork gyroscopes are made of silicone material which can detect the rotation due to the Coriolis effect. MEMS gyroscopes can be represented with a basic mechanical structure, as shown in Figure 1 below.

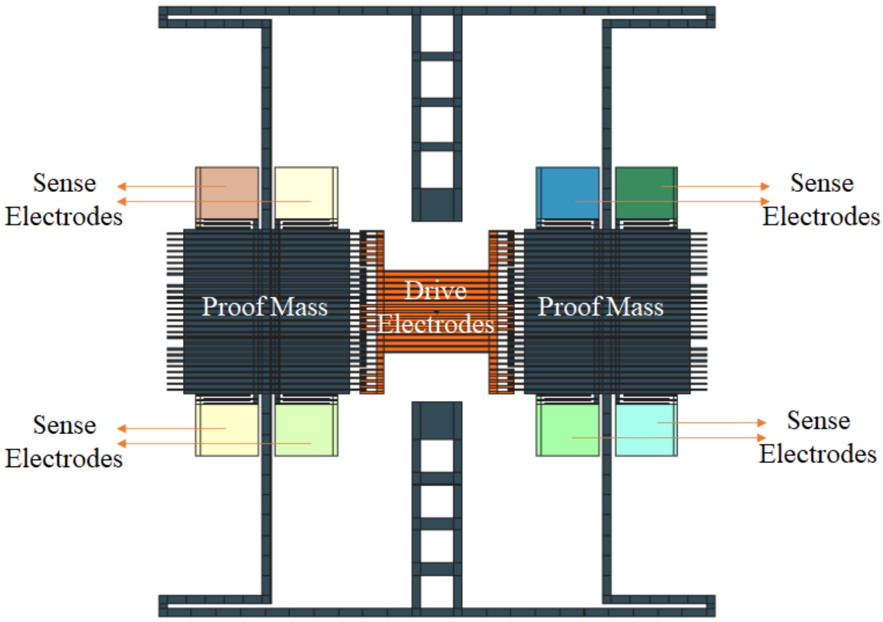


Fig. 1: Gyroscope Mechanical Structure

The huge proof masses on either side of the structure, which are not fixed at the anchors depicted above, are free to move. The gyroscope uses the Coriolis effect to measure rotation; therefore, it must constantly be moving for the device to work because it only affects moving objects. The motion depicted in Figure 2(a) is produced by vibrating the structure at one of its natural frequencies. This type of vibration is discussed here as the Drive Mode.

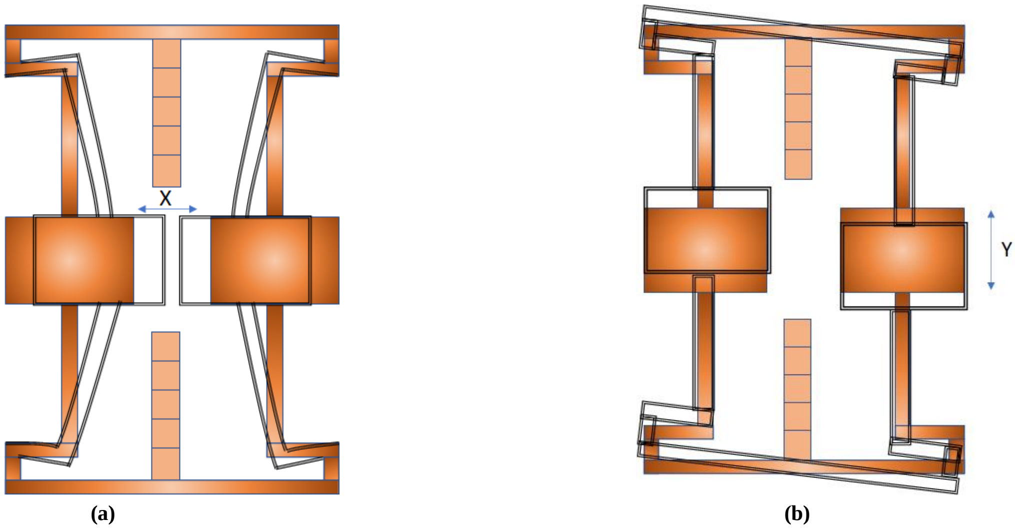


Fig. 2: (a) Drive Mode Vibration (b) Sense Mode Vibration

As shown in Figure 2(b), the direction of the vibration shifts from horizontal to vertical as the structure starts to rotate due to the Coriolis force acting on the moving proof masses. The term "Sense Mode" refers to this vertical vibration, which is usually higher than the horizontal Drive Mode vibration.

Metal plates are positioned above the proof mass, as depicted in Figure 3. These plates combine with the proof mass to form a capacitor. In drive mode, the distance between the proof mass and the plates doesn't change when the proof mass vibrates. Since the capacitance for a parallel plate capacitor like this one depends on the separation between the two plates, it also stays constant in drive mode. The proof mass moves vertically as the structure enters Sense Mode, changing the distance between it and the plates, which alters the capacitance. Electronic devices can recognize this variation in capacitance and translate it into an indication of the corresponding rotation.

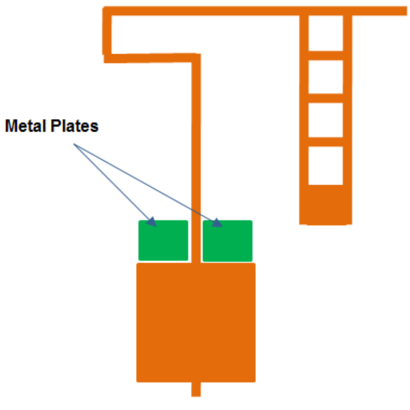


Fig. 3: Sense Mode Parallel Metal Plate Capacitors

3. Simulation Model Analysis

The dynamic analysis of the tuning fork gyroscope envisages the device's resonant frequency, damping coefficient, spring constant, and gyroscope sensitivity. The theoretical aspect of dynamic analysis is based on the simplified 2-Degree of Freedom (DOF) spring-mass system, whereas the accurate analysis of resonant frequency mismatch can be accomplished through a simulation model. IntelliSuite 8.9[8], a simulation platform, is used to perform the resonant frequency for mode-match analysis. This platform provides an element-based design through which drive and sense mode frequency can be analyzed, and the frequency mismatch can be reduced in order to have high sensitivity.

3.1. Element Based Model

SYNPLE module of IntelliSuite 8.9 software is used to build the element-based Tuning Fork MEMS gyroscope model. This design's basic structural model comprises drive beams, sense beams, anchors, comb drive, the double proof mass and decouples frame, etc. Then the structural model is optimized by resizing the horizontal and vertical beam dimensions in order to reduce frequency mismatch between drive and sense mode. The element-based model for tuning fork gyroscope is presented in figure 4.

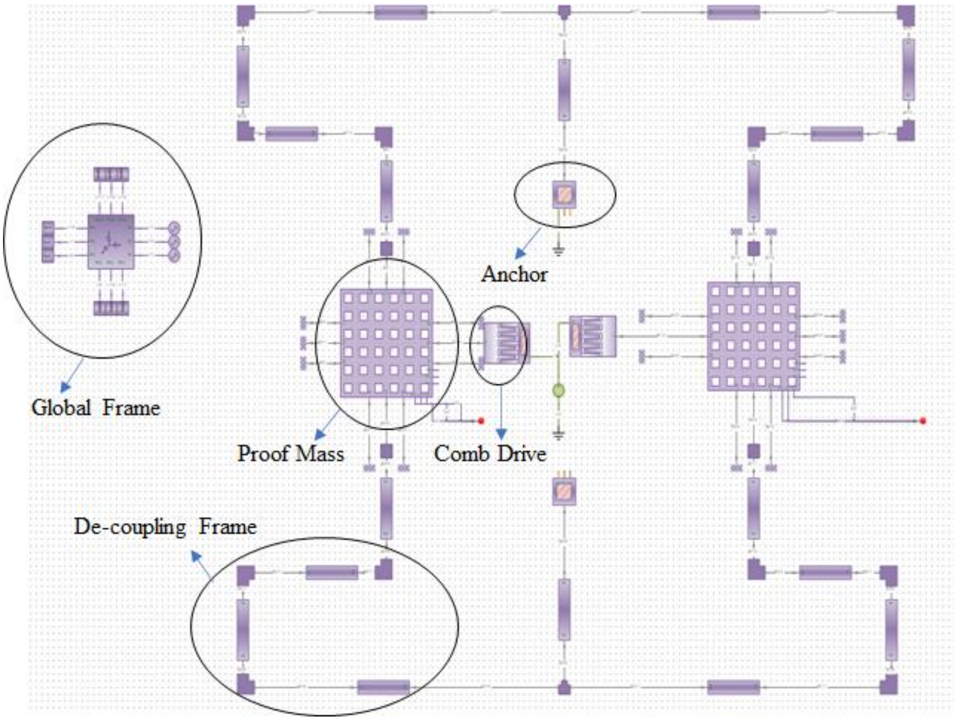
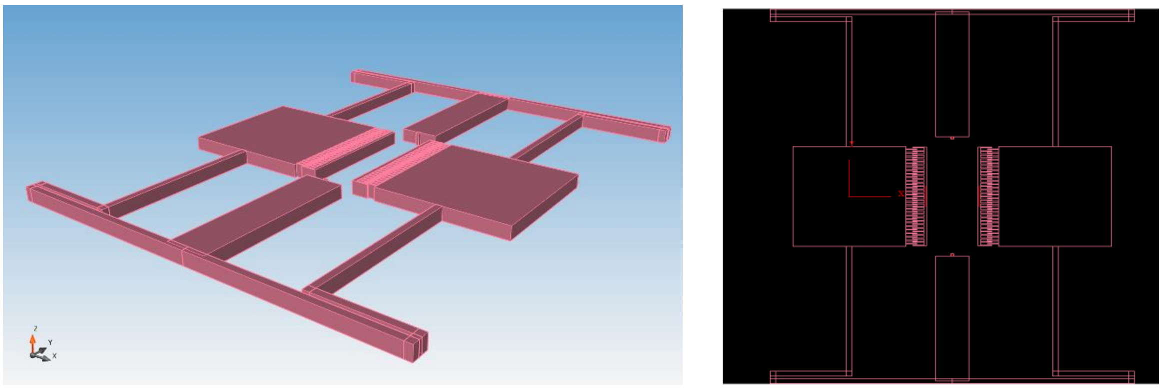


Fig. 4: Element based model - TFG

Further, FEM analysis is performed, and then the 3D model and mask layout are extracted from the SYNPLE module as shown in figure 5;

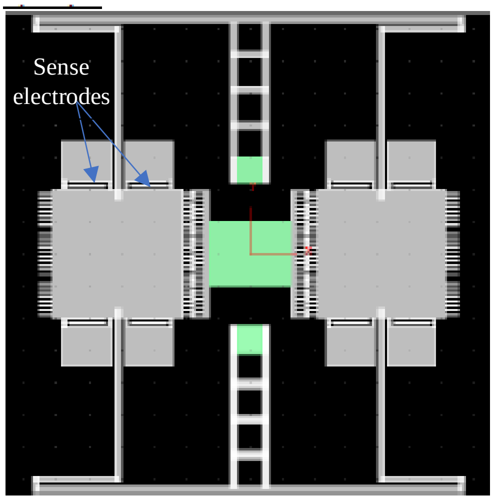


(a) **(b)**

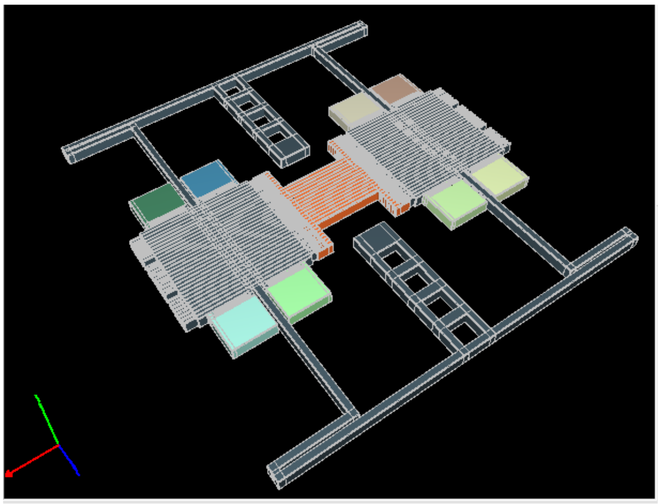
Fig. 5: (a) 3D model and (b) Mask Synthesis Layout

3.2. Model Construction

The tuning fork gyroscope layout model uses a mask layout that includes a set of sense electrodes for the gyroscope, as shown in figure 6 (a). Then 3D builder module of IntelliSuite is used to create the 3D meshed model from the mask layout. Since the complete gyro structure is made of straight lines and right angles, the *Manhattan* mesh type is used for better results. Figure 6 (b) shows the 3D solid structure construction model of the tuning fork gyroscope.



(a)



(b)

Fig. 6: (a) Gyro Layout (b) Solid Structure Construction Model

3.3. Mode-match Frequency Analysis

Frequency analysis was performed to reduce the mismatch between drive and sense mode resonant frequency [9] in order to achieve high sensitivity of the device.

Initially, the lengths of the two essential beams that correspond to the drive and sense modes have been varied to get them within 50-100 hertz and observed a considerable difference in drive and sense frequency. Then, both the lengths have been further changed to bring within 15-30 kilohertz. Figure 7 shows the crucial beam lengths correspond to the drive and sense modes of a tuning fork MEMS gyroscope;

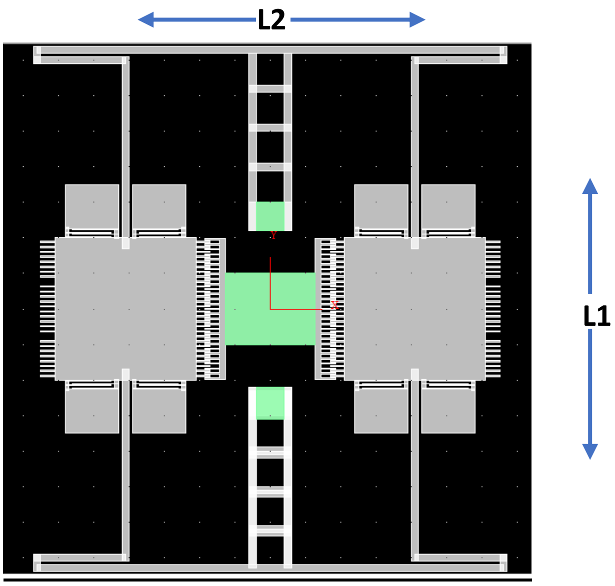


Fig. 7: Critical Dimensions

The schematic for the Frequency Analysis is shown in figure 8 before optimization of the design, which shows a mismatch of 5.8% between drive and sense mode frequency.

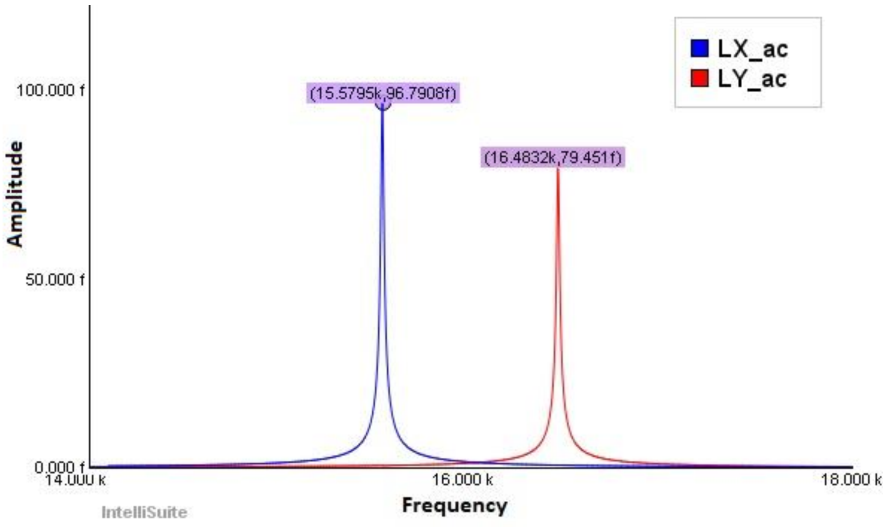


Fig. 8: Drive and Sense Mode mismatch before optimization

3.3.1. Process of Optimization of the Gyro Design

Initially, the L1 length was changed by 10-micron in both directions (above and below) on a total length of 510-micron and checked how the change in size influenced the driving frequency, keeping L2 constant at 620-micron. Then L1 is varied by 1 micron at a time to evaluate how close to the intended range the design could reach by adjusting the first variable after determining where the drive frequency crossed below the sense frequency. Then L2 length is varied while L1 remain constant to examine how this would affect the sense frequency. It was possible to compare and contrast all of these numbers after compiling them in excel to determine roughly how the frequencies would vary when both variables were changed simultaneously. The findings of the above analysis are used to look for locations where the driving and sense frequencies were crossed over at around 15 kHz and within the range of 50 to 100 Hz amplitude. Four times within the data sets, the drive and sense modes were close to one another, with two of those occurrences having to be ignored since the drive mode fell below the acceptable threshold of 15 kHz. Finally, the best values ensure that the model matches the expected frequencies and ranges. The final design parameters where both drive and sense mode frequency are the best match are listed in Table 1.

Table 1: Design Parameters for Best Mode Match Proposed Structure

Design Parameters	Values
Device dimensions, including anchors	1.48 mm x 1.27 mm
Device thickness	10µm
Driving beam length	635µm
Driving beam width	20µm
Central mass length	402µm
Central mass width	402µm
Comb finger length	40µm
Comb finger width	4µm
Total number of finger pairs	30
Driving capacitance gap	3µm
Finger overlapping length	15µm
Frame horizontal arms	1270µm x 20µm
Frame vertical arms	1080µm x 20µm

The schematic for the Frequency Analysis is shown in figure 9 after optimization of design which shows a mismatch of only 0.26 % between drive and sense mode frequency. The results of the frequency analysis are given in Table 3.

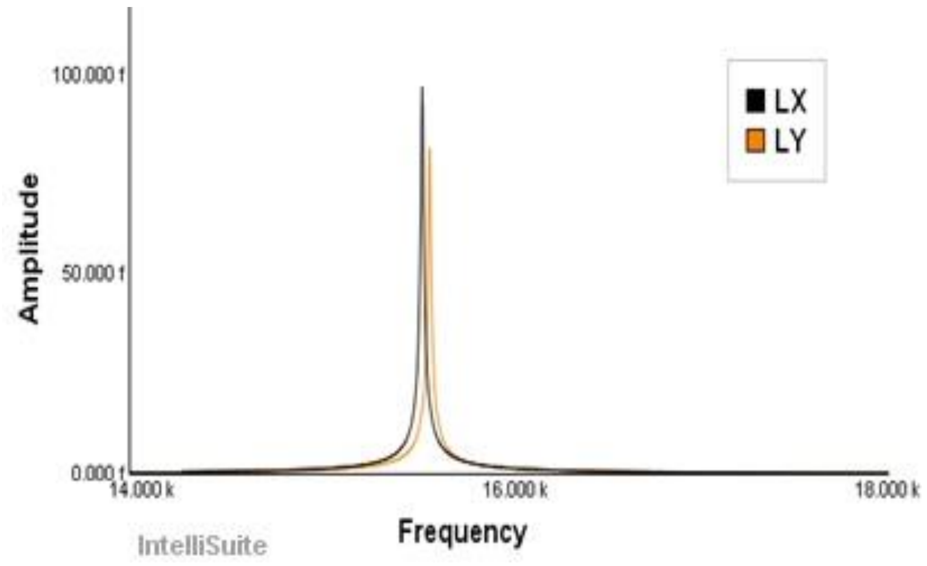


Fig. 9: Drive and Sense Mode mismatch after optimization

Table 3: Resonant Frequencies in X And Y Directions

Design Parameters	Values	Percentage of mismatch
Resonant Frequency in X-Direction (Drive Mode)	15.4975 kHz	0.26 %
Resonant Frequency in Y-Direction (Sense Mode)	15.5384 kHz	

4. Results and Discussions

The maximum displacement of the proof masses occurs at natural frequencies 15497.5 Hz for drive mode and 15538.4 Hz for sense mode) were used as input for MATLAB code to determine the amplitude of the required AC voltage for the drive mode transducer after the physical dimensions of the gyroscope had been decided. Additionally, the code is written to determine the gyroscope's sensitivity. The summary of the computations' outcomes is presented below in Table 4.

Table 4: Summary of the computations' outcomes

Drive Mode Frequency	15.4975 kHz
Sense Mode Frequency	15.5384 kHz
Vibration Amplitude	3.636x10-6 m
AC Voltage Amplitude	0.4008 V
Drive Mode Current	7.5234e-08 A
Sensitivity	1.1528e-06 (V/^{0}/s)

The simulation results for frequency mode-match analysis of a tuning fork MEMS gyroscope have been achieved to its best match and increased the device sensitivity to 1.1528e-6 (V/^{0}/s).

5. Conclusions

In this work, the basic mechanical structure and operation principle of a tuning fork MEMS gyroscope is discussed, and frequency mode match analysis is performed using IntelliSuite 8.9 simulation model. Element-based design is created from where the gyro layout mask is extracted to build the gyro 3D construction model using a 3d builder module. The gyroscope design parameter has been optimized to reduce the mismatch between the drive and sense mode resonant frequency. This mode match-analysis achieved a minimal mismatch of 0.26% compared to the presently available design. This mode match frequency achieved the device sensitivity of 1.1528e-6 (V/^{0}/s).

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Reviewer Comments;

3: (strong accept)
The manuscript titled "Simulation Studies on Tuning Fork MEMS Gyroscope for Mode Matched Analysis" is meaningful and can be useful for better understanding of MEMS Gyroscope. I recommend accepting the paper after all the following corrections are incorporated by the author:

Improve the literature review section, try to include the previous research paper based on MEMS Sensors. you may add some of the following research articles.

https://doi.org/10.1016/j.mejo.2021.105210

Author's Reply:

The Manuscript literature review has been improved by adding the research articles in Ref#5 as per reviewer comments.