Design and Analysis of MEMS Gyroscope

B. Preethi, L. Sujatha* and V.S. Selvakumar
Rajalakshmi Engineering College, Chennai – 602105 India
*E-mail: sujatha.l@rajalakshmi.edu.in

Abstract: MEMS gyroscope technology provides cost- effective method for improving directional estimation and overall accuracy in the navigation systems. This paper presents a tuning-fork gyroscope (TFG) [1] with a perforated proof mass. The perforated proof mass used in the design enables the reduction of the damping effect. This MEMS based gyroscope was designed using COMSOL Multiphysics 4.2a. This gyroscope has two modes- drive mode and sense mode. The driving force is given in the x-direction and the displacement due to the Coriolis Effect is sensed in the y-direction. The device is driven at its natural frequency and the response of the device is analyzed at static and dynamic state. The TFG produced a displacement **of** 2.6×10^{-9} m. The frequency range applied is 0.027 - 0.24 MHz.

Keywords: Tuning- fork gyroscope (TFG), decoupled comb drive, perforated proof mass, Microelectromechanical systems (MEMS).

1. Introduction

A gyroscope is a device that can measure angular velocity. For many applications in guidance and control, it is necessary to make certain directional reference available. These references, which serve as the basis for obtaining navigational data, for stabilization of a vehicle or some of its equipment, must be maintained despite various interferences and should be rotatable on command.

Microelectromechanical system (MEMS) gyroscopes have gained popularity for use as rotation rate sensors in commercial products like cars and game consoles because of their cheap cost, small size and low power consumption compared to the traditional gyroscopes. Several MEMS gyroscopes have been commercialized. As for structure designs, tuning- fork gyroscopes (TFG) are the most popular choice.

Micro machined gyroscopes use vibrating mechanical elements (proof-mass) to sense rotation. They have no rotating parts that require bearings, and hence they can be easily miniaturized and batch fabricated using micromachining techniques. All vibratory gyroscopes are based on the transfer of energy between two vibration modes of a structure caused by Coriolis acceleration.

TFG realizes the Coriolis acceleration to improve the sensitivity. The parameters, of TFG, that are of prime importance are the sensitivity and accuracy [2] of the device. In this paper we report the design and simulation of the tuning-fork gyroscope to improve their sensitivity. The design has been supported using Thermo Electro- mechanical simulations using the COMSOL Multiphysics 4.2a.

2. Structure Design

The schematic of the proposed structure is shown in figure 1. The proposed structure is symmetrical with perforated proof mass. The perforated proof mass enables in reducing the damping effect. 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 [2]. 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 the comb drive. The 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. Multiple electrodes are used for noise cancellation and noise diversity.

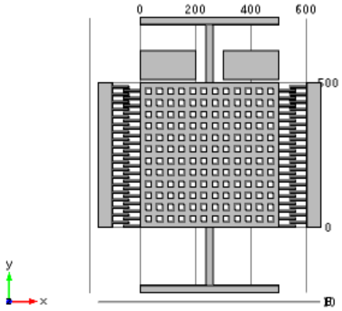

Figure.1. Perforated proof mass

The device is vibrated in natural frequency. This vibration is known as drive mode. When the structure begins to rotate, the Coriolis force acting on the proof mass changes the direction of vibration. This new vibration corresponds to the sense mode.

The metal plates placed above the proof mass, forms the capacitor along with the proof mass. As the proof mass vibrates in drive mode, the distance between the proof mass and the metal plate remains constant, and hence the capacitance does not change. When rotation is introduced and the proof mass vibrates in sense mode, the distance between proof mass and the metal plates varies. This change in capacitance is measured, from which the displacement can be calculated.

3. Principle of Operation

A gyroscope sensor measures the rate of rotation of the object. Vibrating gyroscopes must be driven at resonance in order to function as angular rate sensors. This direction will be referred as the drive direction [3], [5].

When the device is rotated along the rotation axis, a coriolis force is induced in the sense direction. This will excite the device in the sense direction into resonance mode. The sense direction is orthogonal to both the drive direction and the rotation axis.

Hence the gyroscope can be viewed as two-degrees- of freedom (2 DOF) mass- spring damper system whereby, one degree of freedom is the drive direction, and the second degree of freedom orthogonal to the first is the sense direction.

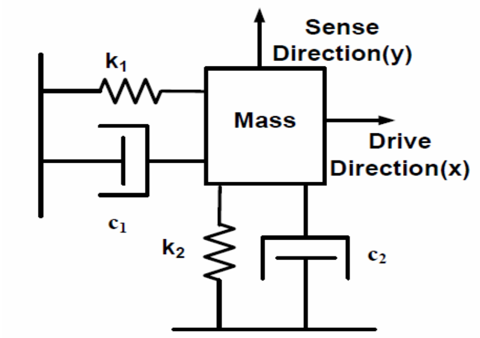

Figure 2. Two- degrees of freedom mass spring damper system

From Newton's second law of motion,

$$\sum F = ma \qquad (1)$$

$$\sum F = m\frac{\partial^2 x}{\partial t^2} \qquad (2)$$

The forces acting on the mechanical system are the spring forces F_s, damping force F_d, and the actuation force F_{el}

$$F_s = -kx \qquad (3)$$

$$F_d = -c\frac{\partial x}{\partial t} \qquad (4)$$

Equation (2) becomes,

$$F_{el} = m\frac{\partial^2 x}{\partial t^2} + c\frac{\partial x}{\partial t} + kx \qquad (5)$$

Where

m = mass of the body

F_{el} = Actuation force on the drive direction

c = Damping co efficient

k = Spring constant.

Thus the equation for a 2 DOF gyroscope is obtained as,

$$F_{r,x} = F_{i,x} + 2m\Omega\dot{y} + m\Omega^2 x + m\dot{\Omega}y \tag{6}$$

$$F_{r,y} = F_{i,y} - 2m\Omega\dot{x} + m\Omega^2 y - m\dot{\Omega}x \tag{7}$$

If the damping effects are taken into account, then the equations become

$$m\ddot{x} + c\dot{x} + kx = F_{i,x} + 2m\Omega\dot{y} + m\Omega^2 x \tag{8}$$

$$m\ddot{y} + c\dot{y} + ky = F_{i,y} - 2m\Omega\dot{x} + m\Omega^2 y \tag{9}$$

Where

c = damping factor,

k = $m\Omega^2$ = Spring constant.

$$m\ddot{x} + c\dot{x} + (\omega^2 - \Omega^2)x = F_{i,x} + 2m\Omega\dot{y} + m\Omega^2 x \tag{10}$$

$$m\ddot{y} + c\dot{y} + (\omega^2 - \Omega^2)y = F_{i,y} - 2m\Omega\dot{x} + m\Omega^2 y \tag{11}$$

The two terms $2m\ \Omega y$ and $2m\Omega x$ are rotation induced coriolis forces, which show the coupling between the drive direction and the sense direction.

4. Simulation

The structure is analyzed using Thermo Electro Mechanical analysis Module (TEM) of COMSOL, a commercial finite element analysis package. In this analysis, structural mechanical model is used for computing the gyroscope. The Coriolis force, that governs the device, is applied as the boundary load.

The device is initially operated at its natural frequency. The frequency range applied is 0.027 - 0.24 MHz.

The device is electrostatically and mechanically meshed to generate a finer mesh. The electrostatic mesh is used at the comb drives, since they are the electrostatic elements. The mechanical mesh is applied for the spring supports.

The device is subjected to static frequency analysis. In this analysis, the device is actuated by applying voltage to the comb drives. The simulation takes few minutes. Both the masses of the gyroscope will move in x- direction. The mode 4 will be the drive mode of the device. Because the proof masses will vibrate in x-direction with a phase shift.

When Coriolis force is applied in z - direction, the proof masses vibrate in direction perpendicular to the applied force. The mode 2 is the sense mode of the device.

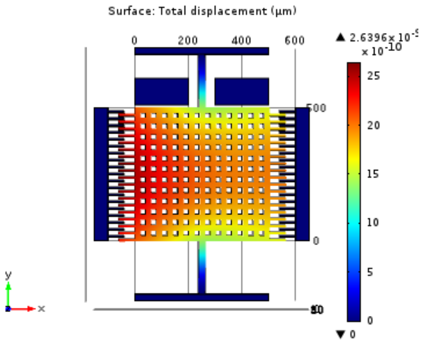

Figure 3.Displacement of proof mass at its natural frequency

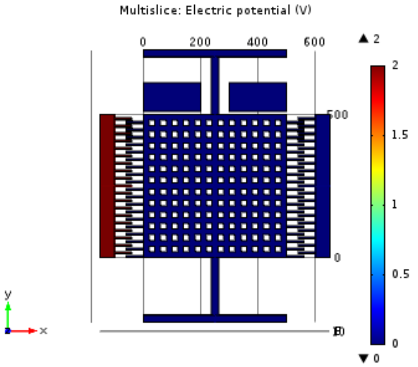

Figure 4. Electric potential profile.

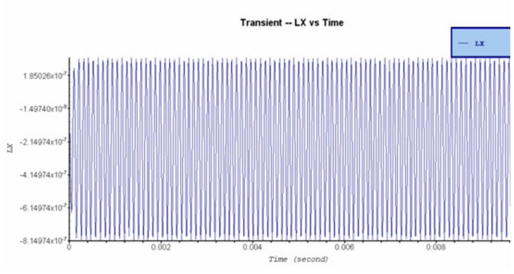

Figure 5. Transient response in x-direction.

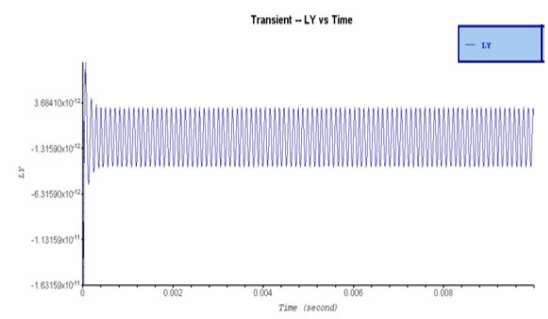

Figure 6. Transient response in y- direction

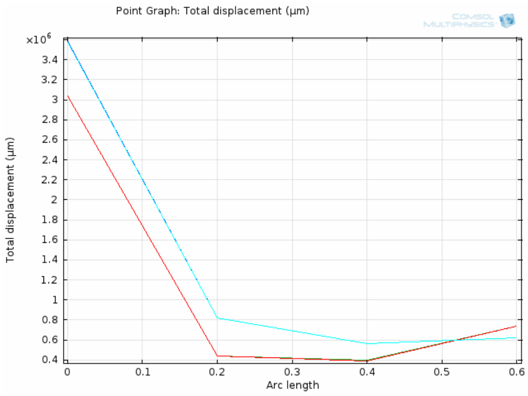

Figure 7. Displacement in different frequencies

5. Results

The figure 3 shows the displacement of the device at its natural frequency. From the fig. it can be seen that the device vibrates at its drive mode at a frequency of 0.027MHz.

The figure 4 shows the electric potential profile. On applying DC voltage at the comb drives the device vibrates.

The transient response of the device is achieved on applying the force. From figure 5 and figure 6, it is observed that the transient response has a phase shift in both x- and y-direction.

This is because on applying the Coriolis force, the proof mass gets displaced with same magnitude but in opposite direction.

6. Conclusions

A comprehensive model of gyroscope is designed and simulated using COMSOL Multiphysics 4.2a. The results show the performance of the device with perforated proof mass. It was found that the device showed a improved displacement on applying force. When the device was operated at its natural frequency it showed displacement at 2.6×10^{-9} m.

7. References

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