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Modeling and Simulation of MEMS based 3D Vibrating Gyroscope for Mobile Robotic Applications

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Abstract: Mobile Robotic Systems are typically used for applications where direct human involvement is too expensive, too dangerous, or just ineffective. MEMS gyroscopes provide a feedback sensing mechanism that can be very useful in optimizing navigation system performance.

In this study, a biomimetic vibrating 3D MEMS Gyroscope is designed, consisting of two circular diaphragms with a club shaped structure placed over one of them. This MEMS based vibrating gyroscope was modeled and simulated using COMSOL Multiphysics 4.1 - MEMS module. In this model there are two modes – driving mode and sensing 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 purpose of the research was to develop an effective gyroscope for guidance and control of mobile robots. The simulated results show that the displacement due to Coriolis effect, used for restoring the body back to its initial position, was greater when compared to that of the electrostatic force. These results let us to conclude that this gyroscope would provide valuable orientation information for robotics applications. MEMS gyroscope technology provides cost-effective methods for improving directional estimation and overall accuracy in the navigation systems.

Keywords: MEMS, gyroscope, biomimetic, Coriolis effect, robotics

Introduction

Technically, 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.

MEMS vibrating gyroscopes aim to create smaller and more sensitive devices. Fundamental to an understanding of the operation of a vibrating structure gyroscope is an understanding of the Coriolis force. Coriolis force is the force exerted on a body when it moves in a rotating reference frame. It is caused by rotation of earth and inertia of mass. It acts perpendicular to rotation axis and velocity of body in rotating frame and is proportional to rotation rate.

MEMS vibrational gyroscopes provide a low cost inertial measurement of rotation rate by sensing the effects of the Coriolis force in a rotating system. A vibrational gyroscope can be understood by considering a mass attached to a rigid frame by springs (Fig 1).

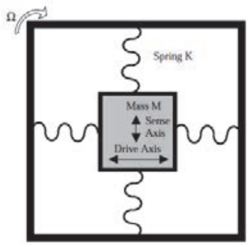

Figure 1: Basic Vibrational Gyroscope

The mass is driven to vibrate along one axis (drive axis). If the gyroscope rotates about an axis perpendicular to the page, a Coriolis force is generated along an axis perpendicular to both the drive axis and the axis of rotation, called the sense axis. The sense axis vibration is measured to determine the rotation rate. The drive direction is typically excited by the electrostatic drive forces to a constant amplitude of oscillation (linear or angular depending on the design), and the sense direction is excited by the rotation-induced Coriolis force.

Among many micro machined gyroscopes, Coriolis vibratory rate gyroscopes have demonstrated a significant progress within the past decade satisfying the requirements of several applications such as guidance, robotics, tactical-grade navigation, and automotive applications. Micro machined vibratory gyroscopes have many potential advantages. They can be mass produced and can have both driving and detecting circuits integrated on-chip for improved sensitivity.

In this study, a biomimetic vibrating 3D MEMS Gyroscope is designed.

Background Theory

Blowfly (*Calliphora vicina*) uses a special organ, the *halteres*, to navigate its flight course. The halteres, functioning as vibrating gyroscope, are small modified hind wings, which beat antiphase to the wings and serve a purely sensory function during flight. It would be very challenging and fruitful to advance the development of new micro machined vibrating gyroscope by taking inspiration from the structure of natural gyroscope, i.e. the halteres. The *Campaniform Sensilla* and chordotonal organs, which are at the base of the halteres and enable extreme high sensitivity for strain detection, encode the strain generated by the Coriolis forces during rotational movements. Therefore, the halteres are very sensitive to Coriolis forces and potentially provide an accurate measure of angular velocity which originates from angular rotations of the body and mediate corrective reflexes during flight. Derham was the first scientist to note that when their halteres are removed, flies cannot keep stability and quickly crash to the ground while staying aloft. In reality, these mechanoreceptors at the base of the halteres function as strain gauges to detect the Coriolis force applied on the halteres.[4]

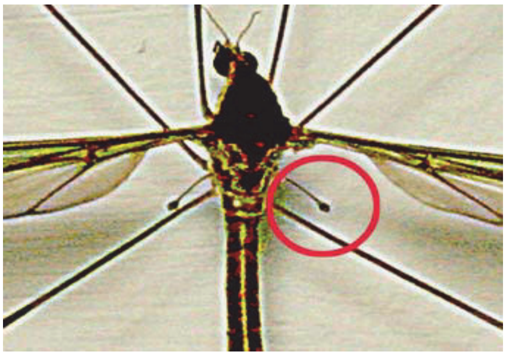

Figure 2: Haltere of an insect

As a result of fly motion and haltere kinematics during flight, a complex force acts on the halteres.

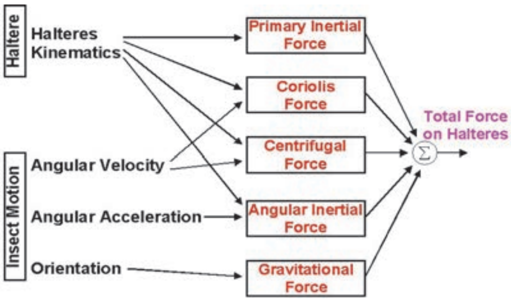

Figure 3: Haltere Force Modulation[2]

Assuming no translational motion of the insect, this force can be expressed in vector notation as following:

$$F=mg-ma-m\acute{\omega}xr-m\omega x(\omega xr)-2m\omega xv \qquad - (1)$$

where m is the mass of the haltere, r, v, and a are the position, velocity, and acceleration of the haltere relative to the insect body, respectively; ω and $\acute{\omega}$ are the angular velocity and angular acceleration of the insect, and g is the gravitational constant. When fly's body rotates, centrifugal$(-m\omega x(\omega xr))$ and Coriolis$(-2m\omega xv)$ forces are produced on its halteres. However, the influence of the centrifugal force to the rotation movement can be neglected. First, the centrifugal force is generally smaller than the Coriolis force and mostly in the radial and tangential directions. Second, as the centrifugal force is proportiona1 to the square of angular velocity of the fly, the sign of rotations would not be influenced by the centrifugal force. Third, the Coriolis force is proportional to the product of the angular velocity of the fly and the instantaneous haltere velocity. The Coriolis force has components in all three directions and contains the information on the axis, sign, and magnitude of the fly's body rotation. The angular acceleration force $(m\acute{\omega}xr)$ is proportional to the product of the angular acceleration of the fly and the instantaneous position of the haltere. Due to the 90º phase shift, the angular acceleration and the Coriolis force signals are separable. The primary inertial force $(-ma)$ depends on the haltere acceleration relative to the fly’s body. This force is of orders of magnitude larger than the Coriolis force and also has only radial and tangential components. The gravitational force *(mg)* is always constant and depending on the haltere position and the fly's body attitude in space, its distribution varies in the three directions. However, because it is a lateral component, the effect of this gravitational force on the angular velocity sensing is negligible. For this reason, the gravitational force can be considered as DC offset on the Coriolis force and can be removed easily by the subsequent signal processing step. In the presence of an angular rotation rate about the z-axis, a sinusoidal Coriolis force at the drive frequency is induced on the proof mass in the direction orthogonal to each drive-mode oscillation directions. Thus, each of the induced Coriolis force vectors lie in the tangential direction, combining to generate a resultant torque on the supporting frame. [1]

Structural Design

In this study, a biomimetic vibrating 2D and 3D MEMS Gyroscope are designed, consisting of two circular diaphragms with a club shaped structure placed over one of them. The inspiration comes from insects having specialized structure called halteres, which are sensitive to Coriolis force and thus used for maintaining the orientation. In this model there are two modes – driving mode and sensing mode. The driving force is given in the y-direction and the displacement due to the Coriolis effect is sensed in the x-direction.

Mobile Robotic Application

A fundamental requirement for an autonomous mobile robot is the ability to localize itself with respect to the environment. With careful and detailed modeling of error sources gyroscopes can provide valuable orientation and position information for mobile robot applications. The principle of operation is to measure the Coriolis acceleration caused by angular rotation of a vibrating cylinder, chosen for its symmetry, around the principal axis.[3]

The sensing operation is done using the capacitive effect. A circular plate with 0V is kept at the bottom of the membrane which is at 1V potential. When the structure deforms due to the electrostatic force, the membrane displaces to a certain extent. So the capacitance between these two is measured and the difference in capacitance from the reference value is calculated. This gives quantified information of Coriolis force that is exerted on the head of the structure in order to reorient it in the original position.

Another approach that can be utilized to maintain the orientation of the object would be a closed loop control system. A closed-loop control system utilizes an additional measure of the actual output in order to compare the actual output with the desired output response. A standard definition of a feedback control system is a control system which tends to maintain a prescribed relationship of one system variable to another by comparing functions of these variables and using the difference as a means of control.

COMSOL Multiphysics Analysis

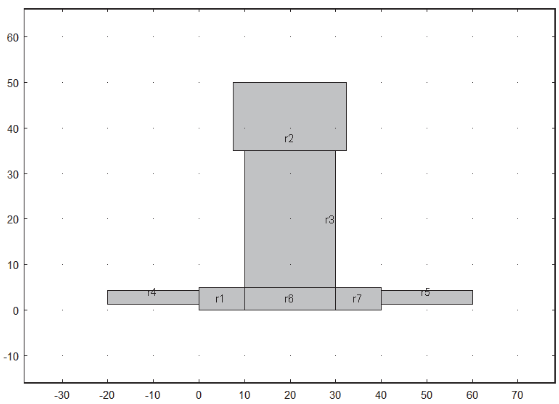

Figure 4: 2D Model of MEMS based Vibrating Gyroscope

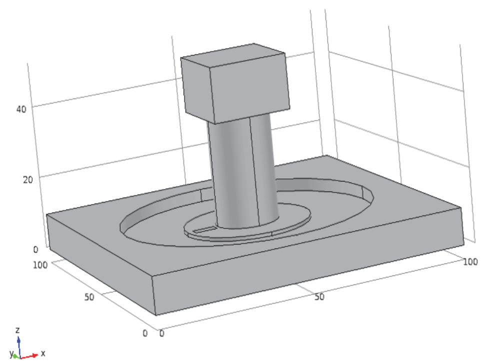

Figure 5: 3D Model of MEMS based Vibrating Gyroscope

This MEMS based vibrating gyroscope was modeled and simulated using COMSOL Multiphysics 4.1 - MEMS module.
Materials defined: The thicker and thinner membranes were made of silicon. The pillar and head were made of polysilicon.

Physics Used:
The Solid Mechanics physics in terms of boundary load was applied to the required boundary. In case of electrostatic force the load was applied to opposite sides of the thicker membrane, whereas in case of Coriolis force the load was applied to the pillar head.

Results and Discussion

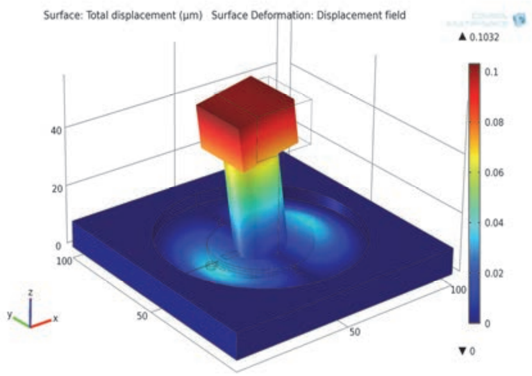

Figure 6: Displacement due to Electrostatic Force in 3D model

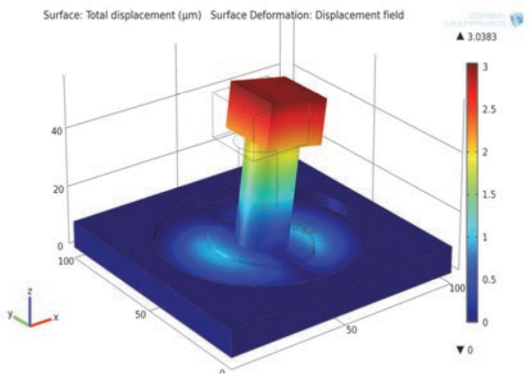

Figure 7: Displacement due to Coriolis Force in 3D model

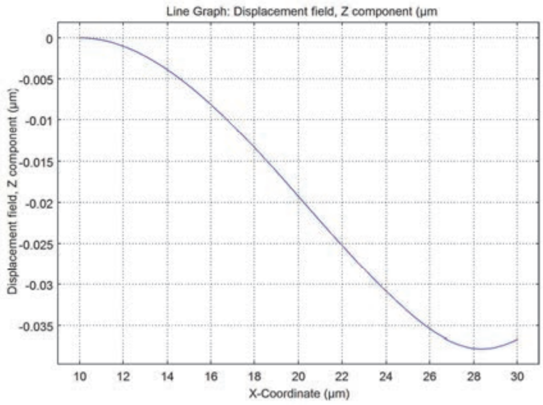

Figure 8: Z axis displacement field in the thinner membrane due to Electrostatic Force

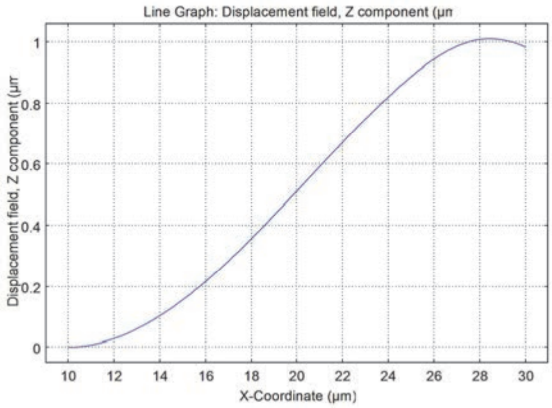

Figure 9: Z axis displacement field in the thinner membrane due to Coriolis Force

The simulated results show that the Coriolis force input on the structure, would cause larger displacement on the suspended thin layer of membrane than the applied pressure, which was defined to simulate the electrostatic driving force. This indicates the momentum amplification property of the biomimetic hammer shaped structure.

Conclusion

The purpose of the research was to develop an effective gyroscope for guidance and control of mobile robots. The simulated results show that the displacement due to Coriolis effect, used for restoring the body back to its initial position, was greater when compared to that of the electrostatic force. These results let us to a conclusion, that this gyroscope would provide valuable orientation information for robotics applications. MEMS gyroscope technology provides cost-effective methods for improving directional estimation and overall accuracy in their navigation systems. There is still a lot of room for improvement in current techniques, especially in increasing sensitivity. We believe that there will be countless other applications discovered for MEMS gyroscopes in the coming years due to their versatility and size.

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