ME –381 INTRODUCTION TO MICROELECTROMECHANICAL SYSTEM
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MEMS GYROSCOPES AND THEIR APPLICATIONS

A STUDY OF THE ADVANCEMENTS IN THE FORM, FUNCTION, AND USE OF MEMS GYROSCOPES

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INTRODUCTION

Gyroscope History

In order to discuss MEMS gyroscopes we must first understand gyroscopes in general and what role they play in science. Technically, a gyroscope is any device that can measure angular velocity. As early as the 1700's, spinning devices were being used for sea navigation in foggy conditions. The more traditional spinning gyroscope was invented in the early 1800's, and the French scientist Jean Bernard Leon Foucault coined the term gyroscope in 1852 [14]. In the late 1800's and early 1900's gyroscopes were patented for use on ships. Around 1916, the gyroscope found use in aircraft where it is still commonly used today. Throughout the 20th century improvements were made on the spinning gyroscope. In the 1960's, optical gyroscopes using lasers were first introduced and soon found commercial success in aeronautics and military applications. In the last ten to fifteen years, MEMS gyroscopes have been introduced and advancements have been made to create mass-produced successful products with several advantages over traditional macro-scale devices.

Traditional Gyroscope Function

Gyroscopes function differently depending on their type. Traditional spinning gyroscopes work on the basis that a spinning object that is tilted perpendicularly to the direction of the spin will have a precession. The precession keeps the device oriented in a vertical direction so the angle relative to the reference surface can be measured. Optical gyroscopes are most commonly ring laser gyroscopes. These devices send two lasers around a circular path in opposite directions. If the path spins, a phase shift can be detected since the speed of light always remain constant. Usually the rings are triangles or rectangles with mirrors at each corner. Optical gyroscopes are a great improvement to the spinning mass gyroscopes because there is no wear, greater reliability and smaller size and weight.

The Move to MEMS

Even after the introduction of laser ring gyroscopes, a lot of properties were desired. MEMS vibrating mass gyroscopes aimed to create smaller, more sensitive devices. The two main types of MEMS gyroscope, discussed in Micromachined Vibrating Gyroscopes: Design and Fabrication, are the tuning fork gyroscope and the vibrating ring gyroscope. In this paper, we will look at two other types of gyros; the macro laser ring gyroscope and the piezoelectric plate gyroscope.

Draper Tuning Fork Gyroscope

Advancements and Applications

One of the most widely used micro-machined gyroscopes is the tuning fork design from the Charles Stark Draper Lab (Fig 1). The design consists of two tines connected to a junction bar which resonate at certain amplitude.

When the tines rotate, Coriolis force causes a force perpendicular to the tines of the fork. The force is then detected as bending of the tuning fork or a torsional force (Fig 2). These forces are proportional to the applied angular rate, from which the displacements can be measured in a capacitive fashion. Electrostatic, electromagnetic, or piezoelectric mechanisms can be used to detect the force. [6]

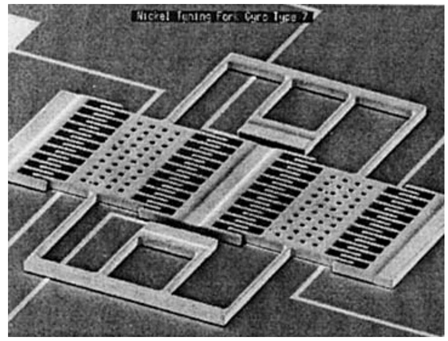


Figure 1 - The first working prototype of the Draper Lab comb drive tuning fork

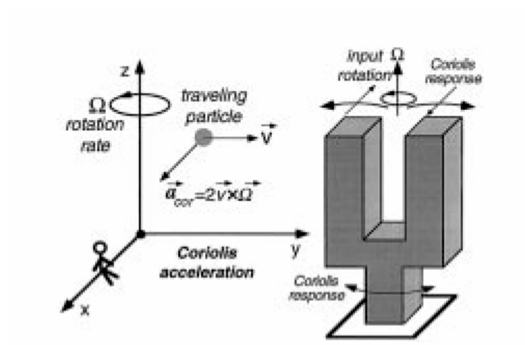


Figure 2: Tuning Fork Physics [6]

Since the development of their first tuning fork gyroscope in 1993, the Draper Laboratory has made significant improvements to the device. Their first gyroscope was developed for the automobile industry. The gyroscope had command of 1 degree/hr drift, and possessed 4000 deg/hr resolution. [4] These devices eventually functioned as the yaw rate sensor for skid control in anti-lock braking applications. Tests run on these sensors involve the examining the change in bias and error of such over a number of variables. Proper data could be retrieved in 0.8 s and sent to the necessary actuator to cause proper breaking in due time. These systems need to operate in a range of temperatures, specifically from -40 to 80 degrees Celsius. Over this range, both the bias error and the scale factor error are both quite stable. The bias error is approximately 2200 deg/h. Scale factor error was approximately 0.08%. Results from these tests are shown in Figure 3 and 4. [4]

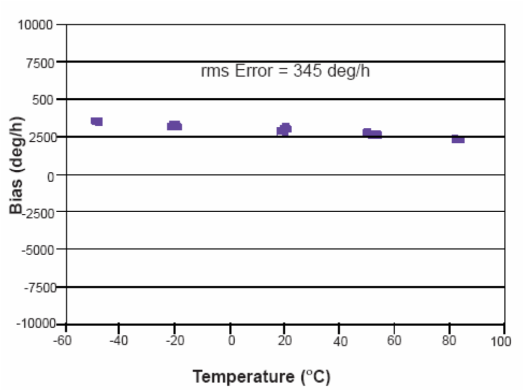


Figure 3: Bias vs. Temperature [4]

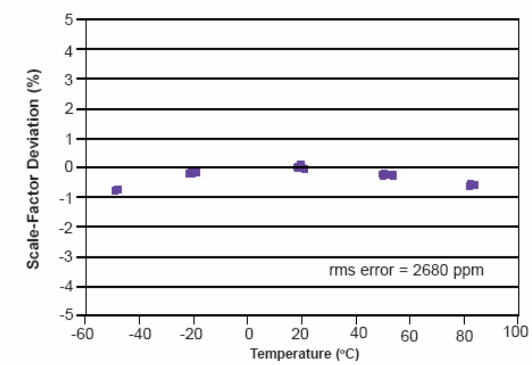


Figure 4: Scale Factor vs. Temperature [4]

Since this initial design, the performance of the tuning fork gyroscope and gradually increased. In 1994, a 500 deg/hr resolution was achieved. The designs in 1997 resulted in resolutions of 100 deg/hr. Drift stability improved an order of magnitude to 0.1 deg/hr. With these types of results, these gyroscopes can be implemented with near exact data replication and production. Along with the increased resolution, the input voltage noise was lowered significantly, leading to a stronger signal-to-noise ratio, providing sensors with the ability to communicate better with their devices. [5]

Piezoelectric Plate Gyroscope

Introduction

While vibrating ring gyroscopes and tuning fork gyroscopes were the first successful MEMS gyroscopes and are still the most widely produced, other successful MEMS gyroscopes have since been created. One of these gyroscopes is the Piezoelectric Plate Gyroscope which uses a PZT plate as its base. This method, which in the past has been used to try to build macro-scale gyroscopes, is actually ideal for micro devices. At micro levels, an entire plate can be made of piezoelectric material. It has advantages over the common vibrating gyroscopes in that it requires a much smaller drive voltage to create readable outputs.

Physical Description

The piezoelectric plate gyroscope is very simple in its design. In fact, it is much simpler than the ring or fork gyroscopes. There is a piezoelectric plate, which has a length and width much larger than its depth. The plate has electrical leads connected to all 6 sides and sits on top of a thin membrane of a cavity in a silicon wafer. The cavity allows more freedom for the PZT to vibrate and deform. The leads provide the driving voltage and measure the output.

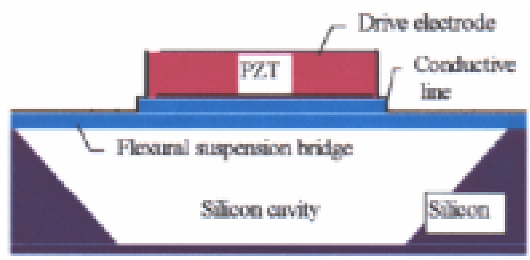
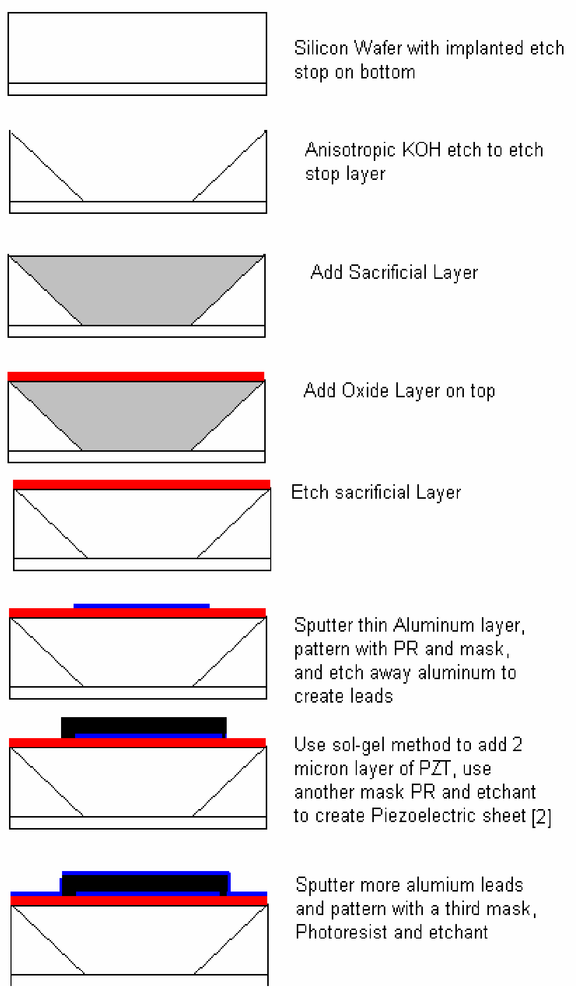


Figure 5: Cross Section of Gyroscope [8]

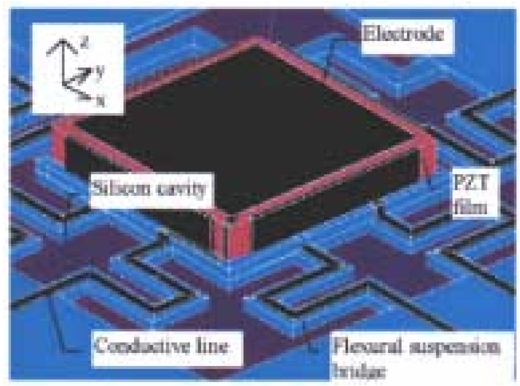
Fabrication

The following diagrams show a basic fabrication process that could be used to create the piezoelectric gyroscope. To save space not every step is shown.



Functional Description

Like other MEMS gyroscope the piezoelectric plate gyroscope works on the principle of a vibrating body. In this case, the vibrating body is a piezoelectric sheet. The sheet does not vibrate like a plate or fork. Instead the thickness vibrates which oscillates with time. This requires an AC driving voltage applied vertically across the plate, which uses the electro-mechanical properties of the PZT to create the vibration. Any piezoelectric material can be used, but PZT has high piezoelectric constants, and can be added at a precise thickness.



[8]

Figure 6: Piezoelectric Plate with orthogonal directions shown

When the vibrating plate is rotated about an axis perpendicular to the drive voltage, a voltage is produced in the third perpendicular direction. This output voltage is proportional to the angular velocity. It can be proven that the relationship is:

$$V_{Out} = -\frac{K}{\varepsilon_{11}^T}\frac{ac}{4}\left(d_{33} + |d_{31}|\frac{a^2}{c^2}\right)d_{15}$$

$$\cong \frac{V_A \rho\, \omega \cos \omega\, t\; a^3}{\varepsilon_{11}^T}\frac{}{4c}|d_{31}|d_{15}\Omega .$$

[8]

Here V_A is the input voltage magnitude, ρ is the PZT density, ω is the input voltage frequency, t is time, a is the plate length perpendicular to the direction of rotation, c is the plate thickness, d_{31} and

d_{15} are piezoelectric constants, ε_{11} is the permittivity constant and Ω is the angular velocity.

Since the plate has x-y symmetry as shown above, it follows that a single plate can measure rotation in two directions. This is an added advantage when compared to traditional gyroscopes, which only measure one direction of rotation.

Extensive testing has been conducted on piezoelectric plate gyroscopes and the following data has been determined. For a gyroscope with properties:

Specifications	
Piezoelectric material	$Pb(Zr_{0.54}Ti_{0.46})O_3$
Density	7.5×10^3 kg m^{-3}
Piezoelectric constant d_{31}	700×10^{-12} m/V
Piezoelectric constant d_{15}	270×10^{-12} m/V
Permittivity $\varepsilon_{11}^T/\varepsilon_0$	3250
Plate length a	1000 μm
Plate width b	1000 μm
Plate thickness c	2 μm

The resulting attributes are as follows:

Measuring conditions and performance	
AC drive voltage V_A	1 V
Source frequency	100 kHz
Lock-in amplifier A_K	10 000
Thermal sensor noise	$< 1 \times 10^{-3}$ V
Maximum output voltage	5 V
Sensitivity ($A_K V_{out} / V_A / \Omega$)	0.0387 V/V/(deg/sec)
Accuracy	2.58×10^{-2} deg/sec
Range	129.2 deg/sec

[8]

Conclusion

The piezoelectric plate gyroscope is a feasible alternative to traditional MEMS gyroscopes. One of its advantages is a lower required drive voltage. However, the sensitivity is only about 38 microvolts, whereas the sensitivity of a ring gyroscope is around 200 microvolts [10]. Also, when there is no rotation, traditional gyroscopes come much closer to the ideal zero volts output than the piezoelectric plate gyroscope, which still outputs up to 100 millivolts.

A major advantage and the one that could prove most practical is the versatility of the piezoelectric plate gyroscope. It can measure rotation in two directions. In addition, if the driving voltage direction is switched, the same device can measure rotation in the third direction, although with much less sensitivity. Since this device is easily incorporated into other IC chips, it could be controlled to do more things than a ring or tuning fork gyroscope, which require three gyroscopes to measure three rotation directions.

Laser Ring Gyroscopes

In order to discuss the difficulties in creating a laser ring gyroscope in the micrometer scale, the theory behind the macroscopic gyroscope must be derived. Below is a picture of a simple laser gyroscope that happens to be in the shape of a triangle rather than a ring. A laser source outputs two beams traveling in an opposite direction around the ring until they reach the detector. The detector counts the beat frequency of the combined light wave. This beat frequency is directly proportional to the angle of rotation of the gyroscope.

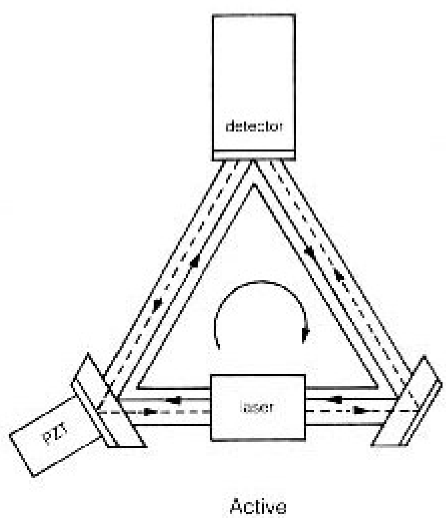


Figure 7: General Ring Laser Gyro

The following formula is derived for any constant laser ring gyroscope [1].

(2) $\Delta\nu = \frac{4A}{\lambda p}\Omega$

A = area of ring

P = perimeter of ring

There are two main sources of error for laser ring gyroscopes. They are varying offset bias and a dead band at very small rotation rates. The offset bias is due to different indices of refraction for the beam pairs. This is caused by small differences in the degrees of saturation in the original beams. [2]

Diddams, Atherton and Diels experimented with a light scatterer placed in the laser pulses at different distances from the detector while keeping the gyroscope at rest. This scatterer represented a reflection of light particles back with the beam traveling the other direction. They found that when the scatterer was more than 500 microns away from the detector, the beat frequency was constant and stable. The width of the dead band also showed good consistency through many tests. When the scatterer was within 100 microns, the beat frequency became nonsinusoidal and therefore very hard to measure. When the scatterer was placed within 10-30 microns of the detector, the beat frequency was erratic and non-continuous.[2]

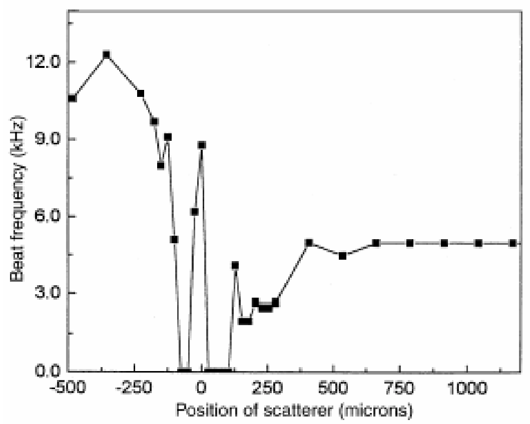


Figure 8: Beat Frequency vs. Scatter Position

The dead band region is another limiting factor for this type of sensor. When you are at very small turning rates, the frequencies of the two light waves are very close to each other. When these frequencies are within a critical value, it creates a phenomenon where the frequencies converge toward each other until they are the same. This gives you a false reading of a zero turning speed when you are actually moving at a small angular velocity. [2]

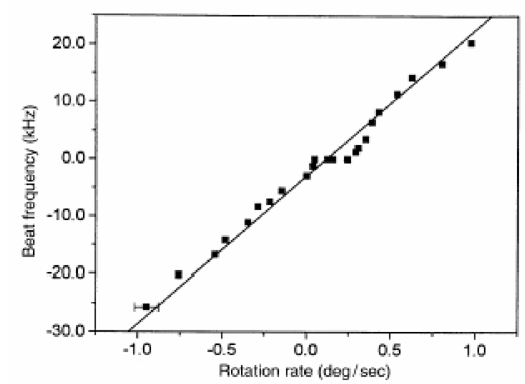


Figure 9: Rotating Rate found by using Beat Frequency

The following formula gives the dead band (flat part on Figure 9) for a laser ring gyroscope.

(3) $$\Omega_L = \frac{r\lambda c}{2A}$$

r - backscattering amplitude for material

Micro-Laser Gyro

The miniaturization of a macro-laser ring gyroscope poses many problems. The largest problem is with scaling the device down to the micrometer level. The following equation is the equation relating the beat frequency to the angular velocity of the gyroscope. [2]

(4)

$$\frac{\psi}{2\pi} = \nu_{\text{bias}} + \frac{\mathscr{R}\Omega}{2\pi} - \frac{c}{2\pi P}\left\langle \frac{r_1(\tau)\mathscr{E}_1}{\mathscr{E}_2}\sin(\psi - \varepsilon_1) + \frac{r_2(\tau)\mathscr{E}_2}{\mathscr{E}_1}\sin(\psi + \varepsilon_2)\right\rangle.$$

This formula scales in the following way:

Beat Freq = (S)* Angular Velocity - 1/S

The scale in the example used a perimeter of 4.84 meters. This would have to be lowered by a factor of 10^{-4} at least to put it at 400 micrometers. This would increase the size of the interference due to backscattered light (1/S) by 10^4. It would also provide less angular velocity sensitivity per beat frequency by a factor of 10^{-4}. This would in turn affect the dead band as seen in equation 2.

Dead Band = 1/S^2

Using the same scaling as in the above example, the resulting dead band is 10^8 times bigger. Instead of getting .25 deg/s drift, a $.25*10^8$ deg/s drift results using the same wavelength of light.

Now consider changing the wavelength of light. If the wavelength of light is decreased to provide the same dead band as in the previous example, a wavelength that is 10^{-14} meters, on the range of gamma rays, results. These gamma rays are very high energy and would have to be shielded from any kind of human interaction. This would make the device very complicated and expensive for the same quality as a macroscopic laser gyro. This would not be competitive with the other MEMS gyroscopes explained previously in price or performance.

Another problem arises with trying to change the frequency to account for a large dead band. The time varying part of the equation would be multiplied by 10^4 no matter the frequency of light produced. This creates a time dependant bias frequency that is very difficult to account for in order to get the correct beat frequency as shown in Figure 8 defined by the large peak very close to the detector. In fact this is only the average beat frequency because the frequency is changing rapidly and never settles at a final value. [2]

Absolute Angle Measurement using MEMS Gyroscope

Introduction

Measuring the angle using a typical MEMS gyroscope over a period of time is not possible by integrating the angular rate, due to the presence of bias errors which would cause a drift. An innovative design of a vibrating gyroscope is being developed which would directly measure both angle and angular rate. The design is based on the principle of measuring the angle of free vibration of a suspended mass with respect to the casing of the gyroscope. [11]

Background workings of an angular rate MEMS gyroscope

A traditional vibrating mass gyroscope consists of a mass suspended by elastic members that allow it to travel in both x and y direction as shown in figure 10. The equations of motion for such a system once appropriately compensated can be approximated as shown below.

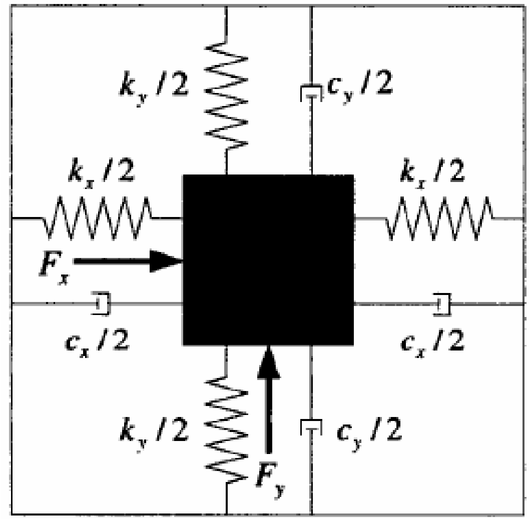


Fig. 10: Schematic drawing of a suspended mass vibratory gyroscope [12]

$$\ddot{x} = -\omega_x^2 x - \frac{c_x}{m}\dot{x} + 2\dot{\theta}\dot{y} + \frac{F_x}{m}$$

$$\ddot{y} = -\omega_y^2 y - \frac{c_y}{m}\dot{y} - 2\dot{\theta}\dot{x} + \frac{F_y}{m}$$

[12]

When experiencing an external angular velocity the $2\dot{\theta}\dot{x}$ term in the 2nd equation causes the y mode to vibrate at the driven frequency with amplitude that is proportional to the angular rate. The value of the angular rate can then be obtained by demodulating the y output signal.

Angle Measurement

The design for angle measurement is based on the principle of measuring the angle of free vibration of the suspended mass with respect to the casing of the gyroscope. The mass is given an initial condition so that it vibrates in a know direction. The angle, θ, in the global frame can be calculated by keeping track of the direction of vibration if the mass in the local frame, given by the angle α, as shown in Figure 11. When the gyroscope is rotated in the global frame the mass continues to vibrate in the same direction with respect to the global frame. [11]

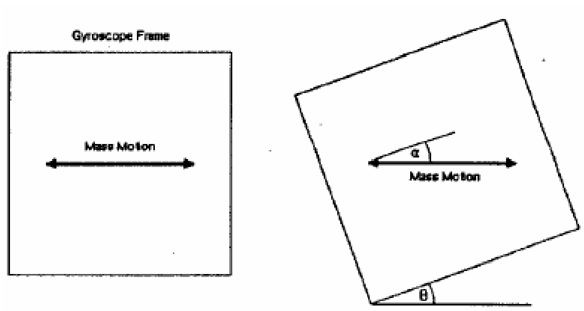


Fig. 11: mass motion with initial x-axis oscillation [11]

The method relies on the free vibration of the mass; therefore the effects of damping forces must be negated as it would drive the motion of the mass to zero. Energy is supplied using actuators, which deliver small forces to the x and y modes proportional to the respective velocities. These forces counteract the effect of damping in the system. Due to various difficulties a fixed force cannot be selected for this purpose. A control loop is used instead to keep the total energy of the system constant. The forces counteracting the damping of the system are continuously adjusted using the equations stated below:

$$F_x = \alpha\left(E - \frac{k_x}{2}x^2 - \frac{m}{2}\dot{x}^2 - \frac{k_y}{2}y^2 - \frac{m}{2}\dot{y}^2\right)\dot{x}$$

$$F_y = \alpha\left(E - \frac{k_x}{2}x^2 - \frac{m}{2}\dot{x}^2 - \frac{k_y}{2}y^2 - \frac{m}{2}\dot{y}^2\right)\dot{y}$$

where E is the energy set point and represents the instantaneous energy of the system and α is a constant positive gain:

$$E = \left(\frac{k_x}{2}x^2 + \frac{m}{2}\dot{x}^2 + \frac{k_y}{2}y^2 + \frac{m}{2}\dot{y}^2\right)$$

[11]

a steady state of energy function can be achieved close to the desired energy by selecting an appropriate positive value for α.

Angular Rate Measurement

In order to measure the angular rate a sinusoidal excitation (ω_d) is added to the steady state equation for the x-axis force defined earlier, while the y-axis force remains the same.[11]

$$F_x = \alpha\left(E - \frac{\hat{k}_x}{2}x^2 - \frac{m}{2}\dot{x}^2 - \frac{\hat{k}_y}{2}y^2 - \frac{m}{2}\dot{y}^2\right)\dot{x} + F_d \sin(\omega_d t)$$

When the system undergoes an angular rotation, the excitation term in the x-axis equation causes vibrations along the y-axis at the driven frequency of ω_d. The value of the angular rate can then be obtained by demodulating the y-axis motion at the driving frequency.

In the above system, the x and y signals obtained from the gyroscope need to go through a separate band pass filter at the natural frequency in order to determine the angle value. When running the gyroscope at both its natural frequency and the driving frequency the relative amplitude of the oscillation at the two frequencies becomes important. Therefore it is necessary to endure that the driving frequency is at least an order of magnitude different from the natural frequency.

Conclusion

Contrary to the popular designs of MEMS gyroscopes which can only measure the angular rate and not the angle due to presence of bias errors, the above mentioned design can accurately measure the angle of rotation. In order to make a reliable and practical sensor a composite nonlinear feedback control system is used to compensate for imperfection induced in the design during the manufacturing process. Thus this gyroscope can accurately measure both angle and angular rate for low bandwidth applications. [11]

Applications

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Gyroscope-based sensor embedded in a shoe insole

A gyroscope based gait-phase detection sensor (GPDS) is used in conjunction with a programmable functional electrical simulation (FES) to help people with a dropped-foot walking dysfunction. The GPDS is entirely embedded in the shoe insole and detects in real time the four phases during the gait cycle; stance, heel off, swing and heel strike. The gyroscope in the GPDS measures the angular velocity of the foot and the three force sensitive resistors measure the force load at 3 different locations. The gait-phase signal is processed in the embedded microcontroller and then transmitted in real time to the electrical stimulator attached to the affected muscles. The electrical stimulations induce muscle contractions in the paralyzed muscles leading to a more physiological motion of the affected leg.

Previous versions of the gait-phase detectors had been insufficiently reliable in everyday use as they would be affected by non-walking activities like standing, shifting the weight from one leg to another, sitting, etc. Therefore those designs had to be turned on and off to avoid stimulations during non-walking activities. Also the gyroscope in this device can be effectively used to measure the angle of the foot relative to the ground and since there is a built in reset mechanism it avoids the accumulation of drift errors in the integrated system.

Tests conducted with the system show positive results. The GPDS works robustly on different types of terrains with an accuracy level of over 96%, increasing comfort and confidence the user has in the system. The GPDS has helped users with dropped-foot walking dysfunctional to effectively walk faster while feeling safer and less tired at the same time. Figure 13 shows by illustration the how the FES reduces the excessive plantar flexion of the foot during the swing phase and provides a better clearance. [13]

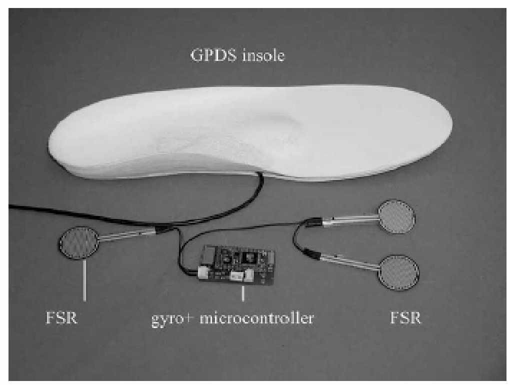

Fig 1 GPDS and the embedded components [13]

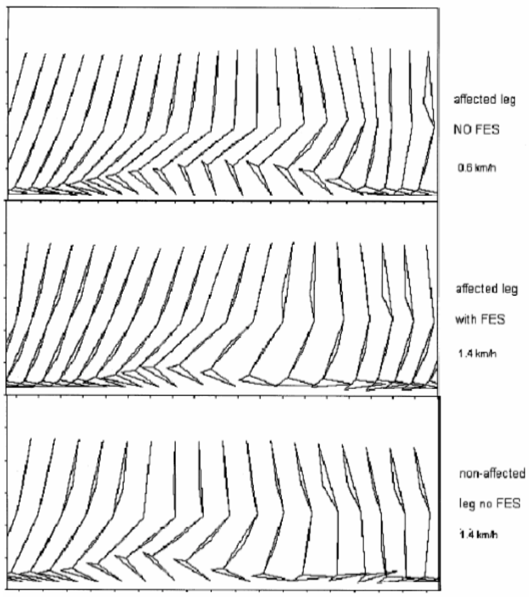

Fig 13: Illustration of the foot position during a gait-cycle under various conditions [13]

GPS Sensors

With the advancements made on the Draper tuning fork gyroscope, it became obvious that this device could be used for more intricate devices such as guided military munitions and exact Global Positioning Devices. Not only are these devices considerably accurate at determining positioning and rates of motion, they are also low cost to manufacture and due to their scale, easy to implement in many military operations. Currently, the Draper Laboratory is working in part with the Competent Munitions Advanced Technology Demonstration Program from the Office of Naval Research. The object is to design a munition that is fully GPS aided and is able to fly inertially to prevent countermeasures or signal jamming from either detonating the explosive early, or running it off course. A MEMS gyroscope is implanted in the fuse assembly of the warhead to sense direction. Joined with an accelerometer, the system is able to control its flight with little adverse conditions. [7]

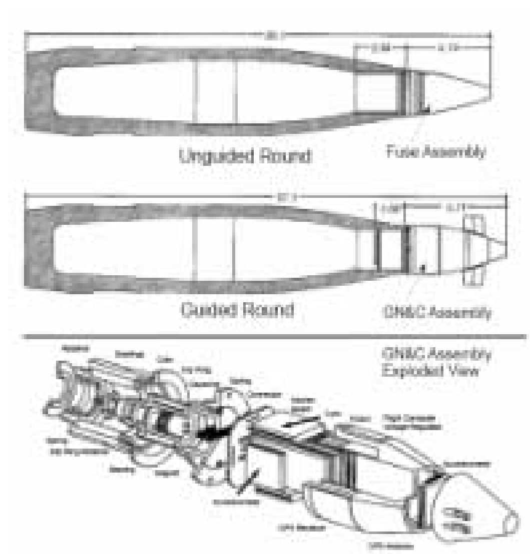

Fig 14: GPS guided munitions [7]

Inertial Measurement Unit

Honeywell has also used the Draper tuning fork gyroscope design for their technology. In 1999, Honeywell acquired the Draper lab technology in MEMS gyroscope design. One of Honeywell's major programs is the development of an Inertial Measurement

Unit, a unit that can measure the rates of motion and displacements of an object in action. At the time, they had been using macroscale gyroscopes, specifically, the ring laser gyroscope. This gyroscope was implemented in the HG1700 system which could function properly and beyond the original requirements for which it was planned. However, this device was too costly, too large, and too high performance for the emerging smaller, gun-launched systems. By acquiring Draper's tuning fork gyroscope, a new inertial measurement unit could be developed that was cheaper and smaller. Eventually, the HG1700 system was integrated with MEMS gyroscopes from the Draper laboratory, replacing the ring laser gyroscope clusters. These systems functioned similarly to their predecessors, with the exception that they could be made smaller at an economical cost. Soon after, the HG1910 was developed with the use of Honeywell designed gyroscopes, utilizing similar techniques taken from the Draper laboratories. This unit was designed to withstand the rigors of an in-combat environment. The table below shows the specifications of the HG1920 which is currently used in combat. [7] Figure 15 shows the exploded view of the HG1920.

HG1920 Specifications		
Parameters	Goals	Delivered Performance
Size	<8 cu in	7.4 cu in
G-Survival	>10,000 G	>10,000G
GYRO CHANNEL		
Operational Range	1440 deg/s	1440 deg/s
Bias, Turn-on error stability	=75 deg/hr	9 – 76 deg/hr
Bias, In-run Error Stability	=50 deg/hr	6 -53 ged/hr
Angle Random Walk	=0.5 deg/vhr	0.02 – 0.17 deg/vhr
Scale Factor Turn-on Error	=750 ppm	91 – 524 ppm
Scale Factor In-Run Stability	=1000 ppm	90 – 516 ppm
G Sensitivity	=10.0 deg/hr/g	=10.0 deg/hr/g
Misalignment	=1200 µ-rad	81 – 479 µ-rad

Figure 15: Exploded View of HG1920

Conclusion

MEMS gyroscopes could be the next big success story after accelerometers. Multiple different techniques of producing gyroscopes were discussed in this paper along with a few applications. There is still a lot of room for improvement in current techniques, especially in reducing drift and increasing sensitivity. We believe there will be countless other applications discovered for MEMS gyroscopes in the coming years due to their versatility and size.

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Biographical Sketches

Aaron Burg (6/30/1983) is a mechanical engineering undergraduate student from Cleveland, Ohio. He is an active participant in intramural ultimate Frisbee. In addition, he is an avid music connoisseur. Someday in the future he will be known only as Dr. Burg and will be a respected member of his community.

Azeem Meruani (11/29/1982) is a mechanical engineering undergraduate student from Karachi, Pakistan. He is an entrepreneur, who seeks innovative ways of video game enjoyment. He plans on continuing his engineering education and someday taking over the world.

Bob Sandheinrich (3/31/1983) is a mechanical engineering undergraduate student from St. Louis, Missouri. His experience includes a long line of menial jobs. He plans include never finding a job and being a bum on the streets of Evanston. If you see him, please give him a quarter.

Michael Wickmann (9/9/1982) is a mechanical engineering major from Northfield, Minnesota. He is currently the oldest member of the group. He is a leading member of the university club baseball team and is a ferocious athlete in many other sports. He will work for Azeem someday.