MEMS Vibrating Beam Gyroscope

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Abstract- *Vibrating cantilever beams are widely used in MEMS Gyroscopes. Even though the dimensions of the gyroscope may vary depending on the manufacturing unit of the sensor, but the basic principle of operation of these gyroscopes is the Coriolis Force, which is described later. This paper also describes the structure and working of a simple vibrating beam gyroscope, its drawbacks and its advancements in detail.*

Keywords- Coriolis force, MEMS Gyroscopes Vibrating Beam Gyroscope.

I. INTRODUCTION

Gyroscope is a device used for measuring the angle of rotation of any object and also used for maintaining the orientation of the object. It is widely used in our day-to-day appliances like smartphones and four wheeler vehicles, and also in fields of high accuracy like navigation, autopilot systems and missile guidance control.The main principles used in most of the gyroscopes are: the conservation of angular momentum and the Coriolis force[1], which is described in the section II.

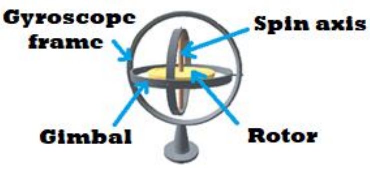

Figure 1. A conventional gyroscope

The most commonly used types of gyroscopes are Spinning Wheel Gyroscope, Optical Gyroscope and Vibrating Mass Gyroscope. The vibrating element in the vibrating mass gyroscope can be of various shapes, but most commonly used shapes are tuning fork[5], rings and beams. Among these, beams are more commonly used in MEMS Gyroscopes[3, 15]. Hence, this paper mainly focuses on vibrating beam gyroscope and the advancements made in it (in further sections of the paper.)

II. CORIOLIS FORCE

Whenever an object is moving in a non-inertial frame of reference with some angular velocity and an observer is also on the same non-inertial frame of reference, then the motion of the object actually follows a straight line path, if viewed from an inertial frame of reference, but for that observer the object seems to follow a curved path.

This is due to the Coriolis Effect, shown in Figure 2, and the acceleration of the object relative to the rotating frame is called as Coriolis Acceleration[15]. The force produced due to this acceleration is known as Coriolis Force. It is produced in a non-inertial frame [2, 10].

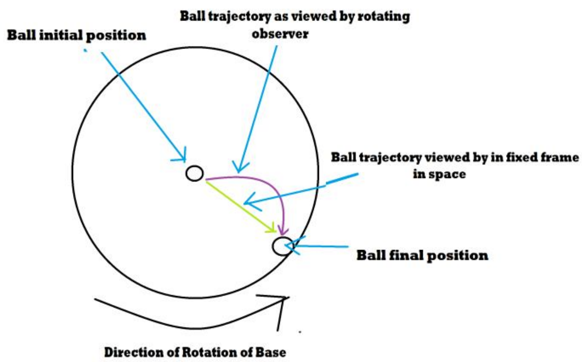

Figure 2. Coriolis Effect

Coriolis Acceleration is given as:

$$a_c = -2(v\times\omega)$$

Coriolis Force is then given as:

$$F_c = -2m(v\times\omega)$$

The direction of the Coriolis Force can found out by the right hand rule. According to the right hand rule, if the index finger denotes the direction of the velocity of the object (v) and the thumb points in the direction of the angular velocity (ω), then the middle finger points in the direction opposite to the resultant Coriolis Force, and hence, in the formula of F_c the negative sign is present[2].

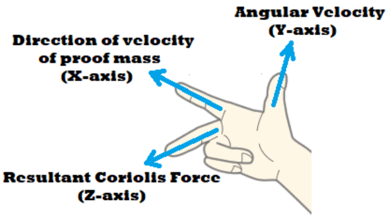

Figure 3. Right Hand Rule for finding the direction of Coriolis Force

III. VIBRATING MASS GYROSCOPE

A vibrating element (say it is vibrating in x-direction) when rotated with some angular velocity (in z-direction), produces secondary vibrations (in y-direction) orthogonal to the original vibrating direction as a result of Coriolis effect. By sensing the secondary vibrations along the sensing axis, the rate of turn can be detected.

An example of the vibrating mass gyroscope is shown in the Figure 4.Various elements such as tuning forks, beams, shells, rings, discs and cylinders are used as the proof mass in MEMS gyroscope[3, 16].

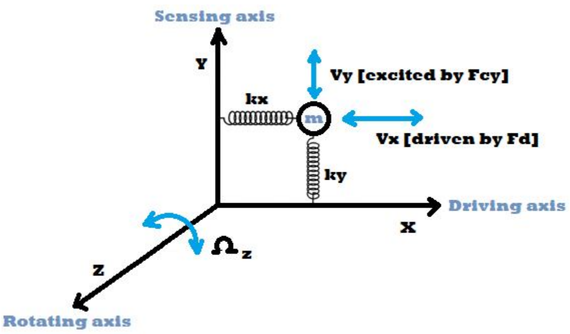

Figure 4. Vibrating gyroscope(mass spring based system)

IV. VIBRATING BEAM GYROSCOPE

When the proof mass in a vibrating mass gyroscope is a beam, then it is referred to as vibrating beam gyroscope. The most commonly used beam in this type of gyroscope is a cantilever beam. A cantilever beam is a rigid structure anchored at one end to a support (from which it protrudes.) The beam should be perpendicular to its base. The structure of a vibrating beam gyroscope consists of a beam with a tip mass and a moving base, as shown in Figure 5. The tip mass can be subjected to a combination of flexural-flexural vibrations or flexural-torsional vibrations.

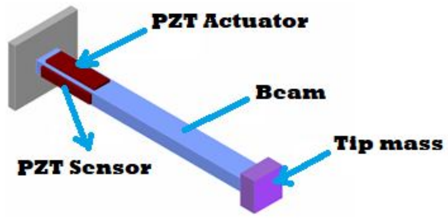

Figure 5. Single beam Gyroscope

The beam is initially given a lateral vibration along a particular axis with the help of piezoelectric actuator. Due to the angular rotation of the beam along the z-axis, secondary lateral vibrations are induced in the beam in a direction perpendicular to the primary vibrations (Flexural-Flexural).

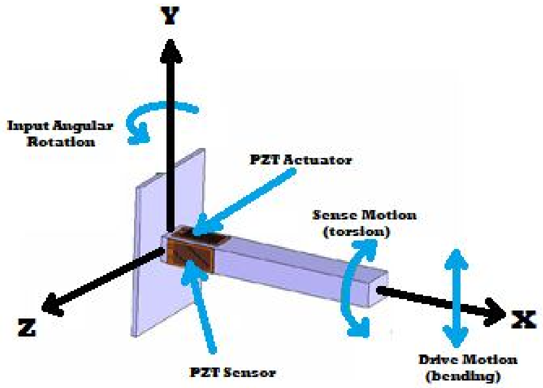

Figure 6. Flexural-Torsional beam gyroscope

In case of Flexural-Torsional vibrations, the secondary vibrations induced are torsional vibrations and not flexural, as observed in earlier case. The rate of angular rotation can be determined by measuring the secondary vibrations. These are sensed using piezoelectric sensors[6], accelerometer or laser sensors[3-4]. The measurement of the rate of angular rotation is not accurate because the base of the gyroscope is also subjected to secondary rotations, apart from the rotation around the z-axis. These rotations produce significant errors, known as Cross-Axis Effect. For example, when the secondary rotations of the base are of a very small magnitude (0.05 to 0.5 rad/s), it is observed that the output of the gyroscope increases almost 40 times. Such small figures of secondary rotations cause a significant change in the output. This is the major drawback of a single beam vibrating gyroscope. To eliminate such drawbacks, advancements have been made in the vibrating beam gyroscope. Rocking Mass Gyroscope is one such advancement[3].

TABLE I
VALUES OF PARAMETERS WITH OF VIBRATING BEAM GYROSCOPE

Parameters	Notation	Values
Beam Length(m)	L	0.15
Beam Thickness	tb	0.8E-3
Beam Width (m)	b	1.5E-2
Mass per unit length (kg/m)	Pb	3960Xbt
Beam elastic Modulus (gpa)	E	70
Beam shear modulus(gpa)	G	30
End Mass length (m)	l	0.01
End Mass Width (m)	Bm	0.02
End Mass height	Hm	0.02

A. Rocking Mass Gyroscope

Rocking mass gyroscope comprises of four beams, beam 1 and beam 3 have piezoelectric actuator attached to them, which produced bending vibrations. The bending of these beams produces torsional vibration in beams 2 and 4 which are sensed by piezoelectric sensors attached to the beams 2 and 4. The structure also contains a rocking mass in the centre of the beams.

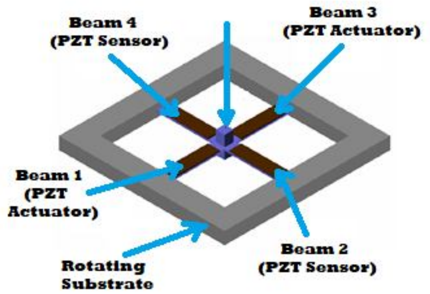

Figure 7. Rocking mass gyroscope

There is angular rotation about the vertical axis due to which the Coriolis force is produced and rocking motion in the mass is produced. This rocking motion causes torsional bending in beams 2 and 4. The angular velocity of the base can be determined by measuring the secondary vibrations.

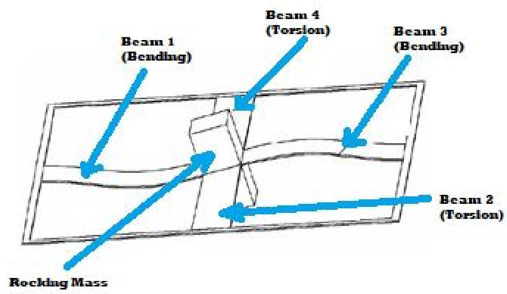

Figure 8. Rocking motion of mass

In a single beam gyroscope it is very difficult to measure the secondary vibrations as their amplitude is small, also there are errors caused by cross axis effect. But we can overcome these drawbacks in rocking mass gyroscopes as the piezoelectric sensors are not placed on the sides of the beams 2 and 4, but on their top.

Due to this the measurement of primary base rotation (bending) is not affected by the secondary base rotation (torsion) as the PZT sensors sense the bending of the beams and not the torsion. Thus, cross-axis effect is eliminated[3].

V. MICRO-ELECTRO MECHANICAL SYSTEM (MEMS) GYROSCOPE

MEMS Gyroscopes are generally fabricated out of a single piece of silicon or quartz.

To measure the angular velocity MEMS Gyroscope generally use a vibrating element which does not have rotating parts that require bearing, thereby making their miniaturization easier[8, 11].

In MEMS gyroscope, instead of using a cantilever beam a planar structure is used as the sensitive element of the sensor.

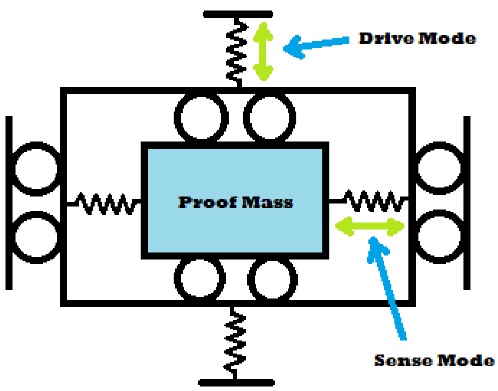

Figure 9. Two dimensional model of MEMS vibrating beam gyroscope

The Figure 9 shows a sample of two dimensional model of MEMS vibrating beam gyroscope. It consists of a proof mass (inner block) installed inside a decoupling frame (outer frame).

Initially the proof mass is subjected to motion along the sense mode (x-axis). Upon rotation around the z-axis, due to Coriolis force, the oscillation in the x-direction causes an oscillation in the y-direction, that is, drive mode. Hence, now the decoupling frame moves along the drive mode[12].

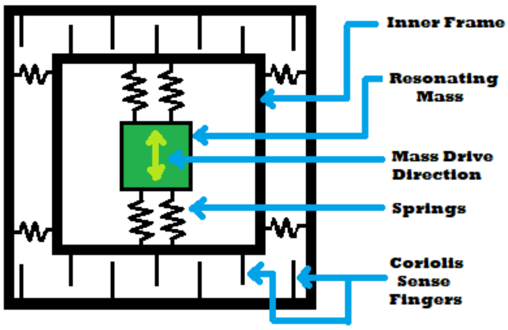

Figure 10. Modified diagram of MEMS vibrating beam gyroscope

In Figure 10, there is small modification made in the structure shown in Figure 9. Coriolis sense fingers are added in between the inner frame and the outer frame. Coriolis sense fingers are used to capacitively sense displacement of the frame in response to the force exerted by the mass[9, 14].

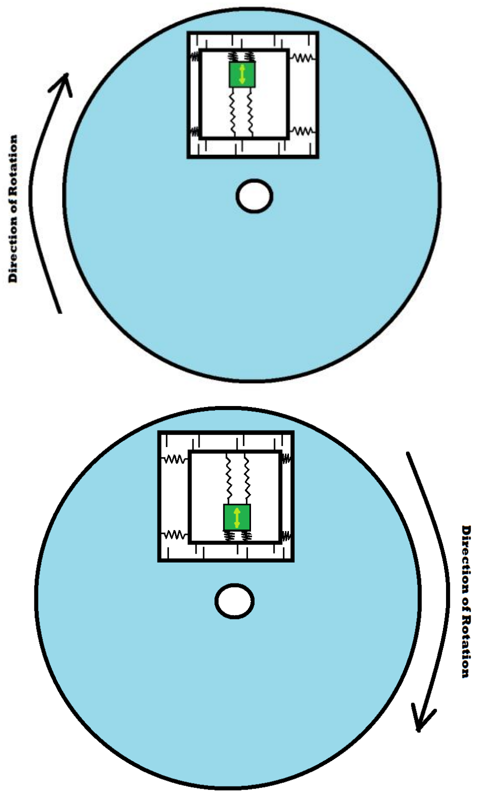

Figure 11. The frame and resonating mass are displaced laterally in response to the Coriolis Effect. The displacement is determined from the change in capacitance between the Coriolis sense fingers on the frame and those attached to the substrate.

VI. CONCLUSION

Vibrating structure gyroscopes (vibrating beam, tuning fork, etc.) work on the principle of Coriolis force. The motion of the vibrating beam gyroscope is governed by flexural-flexural or flexural-torsional vibrations. The Rocking Mass Gyroscope overcomes various drawbacks of a single vibrating beam gyroscope such as Cross-Axis Effect. The Vibrating Structure MEMS Gyroscope consists of a planar structure as the proof mass inside the decoupling frame. Coriolis sense are placed on the outer frame. They sense the displacement capacitively.

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