MEMS Tuning-Fork Gyroscope
Mid-Term Report
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Abstract

MEMS based gyroscopes have gained in popularity for use as rotation rate sensors in commercial products like cars and game consoles due to their cheap cost and small sized compared with traditional gyroscopes. The MEMS gyroscope consists of the basic mechanical structure an electronic transducer to excite the system as well as an electronic sensor to detect the change in the mechanical structures modal shape. The goal of this project is to refine the accuracy and detail given by the MEMS gyroscope to military grade standards enabling the expansion of their use, while maintaining the attraction of their low cost. To achieve this, the structure of the mechanical portion will be analyzed to generate the two modal shapes as close as possible within the 15-30kHz range so as to be differentiable from background noise yet still require minimal power to be detected.
# Table of Contents

Abstract ....................................................................................................................................... 2
Introduction .................................................................................................................................. 5
Background Theory ..................................................................................................................... 6
  Gyroscope Mechanical Structure ............................................................................................... 6
  Coriolis Effect .......................................................................................................................... 8
Electrical Theory: Drive Mode ..................................................................................................... 9
  Monitoring Drive Mode .............................................................................................................. 12
  MEMS Device Fabrication ......................................................................................................... 13
Work Completed ........................................................................................................................ 17
Work Planned ............................................................................................................................. 17
Appendix A: MATLAB Code for Electrical Calculations ......................................................... 18
List of Figures

Figure 1: Gyroscope Mechanical Structure.................................................................4
Figure 2: Drive Mode Frequency................................................................................5
Figure 3: Sense Mode Vibration..................................................................................5
Figure 4: Sense Mode Metal Plates...........................................................................6
Figure 5: Coriolis Acceleration..................................................................................6
Figure 6: Gyroscope with Comb Drive Transducer.....................................................7
Figure 7: Comb Drive Finger Detail............................................................................8
Figure 8: Voltage Sources.........................................................................................9
Figure 9: Gyroscope Drawing in AutoCAD.................................................................11
Figure 10: Mask for a MEMS Device.......................................................................12
Figure 11: Preparation of Photo Resist Layer.............................................................12
Figure 12: Wafer Development..................................................................................13
Figure 13: SOI Wafer...............................................................................................13
Figure 14: SOI Wafer After Etching with HF Acid......................................................13
Introduction

Gyroscopes are becoming more desired for their ability to sense and report rotation. There are many industries using gyroscopes in their products. More precise gyroscopes are in demand and research is being done to accomplish that goal. Main considerations involved are how does it work, why type of design attributes need to be added, and what type of cost considerations are involved.

Gyroscopes are designed to sense rotation. The way they do this is through their underlying principal, the Coriolis effect. The Coriolis effect can be described by having a person stationary on the x axis and a particle moving along the positive y axis. Once a rotation is added about the z axis a force is caused which makes the stationary person believe that the particle is moving toward him or her. When used in a Gyroscope, the Coriolis effect is used to ultimately detect angular velocity. Two modes of vibrations are used to do this. The first mode of vibration is the drive mode. This mode is intentionally introduced to the system for the Coriolis effect to work. This mode of vibration involves two proof masses moving horizontally in opposite directions from one another. The second mode of vibration is caused by introducing an angular velocity to the already moving device. The Coriolis effect causes the proof masses to move in a different direction than the first mode. The proof masses then move vertically in directions opposite each other.

Sense electrodes are placed above the proof masses and can sense the distance that the proof mass is moving. These sense electrodes are able to calculate capacitance which is a function of distance. This capacitance is directly proportional to the angular velocity, thus giving an accurate measurement of angular velocity in terms of capacitance.

The design of a gyroscope is very important for the application of which it use for. The most common gyroscope is the micro-electro mechanical system tuning for gyroscope. This gyroscope is designed with a tuning fork structure meaning that it is symmetrical on both sides. This design uses two proof masses. The structure is composed of long thin beams and anchored in the center that the proof masses are free to move. It is essential to adjust all of the dimensions so that a certain range of frequency is output. It is important so that data can be received and it is not being overwhelmed with noise rather than real measurements.

Gyroscopes are used in many different industries, some new and some old. They are used for gaming in systems such as the wii motion plus attachment, telecommunications such as the iphone 4. Gyroscopes are also used in the automotive industry for many different purposes along with space exploration and ship building. Gyroscopes are desirable because they are very small, it does not take much energy to use them and because they are relatively inexpensive to mass produce.

Most gyroscopes are now made from layered silicon wafers. These wafers are micro machined such that the gyroscope’s form is exposed from the middle of the wafer.

The purpose of this project is to design a precision gyroscope that is comparative to optical devices. If the team succeeds in yielding data with great precision it could be mass produced and added to various different devices to yield better accuracy for many different industries.
Background Theory

Gyroscope Mechanical Structure

MEMS tuning-fork style gyroscopes are small silicon devices that detect rotation. Although they are currently not as sensitive as traditional rotating ring gyroscopes, because of their small size and low cost, they are used in many different electronic devices, including the iPhone 4 and the Wii Motion Plus accessory. The basic mechanical structure of a MEMS gyroscope is shown in Figure 1 below.

The structure is fixed at the anchors shown above, while the rest of the structure, including the large proof masses on either side, is free to move. Since the gyroscope uses the Coriolis effect to detect rotation, the device must be in constant motion to function as the Coriolis force only acts on moving bodies (for more about the Coriolis Effect, click here). This motion is accomplished by vibrating the structure at one of its natural frequencies to achieve the motion shown in Figure 2. This vibration is referred to as the Drive Mode.
When the structure begins to rotate, the Coriolis force acting on the moving proof masses changes the direction of the vibration from horizontal to vertical as seen in Figure 3. This vertical vibration corresponds to a higher natural frequency of the structure than the horizontal Drive Mode vibration and is referred to as Sense Mode.

Metal plates are placed above the proof mass as shown in Figure 4. Together with the proof mass, these plates form a capacitor. As the proof mass vibrates in drive mode, the distance between the proof mass and the plates remains constant. Since capacitance for a parallel plate capacitor such as this one is a function of the distance between the two plates, in Drive Mode the capacitance also remains constant. Once the structure begins to rotate and enters Sense Mode, as the proof mass moves vertically, the distance between it and the plates changes, which changes the capacitance. This change in capacitance can be detected by electronic equipment and converted to indicate the corresponding rotation.
Coriolis Effect

The Coriolis Effect is the name given to the acceleration experienced by a moving point in a rotating reference frame. This Coriolis acceleration is defined as

\[ \vec{a}_{\text{coriolis}} = 2\vec{\Omega} \times \vec{v} \]

where \( \vec{\Omega} \) is the angular velocity of reference frame and \( \vec{v} \) is the velocity of the particle within this reference frame, as shown in Figure 5 below\(^1\) (note that the direction of angular velocity \( \vec{\Omega} \) is clockwise about the z-axis).

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\(^1\) Figure 5 used with the permission of Dr. Julie Hao.
**Electrical Theory: Drive Mode**

The force necessary to keep the proof masses in constant motion in drive mode is provided by a comb drive transducer placed next to one of the proof masses, forming a capacitor as shown below:\(^2\):

![Figure 6: Gyroscope with Comb Drive Transducer](image)

The fingers on the comb drive and the side of the proof mass increase the surface area of the capacitor, which increases the capacitance and allows changes in the system to be detected more easily. Note that only one of the drive electrodes above is used to apply a force to the proof masses; the other is used to monitor the drive mode vibration of the proof masses.

The capacitance \( C \) for one finger of the proof mass is given as:

\[
C = 2 \varepsilon_0 \frac{l_0 h}{g}
\]

where \( l_0 \) is the length of the initial overlap between the finger on the proof mass and the finger on the comb drive, \( h \) is the height of the gyroscope, \( g \) is the gap between the fingers on the comb drive and the finger on the proof mass, and \( \varepsilon_0 \) is the permittivity of free space, a constant.

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\(^2\) Parts of Figure 6 used with the permission of Dr. Julie Hao.
To find the total capacitance of the Comb Drive – Proof Mass capacitor, simply multiply the capacity for one finger by the number of fingers, $n$.

The energy stored in the capacitor, $E$ is given as:

$$E = \frac{1}{2} CV^2$$

where $V$ is the voltage drop across the capacitor. Substituting the value for the total capacitance, $C$ yields:

$$E = n \epsilon_0 \frac{l_0 h}{g} V^2$$

As the proof mass moves a small distance $x$ in drive mode, the overlap between fingers changes from $l_0$ to $l_0 + x$ and the equation for energy becomes

$$E = n \epsilon_0 \frac{(l_0 + x)h}{g} V^2$$

To find the force $F$ acting on the proof mass, take the derivative of $E$ with respect to $x$:

$$F = \frac{dE}{dx} = n \epsilon_0 \frac{h}{g} V^2$$

In order to keep the proof masses in constant motion, an AC voltage source must be used so that the capacitor will not reach a steady state. An AC voltage source is applied to the comb drive transducer as shown below. Note that a DC voltage source is applied to the anchor of the gyroscope for use in sense mode.

Parts of Figure 8 used with permission of Dr. Julie Hao
With these two voltage sources applied, the equation for force becomes:

\[ F = n \frac{\varepsilon_0 h}{g} (V_{DC} + v_{AC})^2 \]

This can be expanded as:

\[ F = n \frac{\varepsilon_0 h}{g} (V_{DC}^2 + 2V_{DC}v_{AC} + v_{AC}^2) \]
\[ = n \frac{\varepsilon_0 h}{g} V_{DC}^2 + n \frac{\varepsilon_0 h}{g} 2V_{DC}v_{AC} + n \frac{\varepsilon_0 h}{g} v_{AC}^2 \]

The term \( n \frac{\varepsilon_0 h}{g} V_{DC}^2 \) is a constant and will only offset the proof mass initially by a small amount. Because it will not contribute to the oscillation of the proof mass, it can be disregarded.

Since \( v_{AC} \) is time dependent, it can be written as \( v_{AC} = v_0 \sin(\omega t) \) where \( v_0 \) is the amplitude of the AC voltage and \( \omega \) is the frequency of the AC voltage, which must be equal to the drive mode natural frequency of the gyroscope. Substituting this expression into the term \( n \frac{\varepsilon_0 h}{g} V_{DC}^2 \) yields \( n \frac{\varepsilon_0 h}{g} v_{AC}^2 (v_0^2 \sin^2(\omega t)) \). However, since \( \sin^2(\omega t) = \frac{1 - \cos(2\omega t)}{2} \), this term becomes a function of two times the natural frequency of the system and can be disregarded, leaving:

\[ F = 2n \frac{\varepsilon_0 h}{g} V_{DC} v_0 \sin(\omega t) \]

Applying Newton's Second Law to the gyroscope mechanical system yields
\[ m \frac{d^2 x}{dt^2} + D \frac{dx}{dt} + kx = F \]

where \( k \) is the spring constant of the system and \( D \) is a damping coefficient given as \( D = \frac{\sqrt{k m}}{Q} \) where \( Q \) is a large number, typically greater than 10,000.

Because the displacement of the proof mass is also time dependent, it can be written as \( x = q_0 \sin(\omega t) \), where \( q_0 \) is the amplitude of the displacement.

The differential equation above can be solved for \( q_0 \), producing

\[ q_0 = \frac{F}{k} Q = 2n \frac{\varepsilon_0 h V_{DC} v_0}{g k} Q \]

This equation gives the amplitude of the proof mass vibration in terms of the amplitude of the AC voltage, which can be used to design the comb drive transducer to achieve a specific amplitude of proof mass vibration.

**Monitoring Drive Mode**

As mentioned above, only one of the comb drive transducers is required to apply a force to the proof mass to keep it in motion. This leaves the other proof mass free to be used to monitor the vibration of the proof mass in drive mode. By measuring the current \( i \) from this transducer, the displacement of the proof mass can be found through the following relationship.

Since \( Q \), the electric charge, can be expressed as \( CV \), and current is merely the derivative of charge with respect to time, an expression for electric current can be obtained by evaluating

\[ \frac{dQ}{dt} = \frac{d}{dt}(CV_{DC}) \]

By applying the chain rule, this becomes

\[ i = \frac{dC}{dt} V_{DC} + C \frac{dV_{DC}}{dt} \]

however, since \( V_{DC} \) is a constant, the term \( C \frac{dV_{DC}}{dt} \) reduces to zero leaving

\[ i = \frac{dC}{dt} V_{DC} \]

As mentioned in the previous section, \( C = \frac{2n \varepsilon_0 h}{g} (l_0 + x) \), so taking the derivative of this function leaves

\[ \frac{dC}{dt} = \frac{2n \varepsilon_0 h}{g} \frac{dx}{dt} \]
Since $x = q_0 \sin(\omega t)$ can also be expressed as $x = q_0 e^{i \omega t}$,

\[ \frac{dx}{dt} = A i \omega e^{i \omega t} = (i \omega) x \]

This value can then be substituted into the equation for $\frac{dC}{dt}$ which can then be inserted into the equation for current, producing the relationship between current and displacement which will allow the vibration of the proof mass to be monitored in drive mode:

\[ i = V_{DC} \frac{2 n e h}{g} (i \omega) x \]

**MEMS Device Fabrication**

After doing many calculations and iterative processes, all the dimensions can be found to make a complete model of the Micro Electrical Mechanical System (MEMS) gyroscope. Below is an image of an AutoCAD drawing of a complete MEMS Gyroscope.

![Figure 9: Gyroscope Drawing in AutoCAD](image)

In order to make a MEMS gyroscope one must transfer the design from a CAD file to a Mask and finally to a silicon wafer. To do this a CAD program is used to design the mask. The design is patterned many times on the mask so as to utilize the space on the wafer as efficiently as possible. The program most used to fabricate the mask is CADENCE. This program allows an auxiliary device to laser etch chrome away from glass to reveal the desired design. Below is an example of a mask. Note that light has the ability to pass through the mask.
The silicon wafer must then be prepared by adding a photo resist layer. A round wafer is loaded onto a spin coater, photo resist is applied and the wafer is allowed to spin which adds a thin uniform layer of photo resist.

After preparing the wafer, the mask is aligned above the wafer. It is exposed to UV light which changes the properties of the photo resist that is exposed. After this exposure is complete the wafer is developed. In a positive photo resist situation the areas that were exposed to light are etched away, however the opposite is true if a negative photo resist is used.
For a MEMS gyroscope to work, most of the mechanical structure must be able to freely move, with the exception of anchors, which hold the whole device in place. In order to accomplish this, a special type of wafer is used. This wafer is composed of several layers. A top layer of silicon is used for the mechanical structure which is 30 microns thick, Silicon dioxide which will release the mechanical structure, and more silicon which creates the bulk substrate. This type of wafer, called a Silicon-On-Insulator (SOI) wafer, is pictured below:

![SOI Wafer](image)

Figure 13: SOI Wafer

To release the mechanical structure a powerful acid, such as hydrofluoric acid is used, resulting in a structure like the one in the following image:

![SOI Wafer After Etching with HF Acid](image)

Figure 14: SOI Wafer After Etching with HF Acid
The silicon dioxide does not completely etch away. The mechanical structure of the MEMS gyroscope has two large proof masses, in which would not be able to be released from the substrate. To account of this, tiny holes are added into the proof masses which then allow the chemicals to etch enough silicon dioxide to release the structure.
**Work Completed**

After having been given the basic design concept, we began the process of inputting the model into Comsol for finite element analysis. Seeking the drive and sense modes to be within 50-100 hertz of each other, while still being between 15-30 kilohertz, we began modifying the lengths of the two critical beams that correspond to these frequencies. Keeping L2 constant at 620 µm, we initially varied L1 by 10 µm lengths above and below the initial 520 µm value we began with to see how the change in length affected the drive frequency. After finding where it crossed below the sense frequency, we proceeded to vary L1 by 1 µm at a time to see how close to our goal we could get with just changing the first variable. Once we had collected these results, we moved onto varying L2 while keeping L1 constant to see how this would affect the sense frequency. After collecting all these values and recording them in excel, we could then compare and contrast them to see approximately how the frequencies would change when adjusting both of our variables at the same time. From these results, we searched for all the points where our drive and sense frequencies were within the 50-100 Hz range of each other, and both above 15 kHz. The drive and sense mode only were within the 50-100 Hz range of each other four times within our data sets, two of which had to be disregarded because the drive mode for them was below the 15 kHz required. This narrowed the field down rather quickly for us, and gave us a quick choice of which numbers to use. After selecting our values to use, we proceeded to re-run the Comsol analysis to double check that our selected values matched up with the predicted frequencies and ranges. With our finite element analysis completed, we solidified our design, and began to collect the strain energy of the system for use in the electrical design section.

Once the physical dimensions of the gyroscope had been finalized, the natural frequencies of interest (15872.9 Hz for drive mode and 15951.4 Hz for sense mode), as well as the maximum displacement of the proof masses, were used as input for Matlab code to calculate the amplitude of the necessary AC voltage for the drive mode transducer. Please see Appendix A for a copy of the rough draft of the code which has been submitted for review.

**Work Planned**

Before the end of the semester, the group plans to finish the sense mode theoretical calculations and use the completed electrical calculations to finalize the AutoCAD drawing for the mask to be used to manufacture the 1 cm x 1 cm gyroscope die. The group will also connect PCBs to use for testing gyroscopes and learn the procedure for testing the gyroscopes using the existing design.
Appendix A: MATLAB Code for Electrical Calculations

% Mechanical Structure Dimensions and physical properties
l=400*10^-6; %meters
w=400*10^-6; %meters
h=30*10^-6; %meters

freq1=15872.9; %drive mode frequency, Hz
freq2=15951.4; %sense mode frequency, Hz
omega1=2*pi*freq1;
omega2=2*pi*freq2;
q0=3.636*10^-6; %meters

viben = 1548.3364; %Strain Energy of mech structure, Joules
k=(2*viben)/(q0)^2; %spring constant of system
m= k/(2*pi*freq1)^2; %mass of proof mass

% Drive Mode settings
n=25; %number of fingers on proof mass
g=3*10^-6; %gap between proof mass fingers and comb drive fingers; meters
epsilon=8.854*10^-12; %permutivity of free space
V=40; %volts DC Voltage
Q=10000;
v0=(q0*k*g)/(2*n*epsilon*h*V*Q) %AC Voltage Amplitude

% Drive Mode confirmation
t=2*pi;
x=q0*sin(omega1*t);
%x=q0*exp(freq1*t);
I1=V*(2*n*epsilon*h)/(g)*omega1*x;%drive mode current

% Sense Mode
d0=3*10^-6; %gap between proof mass and transducer, meters
y=0.4*10^-6; %meters
I2=(epsilon*omega2*h)*(1-2*y)/d0;%sense mode current