# A WIDE DYNAMIC RANGE SILICON-ON-INSULATOR MEMS GYROSCOPE WITH DIGITAL FORCE FEEDBACK

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## ABSTRACT

This paper presents development efforts and initial test data for a Silicon-on-Insulator (SOI) Micro Electro Mechanical System (MEMS), vibratory angular rate sensor intended for hypervelocity and small diameter missiles and munitions. The SOI angular rate sensor (gyroscope), intended for wide dynamic range and harsh environment applications, utilizes advantages offered from the mass and feature sizes achieved by Deep Reactive Ion Etching (DRIE). This particular effort is focused on developing a symmetric device design along with multi-bit sigma-delta force-feedback control to increase dynamic range and reduce susceptibility to environmental parameters, including temperature, vibration, and sustained Z-axis acceleration loading.

A prototype, single layer MEMS chip, consisting of a proof mass placed in a three-fold mode-decoupled symmetric suspension, has been fabricated and tested. The mode-decoupled suspension allows only one degree of in-plane motion for each comb drive, thereby attenuating errors due to oscillation axis misalignment. In addition, suspension symmetry maintains matched oscillation mode frequencies through processing and temperature variations, allowing maximized dynamic range in the discrete-time control loop. Attached to the suspension are comb-drives operating in their linear mode. Use of these actuators eliminates deflection-induced nonlinearity in the control loop.

The rate sensing performance of these devices in an open-loop configuration has been characterized, and a unit is being flight-tested on a prototype hypervelocity missile. Current efforts will reduce random walk through preamp optimization, add an excitation control loop to improve bias stability, and implement the digital feedback loop to increase dynamic range. This paper presents recent development efforts and initial test data for the SOI-based angular rate sensor, intended for small diameter missiles and munitions applications.

## BACKGROUND

The newest generation of Army missile systems, while becoming smaller, faster, and more precise, will see ever-increasing extremes in operational and environmental conditions. The anticipated rotational rates about the longitudinal axis encompass a range of –3000°/sec to +3000°/sec, a rate measurement resolution of better than 10°/hr, and a bias stability of 1°/rt.hr. Furthermore, large shocks of greater than 4000g can be seen at frequencies in the 1kHz to 15 kHz range. Fortunately, various attenuation and mounting techniques are being proposed to reduce that requirement to slightly less than 1000g's (in that frequency range). In either event, the sustained z-axis acceleration load and vibration environment can be detrimental to a MEMS roll rate sensor. Many MEMS devices could not survive these environmental extremes; much less perform accurately through this environment.

The stringent requirements placed on angular rate sensors are not likely to be addressed by Industry, therefore, the Army invested in a Science and Technology Objective (STO) for the development of a MEMS-based Angular Rate Sensor (MBARS) for hypervelocity and small missile and munitions applications. This effort is currently in its fourth year. The following details the specific design objectives of the MBARS program:

<u>Mechanical</u>

- Increase device excitation to increase mechanical sensitivity and improve signal-to-noise ratio.
- Produce sufficient feedback control force and allow large deflections of the mechanical structure.
- Minimize out-of-plane deflections of the proof mass.
- Decouple the effects of external accelerations from oscillation modes used for rate sensing

<u>Electronic</u>

- Accommodate large signal levels and provide large electrostatic forces.
- Maintain resolution at high signal levels (24-bit digital output).
- Rate integration performed in system to maintain angle accuracy.
- Minimize effects of external accelerations on the electrical signal produced by position sensing elements.

## INTRODUCTION

A simplified version of a typical vibratory-rate gyroscope and its associated set of variables is shown in Figure 1. The device consists of a mass-spring system that has at least two orthogonal modes of oscillation. The mass, m, is forced to have a sinusoidal velocity in the frame of reference of the device, along the x-axis, for example. Springs $k_x$ and $k_y$ provide a suspension that constrain the mass to particular orthogonal oscillation modes. When the device experiences a rotation, the



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Coriolis force induces oscillation of the mass orthogonal to its original velocity. Sensors detect this motion and provide a signal from which the rotational rate is extracted. [1,4,5,6,7,8,9]

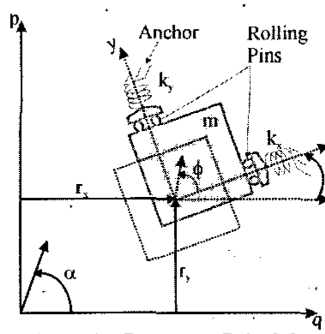


**Figure 1 - Gyroscope Principle**

The prototyped gyroscope presented in this paper is a single layer structure consisting of a proof mass placed in a three-fold mode-decoupled symmetric suspension with matched fundamental oscillation modes (Figure 2). When excited in one mode, rotations about the z-axis result in oscillations in the orthogonal mode. The mode-decoupled suspension allows only one degree of in-plane freedom for each excitation actuator, thereby attenuating errors due to oscillation axis misalignment. In addition, suspension symmetry maintains matched oscillation mode frequencies through processing and temperature variations, allowing maximized dynamic range in a wide dynamic range discrete-time control loop. Attached to the suspension are comb-drives operating in their linear mode. Use of these actuators eliminates deflection-induced nonlinearity in the control loop.

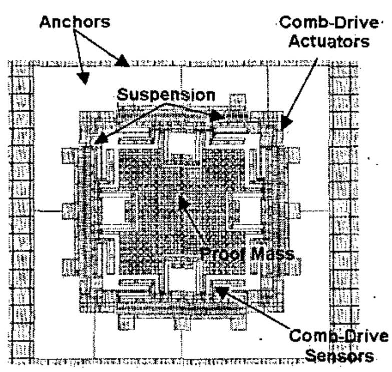


**Figure 2 – Gyroscope Mechanical Structure**

The device is fabricated in a cost-effective and highly-controllable process for in-plane inertial sensors. The process begins with a silicon-on-insulator wafer having a 100μm thick silicon layer on top of a 1μm thick oxide. This, in turn, sits on a standard silicon handle wafer. A thick photoresist mask is patterned on the wafer using standard lithography. Deep Si RIE is performed to define the microstructure. After the deep etch and removal of photoresist, the device undergoes a sublimation-based release process with a post-release anti-stiction coat that reduces process-induced and in-use stiction. After release, metallization is evaporated onto the surface to create electrical contacts. The mechanical structure (Figure 3) is integrated in a vacuum-sealable hermetic package with a separate CMOS readout ASIC. The package is then evacuated and sealed.

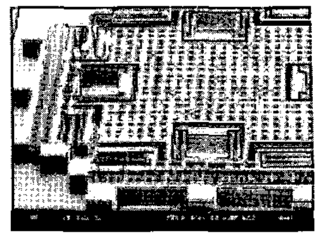

**Figure 3 – Fabricated SOI MEMS Angular Rate Sensor**

Operating in an open-loop mode, this sensor can demonstrate excellent noise performance and the readout electronics can potentially resolve angstroms of motion. However, if experiencing $10^7$ times the minimum detectable rate (the dynamic range requirement), the corresponding displacement of the mechanical sensing element is approximately 1 mm and is clearly not achievable with this device. Therefore, a force feedback sigma-delta control loop architecture is being implemented to extend the dynamic range.

## MULTI-BIT SIGMA-DELTA CONTROL

Sigma-delta control has been demonstrated previously on accelerometers with a low resonant frequency [3,10,11]. Sigma-delta control operates by applying a constant amplitude pulse width modulation signal at a frequency much above the resonant frequency of the sensing element. As the input force to the system increases, the width of the force pulses increase to cancel out that input force. Therefore, the dynamic range of a traditional sigma-delta controller is set by the ratio of minimum force pulse width, as determined by the maximum frequency of the control loop, and the maximum force pulse width, as determined by the resonant frequency of the system.

For accelerometers with a low resonant frequency this control architecture can deliver a large dynamic range. However, for a vibratory-rate gyroscope, the signal-to-noise ratio improves with increased resonant frequency, therefore, it is beneficial to operate these devices at resonances of upwards of 4 kHz, almost three orders of magnitude greater than accelerometers. While this resonance range makes the device less susceptible to the military vibration environment, it severely diminishes the dynamic range of a sigma-delta controller.

To increase the controller's dynamic range, it is possible to provide not only pulse width control on the force pulse stream, but to also provide pulse height control. In this scenario, as the input Coriolis force increases, the pulse widths can increase first. If the pulse width increase is not sufficient to cancel the input force, the pulse heights can begin increasing. The combination of increasing pulse width and amplitude can dramatically improve dynamic range. In this case, the dynamic range is set by the minimum pulse width amplitude possible and the maximum pulse width and amplitude possible.

Transfer functions for the mechanical sensing element in both the s-domain and z-domain have been defined and modeled. Modeling and calculations [2] have shown that the noise sources (quantization noise, preamp current noise, and Brownian noise) are all about an order of magnitude below the force resolution required. This important result shows that achieving the desired resolution and range with this control system is feasible.

## TESTING AND RESULTS

To date, five generations of mechanical structures have been fabricated. The first year focused heavily on the fabrication process. Devices and structures were created to characterize, improve, and determine the limits of the SOI gyro fabrication process. The second year placed a large emphasis on the mechanical structure, including nonlinear analysis, design optimization for the SOI process, design alterations to improve fabrication yield, and development/modeling of parasitics that impact gyroscope behavior. The third year focused on packaging and readout electronics. To that end, circuits and devices were designed to acquire gyro outputs. Plus, partnerships with other organizations were initiated for development of packaging.

This fourth year progressed the overall system greatly. Efforts focused heavily on packaging, device characterization, control electronics, and an initial flight-test prototype. Packaging efforts included initial die attach and lid attach processes, as well as demonstration of regular and repeatable ball and wedge wirebonds. In addition, a number of devices were characterized this year, with special emphasis placed on resonant frequency matching, fabrication uniformity, parasitic resistances, post-packaging stress, and thermal effects. A large amount of this year's resources were focused on the actual implementation of the control loop concept and system-level design developed in previous year's effort. Finally, an open-loop version of the rate sensor was designed and packaged for flight-tests.

Figure 4 shows an example of data collected from the fourth generation SOI MEMS structure, collected under a probe-station at atmospheric pressure. The resonance peak is easily seen. The linear increase to the plot is the effect of parasitic capacitance, feedthrough, and pickup. All of these have a linear dependence on frequency and add to the output signal.

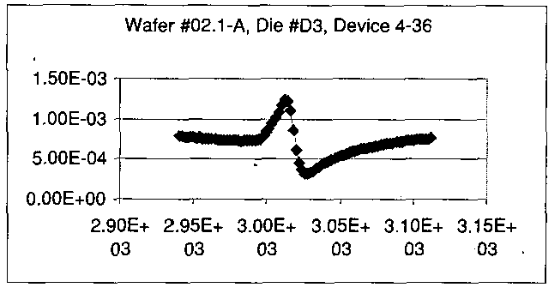


**Figure 4: Bode Plot of 4th Generation Resonance**

Considerable rate table data was collected on our third generation device using second-generation readout electronics and an open-loop architecture. Results shown in Figure 5 indicate that device performance is roughly three orders of magnitude poorer than the device requirements. However, the results are well in line with the status of the current system, with a clear path towards system improvement.

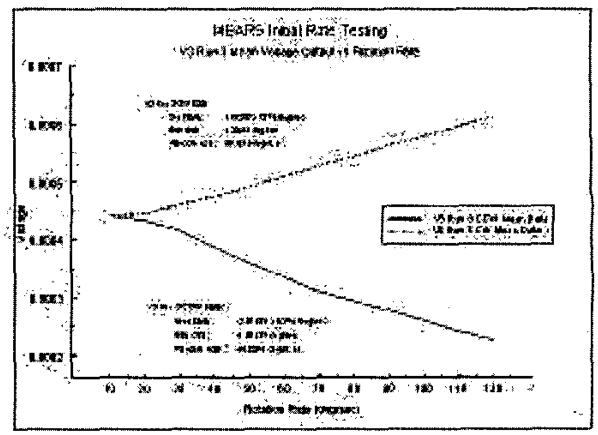

**Figure 5: Open-loop Rate Table Data**

There are three factors influencing the current performance. The first is that the device is being operated in air. Two consequences of operation in air are: increased Brownian noise, and reduced device excitation. In this case, the dominant effect of operation in air is the reduced device excitation. The device excitation amplitude in these tests was determined to be approximately 1.5 microns, roughly 2 orders of magnitude below what is desired. The second factor is related to the first in that smaller device excitations result smaller output signals. Since the data acquisition system was designed for the expected output levels under vacuum (high Q), data collection is not scaled correctly, resulting in significant quantization noise. The third factor is the fact that the gyro is being operated open loop. The control system is designed to reduce noise, especially quantization noise, by a significant amount. Without the control system in place, the device does not get the benefit of that aspect of the system. These three factors, when matured to the point that the design requires, can account for the three orders of magnitude ultimate improvement in performance.

## FLIGHT TEST PROTOTYPE

A recent major achievement was the development of a flight-worthy open-loop, analog version of the MEMS-based roll rate sensor system. An opportunity arose for inclusion on a hypervelocity missile test firing. Only approximately one month's notice was provided prior to the hardware delivery date. In that time, the entire test data collection system was reformatted to fit into the small space allowed on the missile system. Figure 6 shows the unpackaged flight unit.

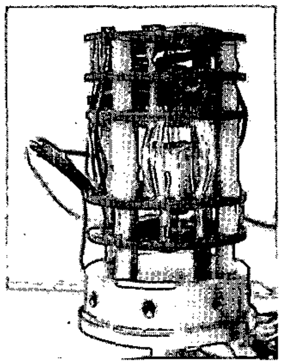

**Figure 6: Flight Test Unit**

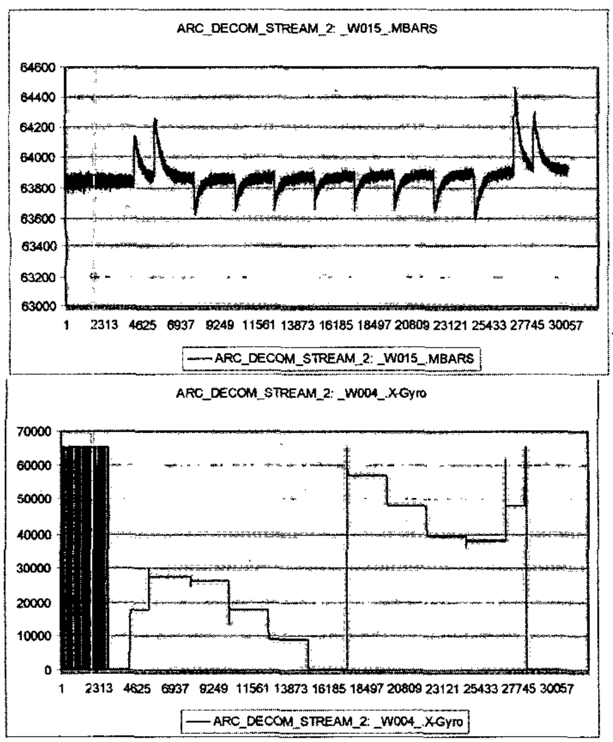


**Figure 7: Flight Unit Data & Reference Gyro Data**

Rate data collected from the flight unit is shown in Figure 7, along with data collected from a reference gyroscope. Comparing the above data, one can immediately see a difference between the open-loop version of MBARS and standard rate sensors data. MBARS has no DC response. The actual bandwidth of the sensor is 1 Hz to 200Hz. Its output is capacitively coupled so that DC bias shifts do not find their way into the sensor output. Therefore, the sensor output will decay if the rotational rate is constant for longer than one second. That is what is occurring in the above test data. Each step in the rotational rate results in a MBARS peak of height equal to the step. If that rate is maintained at a constant level for longer than 1 second, MBARS will decay back to zero until another step occurs. However, if the rate changes within the 1 second, as it is will in short-lived hypervelocity missile flight, then the rate sensor will accurately perform rate measurements.

## SUMMARY AND CONCLUSIONS

A MEMS-based angular rate sensor (MBARS) for extreme environments and large dynamic range has been developed for flight tests. A developer-evaluation version of a high-speed, multi-bit sigma-delta controller for vibratory rate gyroscopes has been fabricated and is under test. The MBARS will provide a unique solution for precision guidance of small diameter and hypervelocity missile systems and munitions.

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