

A Micromachined Vibrating Ring Gyroscope

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Abstract

A new micromachined gyroscope based on a vibrating ring is described. The device measures rotation rate or whole angle inertial rotation by monitoring the position of node lines in a vibrating ring. To sense rotation, the ring is electrostatically forced into an elliptically shaped vibration mode and the position of the node lines are capacitively monitored. When the device is subjected to rotation, the node lines, lag behind the rotation due to the Coriolis force. The control and readout circuitry monitors this lag and develops a corrective voltage, that is proportional to the rotation rate, to hold the position of the node lines fixed. The device is fabricated using a low-cost process based on metal electroforming techniques that allows large amounts of circuitry to be included with the sensor. A resolution of approximately $0.5^\circ/\text{sec}$ in a 10 Hz bandwidth, limited by the on-chip electronics, has been obtained with this new sensor. Further improvements in the on-chip electronics and sensor materials are expected to push the resolution to below $0.5^\circ/\text{sec}$ in a 50 Hz bandwidth.

Introduction

Gyroscope devices for measuring angular rotation or rotation rate have been the subject of extensive research and development over the past several decades. With the development and proliferation of low-cost miniature silicon micromachined accelerometers, attention is naturally turning to the development of a low-cost companion micromachined gyroscope since many applications exist for these devices. Some of the applications being considered for these miniature devices include: automotive applications such as traction control systems and ride stabilization systems; consumer electronic applications such as video camera stabilization and model aircraft stabilization; computer applications such as an inertial mouse; as well as robotic applications; and military applications [1]. Generally the requirements for these sensors are a resolution between $0.1^\circ/\text{sec}$ to $1^\circ/\text{sec}$, a full scale range of $50^\circ/\text{sec}$ and a response bandwidth of 50 Hz at a cost of 10\$ to 20\$ per sensor. Given the large number of potential applications for medium performance gyroscopes many groups are currently developing micromachined designs to meet this need [2,3].

Over the years many different gyroscope concepts have been conceived and successfully developed. The traditional gimballed spinning wheel and the ring laser gyroscope are two well-known designs that have been widely applied and proven in inertial navigation applications [4]. Although highly accurate, these devices are currently too expensive for many of the low-cost applications. Some low-cost fiber optic gyroscopes are currently under development but it is uncertain whether these devices can meet the cost goals of many applications even in large scale production volumes [5]. Another class of successful gyroscope designs, known as vibratory gyroscopes, use vibrating mechanical elements to sense rotation [6]. Although less well known, these devices find many applications in the medium performance range and one vibratory gyroscope, the Hemispherical Resonator Gyroscope (HRG) [7], has achieved inertial navigation performance levels rivaling and even exceeding that of the best ring laser gyroscopes. Almost universally when low-cost is the goal, gyroscope devices are based on vibrating mechanical elements due to their simple structure. Since vibratory gyroscopes have no rotating parts that require bearings they can be readily miniaturized and batch fabricated using micromachining techniques to produce a low-cost device. Furthermore, with the precision of micromachining techniques it is still possible to produce a

medium to high performance device. For these reasons most groups are basing their micromachined designs on vibrating mechanical elements.

In this paper we present a new low-cost micromachined vibratory gyroscope based on a vibrating ring that is designed for medium performance applications [8]. To understand the operation of this device we first review the principles of vibratory gyroscopes using the familiar Foucault pendulum to present these concepts. We then discuss the various types of vibratory gyroscope designs to get a clearer understanding of the advantages and disadvantages of the ring design. After this the more detailed design and fabrication of the ring gyroscope is presented emphasizing the reasons for choosing the ring design for a micromachined device. We next discuss the operation of the sensor with its closed loop electronics. Experimental results are then reported for the rotation response of the sensor and electronics followed by some concluding remarks.

Vibratory Gyroscope Principles

Vibratory gyroscopes use the Coriolis acceleration or force that arises in rotating reference frames to sense rotation. Similar to the centrifugal acceleration, familiar to all amusement park lovers, the Coriolis acceleration is one of the accelerations that are used to describe motion in a rotating reference frame and accounts for radial motion. Its effects must be considered in many phenomena where rotation is involved and can even account for the differences in the motion of air over the earth's surface in the northern and southern hemispheres. To understand how vibratory gyroscopes use Coriolis acceleration it is instructive to first examine a simple vibratory device, the well known Foucault pendulum [9]. This discussion provides the base for understanding the principles of vibratory gyroscopes in general and the ring gyroscope in particular. During the discussion the normal mode method for modeling vibratory gyroscopes is introduced and discussed [10]. Later this model is used to describe the operation of the ring gyroscope. Three ways of operating vibratory gyroscopes are then presented and discussed in terms of the normal mode model followed by a discussion of desired characteristics of vibratory gyroscopes to achieve the best performance.

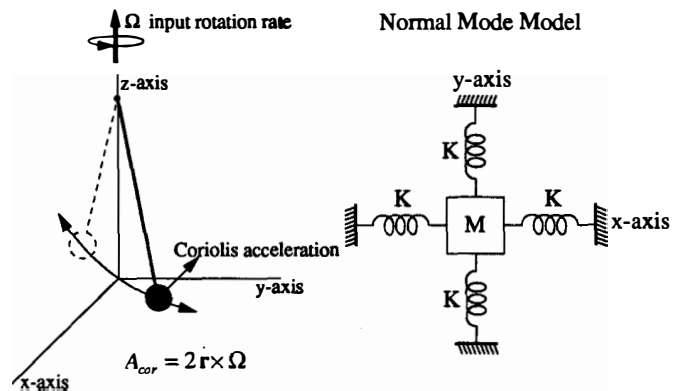


Figure 1 Foucault pendulum and normal mode model

Foucault Pendulum and the Normal Mode Model

In 1851 the French scientist Leon Foucault used a large pendulum to study earth's rotation. As the earth rotated under the pendulum, the plane of the pendulum's swing appeared to rotate or precess at a rate equal to earth's vertical rotation rate. Foucault correctly reasoned that the Coriolis acceleration due to earth's rotation caused the precession of the pendulum. Mathematically this precession phenomenon can be modeled by two independent harmonic oscillators that are coupled by the Coriolis acceleration as shown in Figure 1. This method of describing the Foucault pendulum is known as the normal mode method in vibration theory and the independent oscillators are called the normal modes of the system [10]. In this model the pendulum's swing is resolved into two orthogonal amplitude components x and y , one for each oscillator or normal mode. The path of the pendulum's swing is then obtained as a linear superposition of these two independent motions.

How Coriolis acceleration causes precession in this model can be understood as follows. Consider the case when the pendulum's swing is initially aligned with the x -axis. At this time all the energy or amplitude of vibration is stored in the first normal mode. In the absence of rotation the pendulum swing would stay aligned with the x -axis and all the stored vibration energy would remain in the first normal mode. However, under rotation the normal mode equations reveal that the Coriolis acceleration will transfer energy between the two normal modes causing the pendulum to precess. Solving the normal mode equations for the case of constant rotation shows that the pendulum would precess at a constant rate equal to the rotation rate. This principle of the transfer of energy between two vibration modes of a structure caused by the Coriolis acceleration is the basic operating principle underlying all vibratory gyroscopes [6].

Modes of Operation

So far we have considered the case when the pendulum swing is allowed to freely move under rotation. In this mode of operation, called the whole angle mode, the pendulum operates as a rate-integrating gyroscope and measures the angle of rotation. Vibratory gyroscopes including the Foucault pendulum can also be operated as rate gyroscopes to measure rotation rate in an open-loop or force-to-rebalance mode.

To measure rotation rate, the pendulum would be continuously driven to a fixed amplitude in the first vibration mode along the x -axis. In the absence of rotation there would be no vibration amplitude in the second mode along the y -axis. Under rotation, however, the Coriolis acceleration will cause energy to be transferred from the first mode to the second mode. In the open-loop mode of operation the second-mode amplitude is allowed to build up to a steady state value and provides a measure of the rotation rate. In the force-to-rebalance mode of operation the secondary vibration amplitude is monitored and continuously driven to zero by applying the necessary force along the y -axis to rebalance the Coriolis acceleration. Which operating mode is used in a particular vibratory gyroscope depends on the application and the particulars of the device design.

Design Goals

All vibratory gyroscopes are based on the rotation-induced transfer of energy between two vibration modes of the structure. Independent of the mode of operation, highest performance for vibratory gyroscopes is obtained when these two vibration modes have the same natural frequency and a long damping time or high quality factor [6]. When this is the case, the response to the very small Coriolis acceleration is amplified or multiplied by the quality factor of the resonance which can exceed 50,000, thereby improving the overall sensor performance. Not all vibratory gyroscopes use this principle of matched vibration mode frequencies in their design. Tuning fork designs, for example, often do not match the resonant frequencies of their two vibration modes and still achieve good performance. They do this by careful design that involves detecting small motions. However, the highest performance vibratory gyroscope, the HRG, has used this principle of matched frequencies to achieve inertial-navigation performance levels demonstrating the potential of this design principle [7].

The design goal of matching the vibration mode frequencies is most easily obtained in symmetric structures that naturally have two identical modes of vibration such as the Foucault pendulum or the vibrating shell designs discussed shortly. To obtain a long damping

time for these devices, isolated structures that do not radiate acoustic energy and which are fabricated from low-loss materials are desirable [11]. Also, the damping time is increased as the resonant frequency of the structure is lowered. Consequently, lower natural frequency structures are desirable as well, however, the natural frequency of the structure is generally chosen to be above the environmental noise to improve vibration sensitivity. In this paper we describe a new micromachined vibratory gyroscope design that uses these principles.

Types of Vibratory Gyroscopes

Vibrating elastic bodies can sense rotation just as the Foucault pendulum and many different designs for these structures have been developed. These vibratory gyroscope designs generally fall into one of five classes; vibrating prismatic beams, tuning forks, single or dual accelerometers, vibrating shells, and rotated piezoelectric crystals [6,12]. Each of these classes are represented by commercial or research devices with the highest performance belonging to the vibrating shell class. Since the rotating piezoelectric crystal devices use bearings that are currently unavailable in micromachining technology, this class of devices will not be discussed further. To put the ring gyroscope into perspective, examples of each of these other classes will be discussed highlighting the advantages and disadvantages of each class.

Vibrating Prismatic Beams

Probably the simplest vibratory gyroscope is the vibrating rectangular beam that operates like the Foucault pendulum and uses the two identical primary bending modes of the beam to sense rotation (Fig. 2). Experience with these devices has revealed that they are difficult to mount, have large temperature sensitivities due their construction, and are sensitive to spurious vibrations [12].

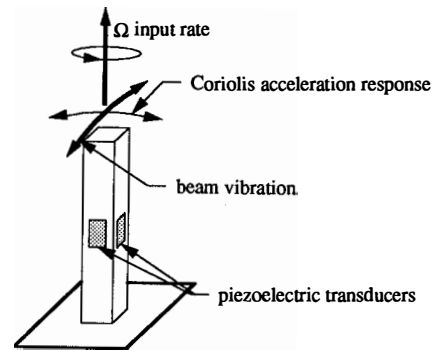


Figure 2 Vibrating prismatic beam gyroscope

Tuning Forks

To overcome the difficulties encountered with vibrating beam gyroscopes, designers have worked with gyroscopes based on tuning forks which being balanced devices are easy to mount and not sensitive to linear vibrations. In operation, the tines of the tuning fork are differentially driven to a fixed amplitude and, when rotated, the Coriolis acceleration causes a differential sinusoidal force to develop on the individual tines orthogonal to the main vibration (Fig. 3). Depending on the design of the device, this force is detected either as differential bending of the tuning fork tines or as a torsional vibration of the tuning fork stem. Due to fabrication difficulties and temperature drift problems, the input and output mode natural frequencies of tuning fork gyroscopes are generally not matched, limiting the device sensitivity [6]. Another problem encountered with tuning fork gyros is large bias errors caused by a misalignment of the mass centers of the individual tines [6]. If the centers of mass are not precisely in the plane of the tine vibration, their inertia produces a vibration response that is indistinguishable from the Coriolis acceleration. To minimize this error, tuning fork devices are often individually mechanically trimmed. In spite of these difficulties a high-quality micromachined quartz device is available from Systron Donner and a silicon-micromachined device has been developed by Draper Labs with impressive sensitivity [3].

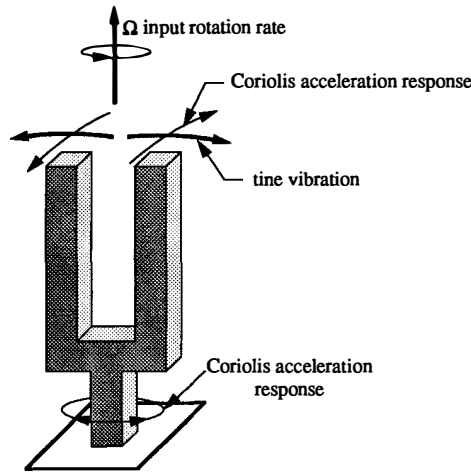


Figure 3 Tuning fork vibratory gyroscope

Single and Dual Accelerometers

Dual-accelerometer gyroscopes are essentially tuning fork gyroscopes whose tines are constructed from identical accelerometers (Fig.4). These devices are operated by vibrating the accelerometer proof masses antiphase in one plane and measuring the resulting differential Coriolis acceleration in an orthogonal plane. Since this class of devices is so similar to the tuning fork class, they share many of the same advantages and disadvantages, although, they can also measure acceleration, which is an important advantage in many applications. For less demanding applications a single accelerometer can be used to measure the Coriolis acceleration but like the prismatic beam this device is more sensitive to spurious vibrations.

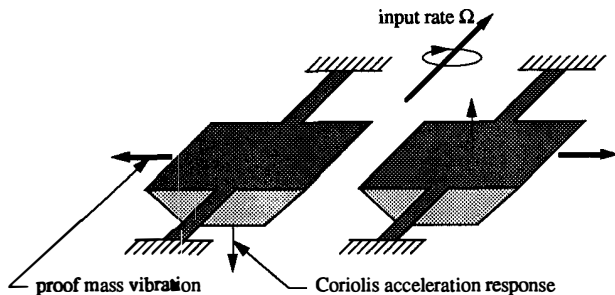


Figure 4 Dual accelerometer vibratory gyroscope

Vibrating Shells

Tuning fork gyros are based on the rotation-induced transfer of energy between two different vibration modes of the structure. This can cause the device to have low sensitivity or a large temperature drift. In contrast, vibrating-shell gyroscopes transfer energy between two identical modes of the structure just as the Foucault pendulum does, thus avoiding these problems [6,7,12]. Because of their shape, vibrating shells have two identical modes of vibration with nominally equal resonant frequencies. They may be shaped like a wine glass (HRG), like a cylinder, or like a ring [6]. Although the vibrating disk is not, strictly speaking, a vibrating shell it can be included in this category as well [12].

The rotation sensing principles of the vibrating-shell gyroscope were first analyzed by G. H. Bryan in 1890 and are best illustrated by the ringing wine glass vibrating in its fundamental flexural mode shown in Figure 5 [13]. In this mode of vibration, the lip of the wine glass vibrates in an elliptical-shape mode that has two nodal diameters. When the wine glass is rotated, the node lines lag behind the rotation or precess much like the swing of the Foucault pendulum precesses. During a 90° rotation, the node lines are observed to precess by about 27°. The precession rate is a geometric constant

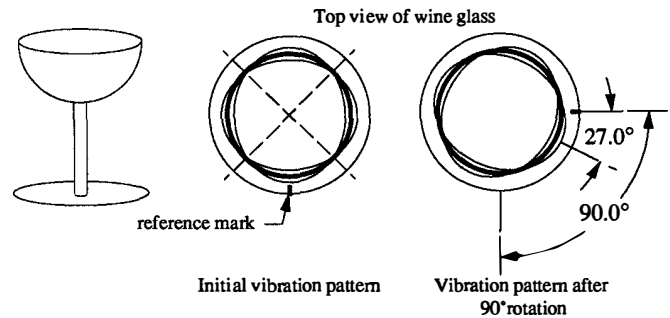


Figure 5 Vibrating shell gyroscope

for each type of vibrating shell gyroscope-called the angular gain-and is approximately 0.3 for a wine glass.

Due to their shape, vibrating-shell gyroscopes are inherently rugged but are still highly sensitive to rotation. They are less sensitive to spurious vibration than other vibratory gyroscopes for, ideally, spurious vibrations do not couple to the shells identical vibration modes. Only when the shells have mass or stiffness asymmetries, can environmental vibrations induce a spurious response. Vibrating shell gyroscopes can be operated in either the whole angle, the open-loop, or the force-to-rebalance mode depending on the demands of the application [1,6,7,12].

Device Description

Given the many advantages of vibrating-shell gyroscopes, we chose to develop a micromachined, vibrating-shell gyroscope to explore the potential of such a device. After some consideration we based our device on a vibrating ring; rather than a hemisphere, cylinder, or disk, as micromachining versions of the other shapes can be problematic. Although hemispherical wine-glass shapes can be micromachined, it would be difficult to fabricate attached versions of these structures with the associated capacitive drivers and pickoffs in a batch process. Furthermore, to obtain low natural frequencies with long damping times, cylinder structures would require very tall, thin walls that demand special, expensive fabrication techniques such as LIGA. The main difficulty found in fabricating these two structures is their three-dimensional nature which demands special micromachining techniques. Although disk structures are more two dimensional, they would still have to have very large diameters to obtain reasonable natural frequencies as their vibration mode is primarily extensional. In contrast, the ring structure that we have developed is a small quasi-two dimensional device that can be easily batch fabricated, thus avoiding the difficulties associated with these other structures. As we shall see, the ring gyroscope can be fabricated with a simple inexpensive process using conventional process equipment based on electroforming.

The ring gyroscope, shown in Figure 6, consists of three main elements; the ring itself, the support springs, and the drive pickoff and control electrodes [8]. Like the vibrating wine glass device, this device uses the two primary flexural vibration modes of the ring to sense rotation. In these modes the ring vibrates in the plane of the substrate in an elliptically-shaped pattern with two node lines. The device can be operated in the whole angle mode, the open-loop mode or the force-to-rebalance mode, although in this paper we will concentrate on the force-to-rebalance mode of operation.

To suspend the ring above the silicon substrate, we have developed a novel support arrangement using eight semicircular springs that attach the ring to the substrate at the ring center. This spring arrangement supports the ring without drastically restricting its in-plane motion, thus allowing the ring to still vibrate in a low-frequency, elliptically-shaped mode. Symmetry considerations require at least eight springs to support the ring to give a balanced device with two identical modes that have the same natural frequency. The attachment point in this structure forms a balanced isolated support for the ring that is similar in spirit to the base in tuning fork designs. As a result of this isolation, the support structure is compatible with high Q, long time constant devices for high performance applications. Another feature of the support structure is its released design which eliminates the effects of package-induced stress on the device.

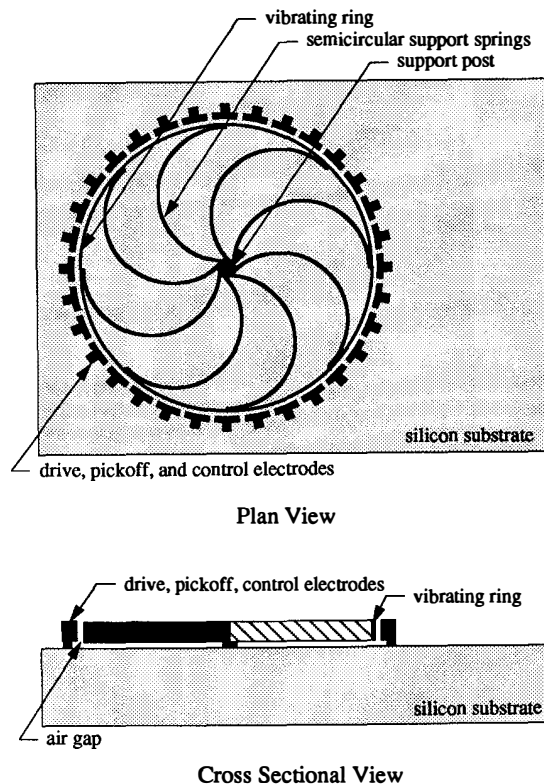


Figure 6 Plan and cross sectional views of ring gyroscope

Since the vibrating ring is a shell structure, it naturally has two identical modes that have nominally equal resonant frequencies. To obtain two identical frequencies in either tuning fork or beam structures, it is necessary to match both the thickness and width of the structure which is difficult, if not impossible, to do with the required precision in a batch-fabricated process. In contrast, to obtain two identical frequencies in the ring device, it is not necessary to precisely control any dimension of the device, rather, it is only necessary that the device be uniform in its dimensions and material properties at the die level. This makes fabrication of the ring gyroscope much simpler as these requirements are easy to achieve in a batch fabrication process.

Thirty-two capacitive electrodes are located around the outer circumference of the ring to drive, sense, and control its vibration. The electrostatic drive and detection scheme used in this device is ideal for a micromachined device and results in a clean, simple, one-element mechanical structure [14]. In developing the ring gyroscope, we have used these electrodes in two different sets; a simple unbalanced set and a balanced set. The balanced electrode set uses all thirty-two electrodes in a symmetrical arrangement that electronically cancels the electrostatic effects of rigid body motions of the ring on the sensor's operation. It is envisioned that this complete electrode set would be used when vibration performance of the sensor is crucial. Otherwise, the simpler unbalanced electrode set would be used. As discussing both electrode sets would be redundant, we will discuss the simpler set in this paper. All the basic operating principles of the device are covered in this discussion without loss of generality using this electrode set. For a further discussion of the balanced set the interested reader is referred to [8].

In the simple electrode set, two pickoff electrodes, located at 0° and 45° , are used to capacitively sense the ring vibration. Two electrodes located across from the sense electrodes at 180° and 225° are used to electrostatically drive the ring vibration. Four electrodes located at 67.5° , 90° , 112.5° , and 135° are used to electrostatically balance the ring so that the two flexural vibration modes of the ring have the same natural frequency. Ideally, these two modes are identical and would have the same natural frequency. However,

actual rings usually have some imperfections that cause these two frequencies to be slightly different. By applying the proper voltages to the balancing electrodes, as discussed shortly, this frequency split can be removed [7]. The remaining electrodes are not used and are held at ground potential.

The ring gyroscope design is more compliant than wine glass designs or cylinder designs due to its support structure. This makes the ring gyroscope somewhat more sensitive to spurious vibrations than other shell designs since three vibration modes of the structure have resonant frequencies below the flexural mode frequencies used to sense rotation. The first vibration mode of the ring gyroscope is a torsional mode in which the ring remains rigid and rotates about the support center. Often when people are first exposed to this sensor they mistakenly assume that this is the vibration mode used to sense rotation. However, for the range of rotational accelerations normally encountered when using this sensor the torsional mode is not excited and the ring structure faithfully follows the applied rotation. The second and third vibration modes of the ring gyroscope are x- and y- translational modes in which the ring remains rigid. In perfectly balanced devices these modes do not contribute to the rotation response of the device. However, when mass or stiffness asymmetries exist in the sensor structure these modes can cause the device to be sensitive to environmental vibration [15]. In demanding applications, rigid-body motions of the ring can be electronically rejected using the balanced electrode set to further improve sensor performance in high vibration environments.

Out-of-plane vibration modes of the ring can be moved to high frequencies by using high aspect ratios in the sensing element. When these modes have high frequencies, they do not significantly contribute to the sensitivity of the sensor to spurious vibrations. It is, therefore, desirable to use a high-aspect ratio process to fabricate the sensor element such as the electroforming process described later. At this time, it should be remembered that even the high performance HRG shell design has torsional and translational modes that lead to unwanted vibration sensitivity [15]. The ring gyroscope support structure only lowers these frequencies. This design trade-off is one compromise in the sensor design. Although, hemisphere or cylinder shells do not require this compromise the ring gyroscope is much easier to fabricate as mentioned earlier.

Device Operation and Control and Readout Electronics

Just like the Foucault pendulum, the operation of the ring gyroscope can be understood from the normal mode model. For the ring, the two identical modes of the structure have an elliptical shape with their antinodes lying 45° apart. For the purposes of this discussion we will initially consider a balanced device in which case one mode, which we will call the primary mode, can be considered to be aligned with 0° pickoff; and the other mode, which will be called the secondary mode, will then be aligned with the 45° pickoff.

The ring gyroscope uses electrostatic drive and detection biased by a polarization voltage applied to the ring. Each pickoff electrode incorporates a low-input capacitance, unity-gain, buffer amplifier to sense the small capacitance changes due the ring vibration [16]. The pickoff electrode capacitor and the input capacitance of the buffer amplifier form a capacitive voltage divider which is biased by the ring polarization voltage. This circuit arrangement converts the ring vibration into a buffered output voltage for the control and readout electronics. For simplicity and ease of fabrication, the initial device design has used a source follower for the unity gain amplifier shown in Figure 7. Resolution of the sensor is currently limited by noise in the buffer amplifier and could be improved with an improved buffer design [16]. In the current design, with large $7\ \mu\text{m}$ electrode gaps, the polarization voltage is 60V. This voltage can be reduced to more conventional IC voltages by scaling the device to reduce its gap sizes.

The block diagram of the control and readout electronics for operating the ring gyroscope in the force-to-rebalance mode is shown in Figure 8 [1,6,12]. To sense rotation rate, the primary mode is driven to a fixed amplitude at the ring resonant frequency with a phase-locked loop, oscillator circuit and an amplitude control loop. The primary or main drive loop incorporates an amplitude control

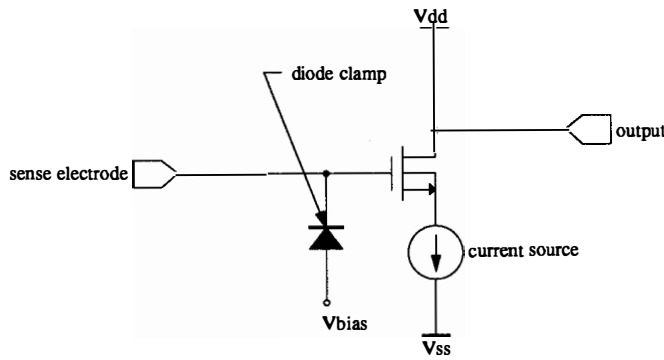


Figure 7 On-chip source follower buffer amplifier

loop to set the primary mode amplitude to a predetermined level. Since the scale factor of the sensor is proportional to the amplitude of the primary mode it is important to control this amplitude to eliminate the effects of device parameters, such as Q , on the sensor response [1].

When the device is not rotating, the secondary mode will not be excited and therefore has zero amplitude. Rotating the ring causes the secondary mode to be excited by the Coriolis acceleration and to build up amplitude. The sensor could be operated in this open-loop mode with the amplitude in the secondary mode giving the rotation rate. However, in this mode of operation the response to a step change in rotation rate would not be instantaneous, since time is required for the amplitude to build up. The amplitude build up is approximately exponential with a time constant given by

$$\tau = \frac{2Q}{\omega}$$

where Q is the quality factor of the resonance and ω is the angular natural frequency [1,6].

This response time may be too slow for some applications so the sensor electronics includes a second control loop to continuously force the secondary mode amplitude to zero thus operating the sensor in a force-to-rebalance mode [1,6]. With this feedback control arrangement, the sensor response time and damping are entirely controlled electronically, as the control system can apply large drive forces to rapidly and continuously rebalance the Coriolis acceleration. The rebalance voltage is used to measure the rotation rate and is given by

$$\frac{v_b}{v_d} = 4A_s Q \frac{\Omega}{\omega}$$

where v_b is the secondary mode drive voltage required to rebalance the device, v_d is the primary mode drive voltage, A_g is the angular gain, and Ω is the rotation rate to be measured.

Up to this point in the discussion we have been considering ideal balanced rings with two equal normal mode frequencies. Actual rings usually have some mass or stiffness asymmetries that split these two frequencies somewhat. Without compensation, this small frequency split produces a scale factor error and, if the split is large, the sensitivity of the sensor is greatly reduced since then there would be no Q amplification. To balance the device, voltages are applied to the balancing electrodes to force the normal mode frequencies to be equal [7]. Placing voltages on the balancing electrodes can be thought of as adding 'electrical' springs to the ring at the electrodes to compensate for device asymmetries. When the vibrating ring deforms at a biased electrode there is net force tending to make it deform still further due to the nonlinear electrostatic force. For small vibrations of the ring this additional displacement is modeled as a negative 'electrical' spring.

How balancing of the ring is performed can be understood by considering the simple nonsymmetrical mass distribution, shown in Figure 9, with extra mass at 0° . For this simple mass distribution the primary mode located at 0° has a lower natural frequency than the secondary mode located at 45° . To balance this extra mass, a negative electrical spring is applied to the secondary mode thereby reducing its frequency to match that of the primary mode. All asymmetries, whether due to mass or stiffness variations in the ring,

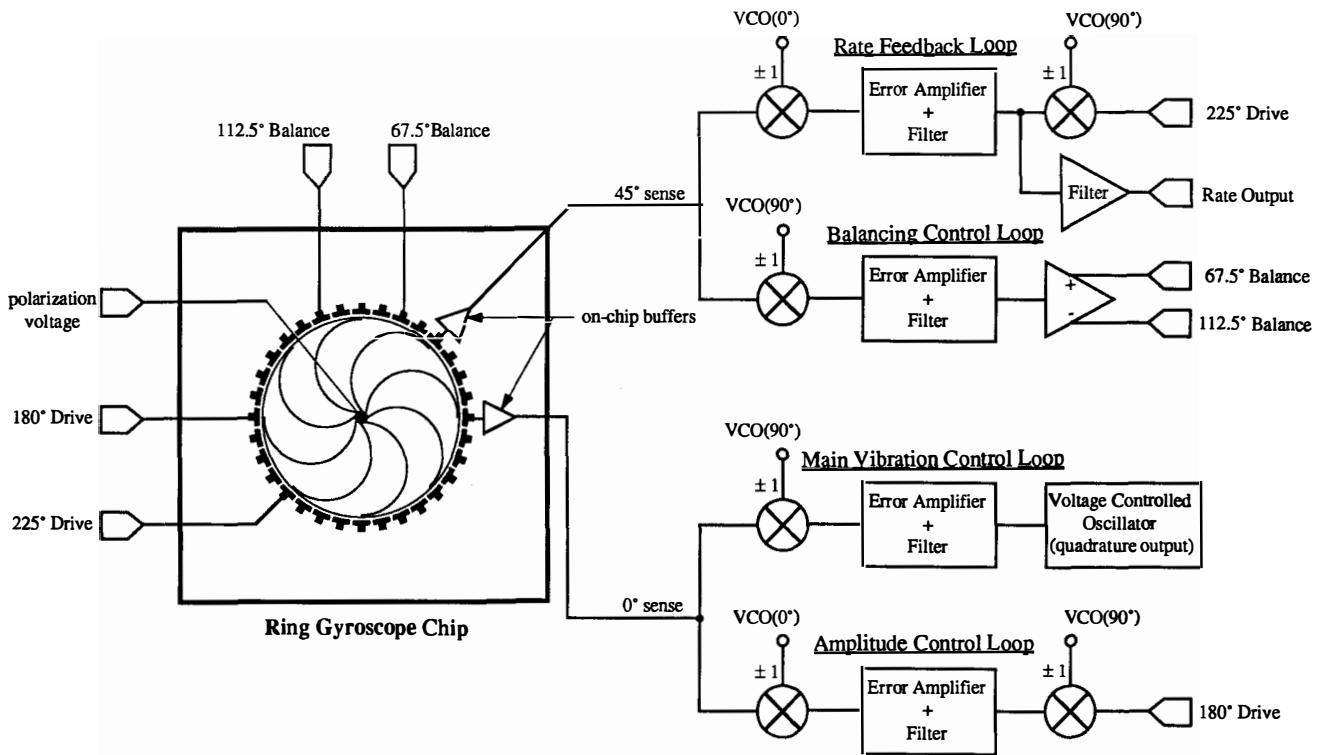


Figure 8 Block diagram of control and readout electronics

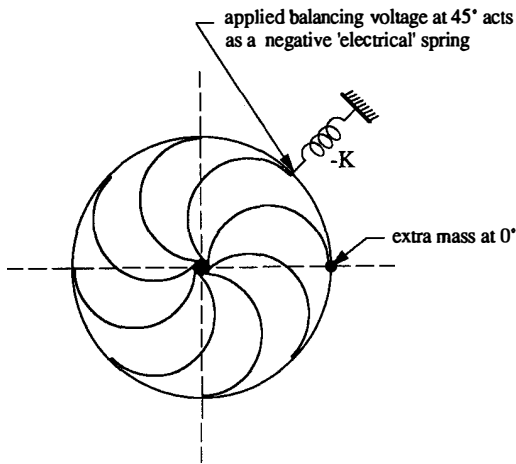


Figure 9 Balancing of simple nonsymmetrical mass distribution

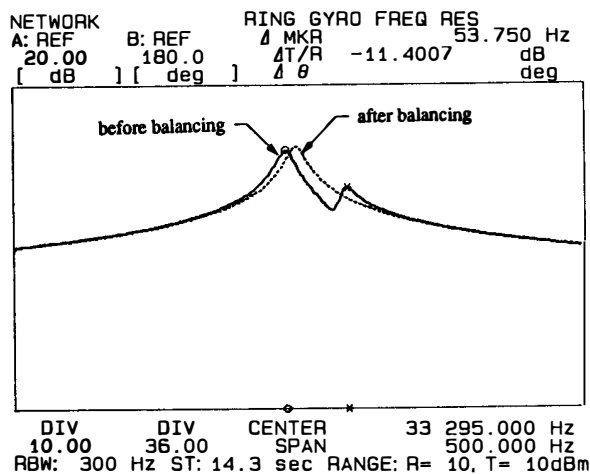


Figure 10 Frequency magnitude response before and after balancing

can be balanced in this manner as long as the frequency split is not excessively large. Initially, sensors are open-loop trimmed for course balance (Fig. 10) and, in operation, the control electronics uses the quadrature imbalance to continuously balance the device. [7].

Ultimately, the resolution of the sensor is limited by Brownian motion of the ring itself. However, this resolution has not been obtained in the current design due to noise in the buffer amplifier. The sensitivity of the device can be improved with a higher Q and by improving the buffer amplifier design.

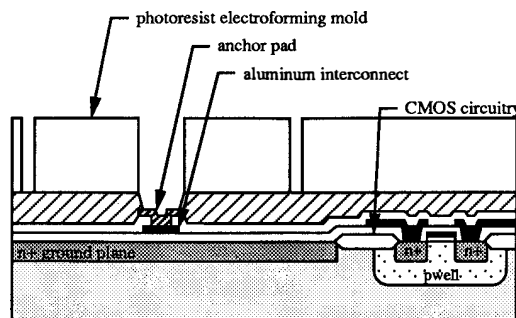
Fabrication

To fabricate the ring gyroscope, we have developed a LIGA-like post circuit process for incorporating high aspect-ratio, electroformed metal microstructures with CMOS circuitry [17]. In the electroforming process a nonconducting mold is fabricated into which metal is electroplated to form the sensor element. Although other micromachining techniques exist for fabricating high aspect-ratio structures [18,19], we have selected electroforming because of the ease of integration and potential low-cost of this process. Our general approach is to fabricate the on-chip circuitry using a state-of-the-art standard CMOS technology, and to add the gyroscope in a series of low-temperature, post-circuit fabrication steps without any disturbance to the underlying circuitry. This partitioned approach enables one to include a large amount of on-chip circuitry with the sensor for signal readout, compensation, calibration, and external

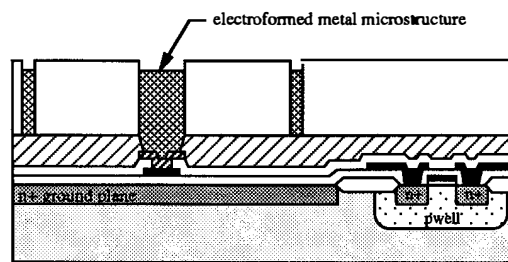
interfacing without sacrificing overall yield or increasing cost. The process is simple and uses only conventional techniques and standard equipment and can, therefore, be implemented on most IC fabrication lines with minimal additional equipment.

Fabrication of microstructures by electroforming, although not new, is currently experiencing a revival of interest for fabricating novel, high aspect-ratio microstructures. Several electroforming processes have been developed ranging from the very high aspect-ratio LIGA process to lower aspect-ratio low cost processes [17,20,21]. Similar techniques were developed over a decade ago and are now being used to fabricate thin film magnetic recording heads for computer disk drives [22]. These processes are based on fabricating a nonconducting mold into which the metal structure is electroplated. Movable microstructures are fabricated in these processes by including sacrificial spacer layers for surface micromachining.

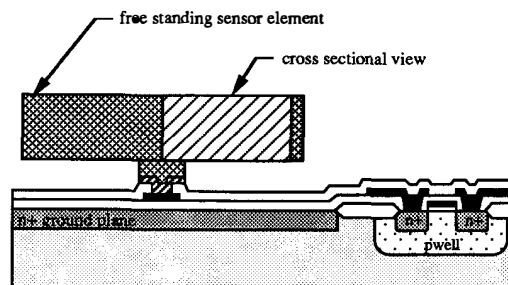
The basic process, shown in Figure 11, for fabricating the ring gyroscope begins with a standard CMOS process to fabricate the on-chip buffer circuitry. After completion of the CMOS, the aluminum metallization is passivated and anchor regions where the sensor elements are attached to the silicon substrate are defined. Next, a conductive sacrificial spacer is deposited and patterned. This layer defines the movable portions of the sensor element and also serves as a plating base layer for electroforming the microstructure. At this point, the electroforming mold is defined, and the sensor element is formed by selective electroplating in the open mold areas. The mold and sacrificial layer are then removed, completing the sensor process.



1. Electroforming mold defined by UV exposure



2. Electroforming of sensor element



3. Mold and sacrificial spacer removed

Figure 11 Electroforming fabrication sequence

The most important step in the ring gyroscope process is the formation of the electroplating mold. Initially, in the development of the ring gyroscope, we used a polyimide layer that was patterned by reactive ion etching for the electroforming mold [8]. Currently, we are using a contrast-enhanced, optical lithography process to fabricate the electroforming mold. The process uses a thick positive photoresist of high viscosity and high transparency that is defined with conventional UV lithography equipment. This is a low-cost mature technology that was originally developed for the thin film magnetic recording head industry and is, therefore, well suited to fabricating sensors [22]. Molds fabricated with this technology have nearly vertical walls with aspect ratios of about 7, almost matching the quality of molds produced by reactive ion etching (Fig.12).

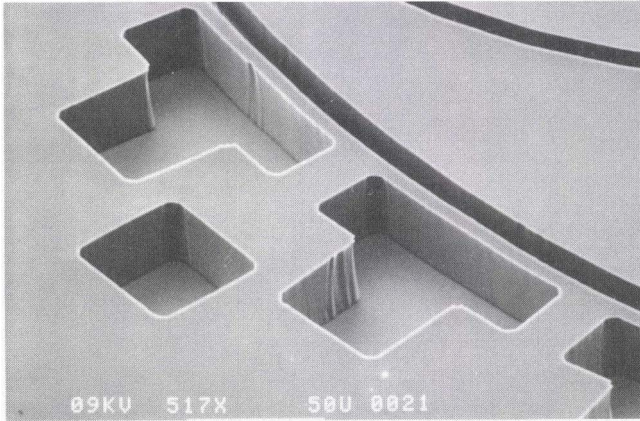


Figure 12 SEM photograph of photoresist electroplating mold

A concern with this process is that a metal structure is used for the vibrating sensor element that may exhibit creep, fatigue, or long-term drift problems. One could legitimately ask why even consider a metal sensor element, after all silicon is an excellent mechanical material and many techniques are available for micromachining this material. Certainly a high aspect-ratio polysilicon fabrication could be used to fabricate the ring gyroscope and produce a high quality device. However, one should not prematurely rule out using a metal element for the sensor, given the integration and cost advantages of the electroforming process. Furthermore, using metal structures for vibrating elements is not without precedence as many resonator devices have metal elements including a macroscopic vibratory gyroscope [1]. For these applications metal alloys are available that have been specifically designed with elastic moduli independent of temperature so that the natural frequency of these devices does not vary with temperature.

In the ring gyroscope process, we have initially used nickel as the material for the sensor element. Nickel was selected because of the ease with which it can be electroformed and because of its moderate hardness. We have found that nickel is not an ideal material for the sensing element. Ring gyroscopes have a maximum Q of around 4000 which limits the performance of the device. To improve the sensor's performance we are investigating other electroplated materials for the sensing element that potentially have a higher Q. Even with a lower Q, the gyroscope devices have shown a sensitivity of 0.5°/sec in a 10 Hz bandwidth.

Fabrication of the ring gyroscope is not limited to this electroforming process. Other micromachining techniques, including LIGA, surface micromachining of polysilicon, or reactive ion etching of bulk silicon could be used and may be advantageous for some applications [17,18,19]. The LIGA process could produce very tall devices with larger pickoff capacitors and, consequently, better sensitivity. Polysilicon devices would have higher Q and, therefore, better sensitivity. If the Young's modulus variation with crystal orientation of heavily doped silicon is not excessive the dissolved wafer process could be used to fabricate very high Q ring gyroscopes. With better materials and processes the ring gyroscope could potentially be used in low grade, short term, inertial navigation applications such as belt-buckle size, personal navigation systems.

Experimental Results

The ring gyroscope with integrated CMOS buffer amplifiers has been fabricated using the electroforming process and the sensor has been tested. Figure 13 shows a die photo of the fabricated device including the on-chip buffer amplifiers. The ring has a diameter of 1mm, a thickness of 19 μm, a width of 5 μm, with electrode gaps of 7 μm. Circuit performance was evaluated by wafer probing before and after the electroforming process and no change in the circuit performance was observed confirming the integration potential for this fabrication process.

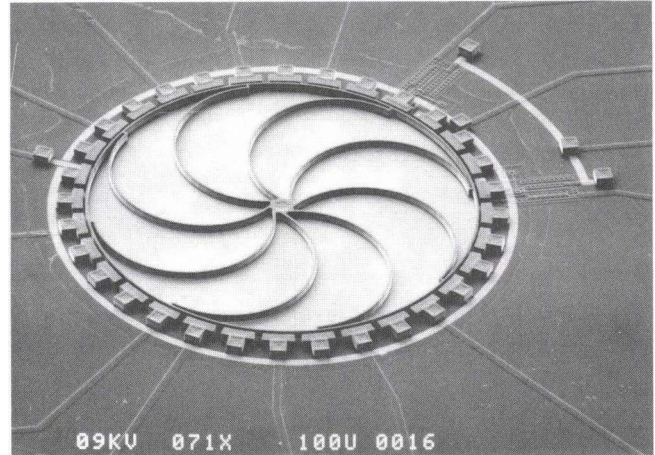


Figure 13 SEM photograph of ring gyroscope sensor

The device has been operated in the force-to-rebalance mode using the closed loop circuitry described earlier. Initial electrostatic balancing of the device was performed manually and then further automatically trimmed with the balancing control loop. Figure 14 shows the results of rotation testing of the complete sensor system and plots the analog output voltage as a function of the applied rotation rate. For these tests the device was packaged in a 24-pin ceramic DIP and continuously pumped using a metal lid with an o-ring seal. This arrangement gave a marginal vacuum level that reduced the Q of the device to 2000 down from its intrinsic Q of 4000. The sensor system shows excellent linearity and moderate sensitivity. Resolution of the system is approximately 0.5°/sec in a 10 Hz bandwidth limited by noise from the on-chip buffer amplifiers and by the low Q of the device. Using the measured secondary mode rebalance voltage and the measured primary mode drive voltage the angular gain of the ring gyroscope is found to be approximately 0.3 which is in good agreement with theoretically calculated value of 0.33 [8]. The step response of the sensor is shown in Figure 15 which shows the analog output voltage of the sensor as the rotation rate is stepped from 0°/sec to 10°/sec to 0°/sec to -10°/sec and back to 0°/sec demonstrating the transient performance of the system.

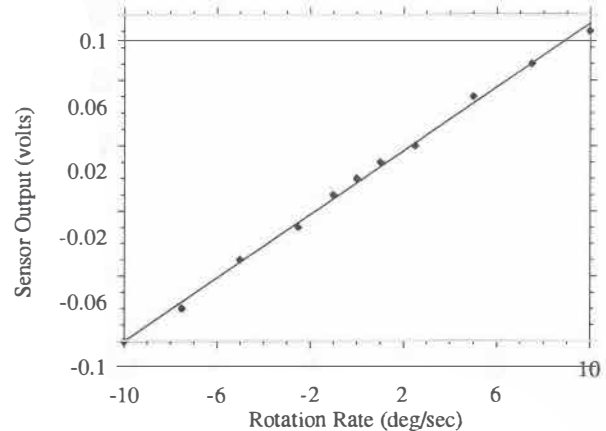


Figure 14 Measured rotation response of sensor

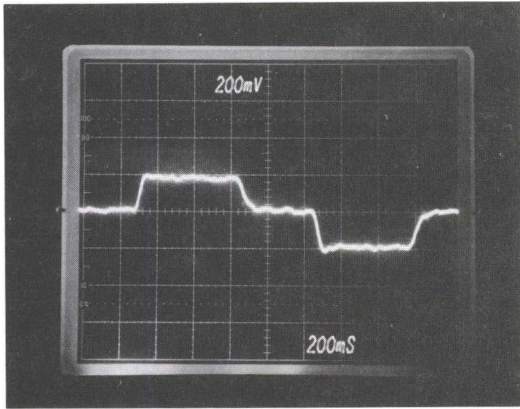


Figure 15 Step response of sensor for 10°/sec changes

Conclusions

Micromachined gyroscopes are currently receiving a great deal of attention as many applications exist for these devices. In this paper, we have described a new, low-cost, micromachined gyroscope based on a vibrating ring. The vibrating ring design is small and naturally suited to fabrication by micromachining. It is fabricated by a simple mature process that allows for the inclusion of large amounts of on-chip circuitry, thus lowering the unit cost. Precise control of the device dimensions and material properties is not required as it is only necessary that the device be uniform—something that is easily achieved in a batch fabricated process. The device design is inherently insensitive to secondary parameters such as linear acceleration, and package-induced stress, simplifying the overall system design. Control and readout electronics for the device are relatively simple and could potentially be integrated with the device producing a reliable, low-cost, total sensor system with autocalibration and self-test features.

In comparing the ring design with other micromachined designs such as the tuning fork design [3] each device is seen to have advantages and disadvantages. The ring device is a shell design with two identical modes, so the response of this device is amplified by the quality factor Q . For a given amount of driven motion there is more motion to detect in the ring device than in the tuning fork device. However, this motion is measured in a smaller capacitance in the ring device. At this point in time, due to the low Q of the device and the buffer amplifier design, the ring gyroscope is less sensitive than the tuning fork design. As Q increases, however, the ring and tuning fork designs become more competitive in terms of raw sensitivity and then additional features of the ring gyroscope, such as its simple low-cost fabrication process and high integration potential, become very attractive.

Currently, the resolution of the ring gyroscope is about 0.5°/sec which is suitable for some, but not all, of the perceived applications. This performance level represents our initial experience with this new device and we feel many options are available to greatly improve the device. Simply increasing the device diameter lowers the resonant frequency and increases the pickoff capacitance, improving the sensitivity of the device. Reducing the electrode gaps reduces the voltage requirements for the device to more reasonable IC voltage levels without decreasing sensitivity. As mentioned earlier, the resolution of the sensor is presently limited by noise from the on-chip buffer amplifier. Better buffer designs with lower input capacitances will further improve the sensor performance. Further improvements in the sensor's performance can be obtained by increasing the quality factor of the device. Already we have measured a Q of 10,000 on some of our nickel structures and we have reason to believe that the Q for the ring will ultimately be above this level when we incorporate new materials in our electroforming process. Combining all these potential improvements we feel that a resolution below 0.05°/sec can be obtained with this device structure and fabrication process, opening up many new applications for this new sensor.

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References

- [1] "The Vibrating Structure Gyroscope," British Aerospace Systems and Equipment report #TR5102, March 1993
- [2] J. Bernstein and M. Weinberg, "A Micromachined Comb-Drive Tuning Fork Gyroscope," *21st Joint Serv. Data Exchng for G. N. and C.*, Palm Springs, California, Oct. 1992
- [3] J. Bernstein et al, "A Micromachined Comb-Drive Tuning Fork Gyroscope," *Digest IEEE/ASME Micro ElectroMechanical Systems (MEMS) Workshop*, Ft. Lauderdale, Fl., pp. 143-148, February 1993
- [4] A. Lawrence, *Modern Inertial Technology Navigation Guidance and Control*, Springer-Verlag, New York, 1993
- [5] T. Kumagai, "Development of Optical Fiber Gyroscopes for Industrial Use," *Hitachi Cable Review*, No. 9, pp. 43-48, August 1990
- [6] A. Lawrence, *Modern Inertial Technology Navigation Guidance and Control*, Springer-Verlag, New York, 1993, pp. 148-161
- [7] E. J. Loper and D. D. Lynch, "Projected System Performance Based on Recent HRG Test Results," *Proceedings 5th Digital Avionics System Conference*, Seattle, Washington, Nov. 1983
- [8] M. W. Putty, "A Micromachined Vibrating Ring Gyroscope," *Ph.D. Thesis*, University of Michigan, Ann Arbor, MI, to be published
- [9] R. R. Ragan and D. D. Lynch, "Inertial Technology for the Future, Part X: Hemispherical Resonator Gyro," *IEEE Transactions on Aerospace and Electronic Systems*, Vol. AES-20, No. 4, pp. 432-434, July 1984
- [10] S. Timoshenko, D. H. Young and W. Weaver, *Vibration Problems in Engineering*, 4th ed., John Wiley and Sons, New York, 1974
- [11] E. P. EerNisse and J. M. Parcos, "Practical Considerations for Miniature Quartz Resonator Force Transducers," *Proceedings, 28th International Instrumentation Symposium*, pp. 33-34, 1982
- [12] J. S. Burdess and T. Wren, "The Theory of a Piezoelectric Disc Gyroscope," *IEEE Transactions on Aerospace and Electronic Systems*, VOL. AES-22, No.4, pp. 410-418, July 1986
- [13] G. H. Bryan, "On a Revolving Cylinder or Bell," *Proceedings of the Royal Society (London)*, 47, 1890
- [14] R. T. Howe, "Resonant Microsensors," *Proc. 4th Int. Conf. Solid-State Sensors and Actuators (Transducers '87)*, Tokyo, Japan, pp. 843-848, June 25, 1987
- [15] D. D. Lynch, "Vibration Induced Drift in the Hemispherical Resonator Gyro," *Annual Meeting of the Institute of Navigation*, Dayton, Ohio, June 1987
- [16] W. Yun, R. T. Howe and P. R. Gray, "Surface Micromachined, Digitally Force Balanced Accelerometer with Integrated CMOS Detection Circuitry," *Tech Digest, Solid State Sensors and Actuators Workshop*, Hilton Head, S. C., pp. 126-131, June 1992
- [17] H. Guckel, et al, "Deep X-Ray and UV Lithographies for Micromechanics," *Tech Digest, Solid State Sensors and Actuators Workshop*, Hilton Head, S. C., pp. 116-122, June 1990
- [18] D. Kobayashi et al, "An Integrated Lateral Tunneling Unit," *Proceedings, IEEE Workshop on Micro Electro Mechanical Systems (MEMS' 92)*, Travemunde, Germany, pp. 214-219, Feb. 1992
- [19] Y. Gianchandani and K. Najafi, "A Bulk Silicon Dissolved Wafer Process for Microelectromechanical Systems," *Digest, International Electron devices Meeting*, Washington, D. C., Dec. 1991
- [20] G. Engelmann, et al, "Fabrication of High Depth-to-Width Aspect Ratio Microstructures," *Proceedings, IEEE Workshop on Micro Electro Mechanical Systems (MEMS' 92)*, Travemunde, Germany, pp. 93-97, Feb. 1992
- [21] A. B. Frazier and M. G. Allen, "High Aspect Ratio Electroplated Microstructures Using a Photosensitive Polyimide Process," *Proceedings, IEEE Workshop on Micro Electro Mechanical Systems (MEMS' 92)*, Travemunde, Germany, pp. 87-92, Feb. 1992
- [22] J. Bond, "The Incredible Shrinking Disk Drive," *Solid State Technology*, Vol. 36, No. 9, pp. 39-45, Sept. 1993