Toward a Navigation-Grade Miniaturized Gyroscope

Mehdi Katoozi, Thomas Bocek, Bryan Buchanan
Solid State Electronic Development (SSED)
Boeing Corporation
Tukwila, Washington 98168 - USA
mehdi.katoozi@boeing.com

Abstract: *Navigating guided munitions requires operating in theatres with a high probability of GPS-denial. In such environment an Inertial Navigation System (INS) capable of autonomous navigation for several minutes without relying on GPS is highly desirable. One main ingredient of such a system is an accurate gyroscope. For years, Boeing has been perfecting the design of a Disc Resonator Gyroscope (DRG) based on Micro-Electromechanical Systems (MEMS) that shows the promise of meeting the requirements needed for this task. This paper describes Boeing's DRG technology targeting a Bias Instability < 0.01 deg/hr and Angle Random Walk (ARW) < 0.001º/√hr. A Digital Signal Processing (DSP)-based INS, built using this Gyroscope, targeting a final azimuth accuracy of ±1 mil in less than 60 seconds is also discussed. The paper focuses on the impact of packaging on gyroscope performance, in particular the sensitivity of DRG stability to strains caused by stresses during packaging and assembly.*

Keywords: Disc Resonator Gyroscope; Micro-Electromechanical System (MEMS); Inertial Navigation System (INS); Angle Random Walk (ARW); Bias Stability.

Introduction

Micro-electromechanical system (MEMS) gyroscopes have been developed and commercialized in the last two decades for a wide range of applications, from automotive safety to cell phone motion detection. However the vast majority of the commercially-available gyroscopes exhibit high bias instability, rendering them unsuitable for applications involving precision navigation.

In 2006 a Boeing-JPL team patented the Silicon Disc Resonator Gyroscope (SiDRG) [1]. Due to its axisymmetric design and advances made in the manufacturing process, the SiDRG exhibits a high quality factor (70,000 - 90,000), which allows the bias stability to reach well below 1 deg/hr and Angle Random Walk (ARW) to approach 0.002 deg/√hr, which makes the SiDRG a feasible candidate for a navigational grade gyroscope.

Boeing recently developed a prototype Inertial Navigation System (INS) using the SiDRG. The DRGs in this system initially suffered from rate instability in the form of ramping with very long time constants. This paper focuses on the root cause of rate ramping, and its impact on gyroscope performance.

The Boeing DRG

The Boeing DRG consists of a series of concentric rings connected through alternating spokes to a central mounting disc, as illustrated in Figure 1. This greatly reduces the radial stiffness of a solid disc enabling larger in-plane vibration amplitude while yielding a rich set of co-etched internal electrodes for forcing, and electrostatic trimming. The electrodes are co-etched with the resonator by through etching a wafer bonded to a base-plate that has been pre-etched with electrode support pillars. The electrodes and the resonator remain separately bonded to the base-plate, while the through-etched sidewalls form the capacitive gaps between the electrodes and the released resonator.

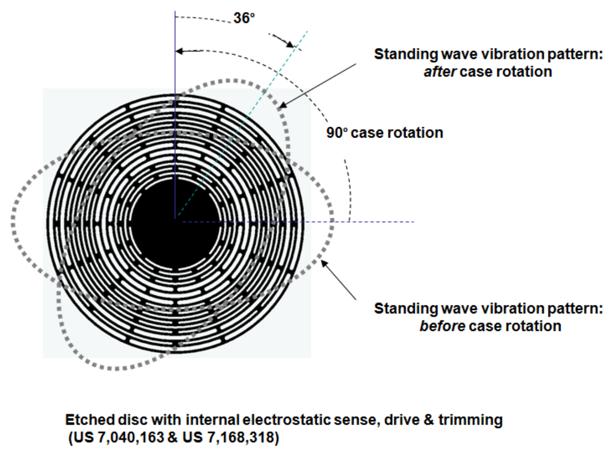

Figure 1. DRG Geometry and Principal of Operation

To sense rotation about an axis normal to the plane of the disc an oval or wineglass natural vibration standing wave pattern is established as shown in Figure 1. With no damping or control forces applied, this vibration pattern will lag by a fixed angle behind the case rotation due to conservation of momentum. The amount of lag of the pattern is always a fixed fraction of the case rotation, determined only by the resonator geometry or mode shape. This fraction is referred to as angular gain, k and is 0.4 for a DRG. In practice, the pattern angle is not measured but rather the force to maintain the pattern fixed in the case is measured. For a full treatment of the theory of a Coriolis Vibratory Gyroscope such as the DRG refer to IEEE Std. 1431, Annex B [2].

Using the DRG as a high performance rate sensor involves electrostatic tuning of the modal frequencies, as well as closed-loop control of the gyro modes [3,4]. For clarity, a brief description of the control loops is given here. There are three major loops that operate simultaneously: a drive amplitude control loop, a force to rebalance loop, and an environment regulation and compensation loop. The amplitude control loop establishes the modal vibration, and maintains its constant amplitude. The force to rebalance loop forces the vibration modal shape to remain fixed with respect to a sensor fixed axis. The rebalance force applied to null the Coriolis coupling is directly proportional to the input rate. The environment regulation and compensation loop is designed to reject external disturbances other than angular rates, e.g. ambient temperature variations.

The Boeing INS

In preparation for building an INS, Boeing has already designed, prototyped and tested a three axis Inertial Measurement Unit (IMU) using its DRG sensors. Figure 2 show the block diagram of this design. The design is partitioned into four main functions: sensor interfaces, central processing, power conditioning and I/O interfaces.

The sensor interfaces provide bias generation and signal conditioning for the DRG in addition to analog-to-digital and digital-to-analog conversion for the DRG rate and accelerometer outputs. The central processor implements DSP-based DRG control and general purpose processors with floating-point co-processor and memory. The I/O interface provides external Joint Test Action Group (JTAG) and RS-422 communications. The power conditioning block converts external input power to regulated internal supplies for sensors and electronics. The existing prototype design uses Honeywell RBA-500 accelerometers.

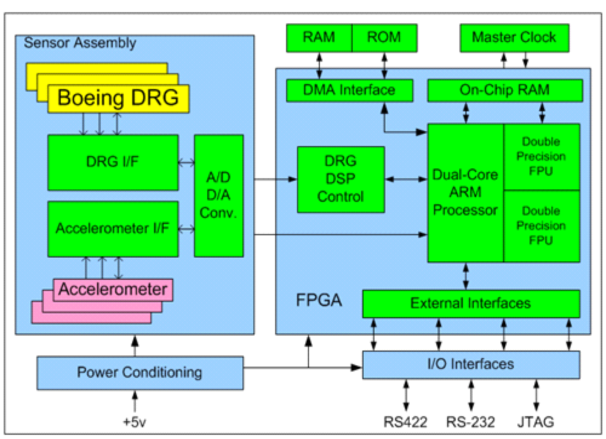

Figure 2. Boeing IMU Block Diagram

The IMU electronics is physically partitioned into two board stacks (Figure 3): a sensor stack which implements a single sensor interface function and a core stack which implements the power conversion, FPGA and I/O interface functions. There are three sensor stacks in the system one for each axis. Each sensor stack is a flexible circuit board consisting of three rigid boards. The flexible connectors can be bent to form a sensor stack with the rigid boards. The rigid boards are: Gyro Interface Board, Data Conversion Board and Bias / Accelerometer Board. The core stack consists of four boards. Central processing is implemented in one flexible board that consists of two rigid boards connected with a flexible connector. It contains a Xilinx 7020 FPGA with supporting memory and clock hardware. It also contains three flexible connectors that connect the central processor to the three sensor stacks. The power conditioning function consists of two separate rigid boards, and the last rigid board implements I/O interface.

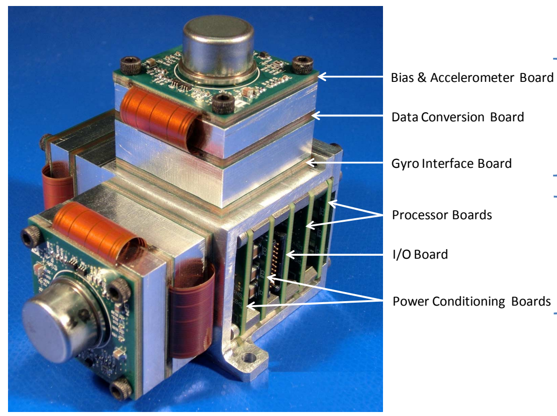

Figure 3. Boeing Prototype IMU

Rate Stability and Stress

In the process of testing the first IMU prototype, it was noticed that excessive ramping in the DRG rate was preventing any measurement of the IMU's true performance. Once the effect of temperature fluctuations were removed, thousands of hours of data revealed steady ramping in the rate with a very long characteristic time constant of the order of days. Figure 4 illustrate the temperature-compensated rate for one such DRG. As shown, the rate continues to ramp at more than 0.5 degree/hour/hour even after 70 hours of continuous operation. This phenomenon was postulated to be of a mechanical origin, which was proven to be correct through changes in mechanical stress on the board housing the DRG. Slight changes to the stress patterns on the board were observed to have large impacts on the magnitude of the DRG bias in otherwise static conditions.

A mounting technique was then developed to mechanically decouple the DRG from the printed circuit board. Figure 5 shows the static rate after the application of this technique in comparison to Figure 4. An improvement of > 50x in rate stability can be observed after 50 hours. Furthermore the rate stabilizes to a much higher degree than before in just 2 hours. This confirms the extreme sensitivity to DRG to board changes in board strain and underscores the need for developing a stress free packaging platform for navigation-grade applications.

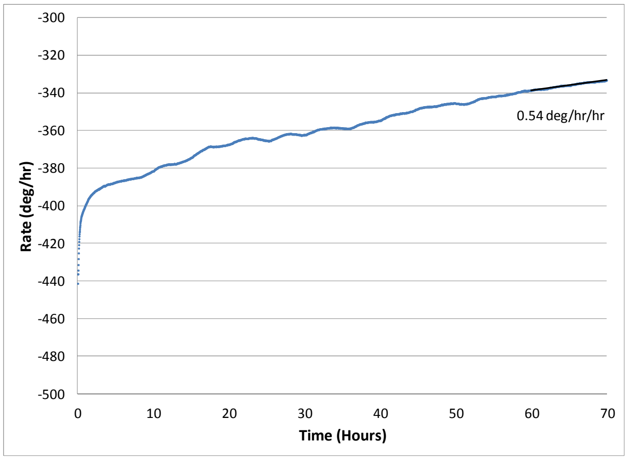

Figure 4. DRG Rate Ramp

In spite of the sizable improvement in rate ramping achieved through mechanical decoupling, small fluctuations in the order of < 1 degrees/hour can still be observed in the rate (Figure 6). Since a very high degree of mechanical decoupling is achieved by the latest techniques, these changes are postulated to be due to mechanical coupling to the package itself through the die attach. It is also possible that they are related to the mechanical structure of the DRG itself. Further improvement in rate stability requires a better understanding and characterization of the mechanical processes inside the package.

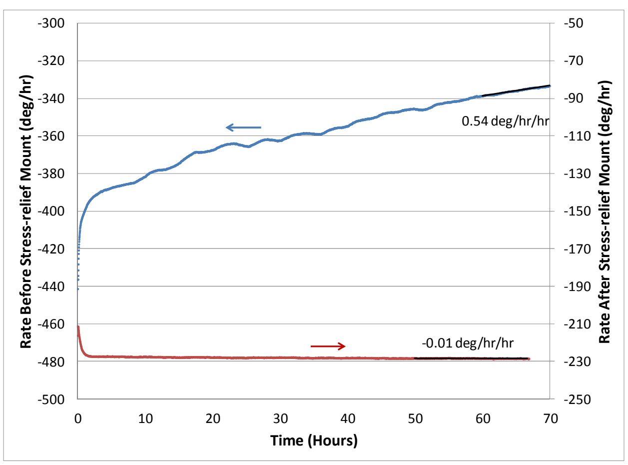

Figure 5. DRG Rate Ramp Post Mechanical Decoupling

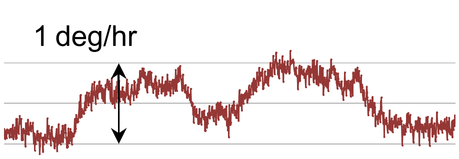

Figure 6. Rate Fluctuations after Mechanical Decoupling

Rate Stability and Noise

Figure 7 shows the Alan Deviation of rate in static condition after mechanical decoupling. Two distinct slopes are observed – a -1/2 and a -1 slope. The -1/2 slope is characteristic of white noise, and the -1 slope is characteristic of differentiated white noise. At lower time intervals, the white noise is the system is differentiated by the differentiator circuit used at the frontend to sense the current in the vibrating capacitors formed by the gyroscope sidewalls. At larger time intervals (> 1 second) this type of noise starts to get overwhelmed by undifferentiated white noise in the system. This excess white noise of unknown origin prevents the bias stability from reaching 0.01 degrees/hour in less than 1000 seconds. However once this noise is identified and removed, the system has the potential of reaching 0.01 degree/hour bias stability 10x than currently possible.

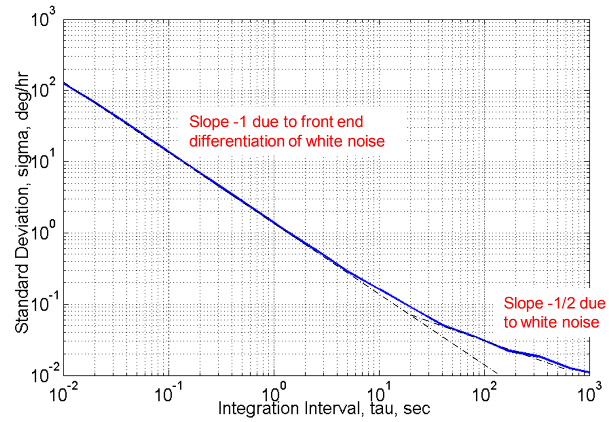

Figure 7. Alan Deviation Post Mechanical Decoupling

Similarly Figure 8 shows the current Power Spectral Density (PSD) for the system indicating an Angle Random Walk (ARW) of 0.005 degrees/hour/√Hz with potential for a 5x improvement. It should be noted that little to no ramping is observable in either Figure 7 or 8 since it has been largely removed through the application of mechanical decoupling.

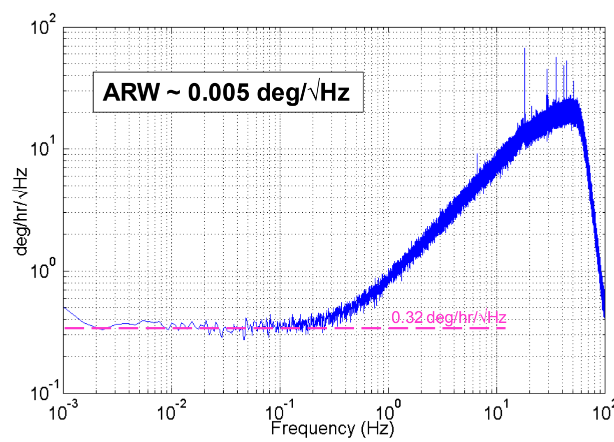

Figure 8. PSD Post Mechanical Decoupling

Conclusion

This paper has summarized the result of days of testing of multiple DRGs and identified several areas of investigation and development on the way to creating a precision navigation-grade system:

- Develop a packaging platform capable of isolating the DRG from external stress
- Develop a stress-free method of bonding the DRG to its platform
- Improve the thermal stability of the package such that thermal gradients across the package are minimized
- Eliminate sources of electrical and mechanical noise to reduce integration time

Once navigation-grade performance is achieved through the above improvements, power consumption and size can be reduced by decreasing sample rate and moving to Application-Specific Integrated Circuits (ASICs).

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