Force Rebalance, Whole Angle, and Self-Calibration Mechanization of Silicon MEMS Quad Mass Gyro

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***Abstract* — This paper reports experimental demonstration and characterization of the MEMS Quadruple Mass Gyroscope (QMG) operated in three distinct mechanizations, namely force rebalance, whole angle, and virtual carouseling self-calibration. The three runtime interchangeable control modes are implemented using a custom standalone electronics suite running control firmware with a separate computer GUI for experiment control and data logging. The results of this work demonstrate that the Coriolis Vibratory Gyroscope (CVG) Class II theoretical framework developed by D.D. Lynch is directly applicable to MEMS devices and establishes a path for potentially groundbreaking improvement of their long term stability in support of inertial navigation through self-calibration. While the simple fabrication and outstanding measured characteristics of the QMG ($Q>10^6$, $\Delta f<0.2$ Hz, $\tau>170$ s, $\Delta(1/\tau)<10^{-4}$ Hz) make it an ideal MEMS Class II CVG, a wide variety of other planar and 3-D mode-symmetric MEMS gyroscope resonators can leverage the developed approach, hardware, software, and analysis tools.**

Keywords* — *Coriolis Vibratory Gyroscope, MEMS, Foucault pendulum, inertial sensor, whole angle gyroscope, self-calibration.

I. Introduction

Coriolis Vibratory Gyroscopes (CVGs) can be divided in two classes according to the nature of the physical shape of the resonator and the vibration modes involved [1]. Class I MEMS CVGs are asymmetric structures, typically implemented as high Q-factor dual mass tuning forks, have shown potential for lower end and medium tactical grade performance. However, the technology appears to have reached its fundamental limitation with bias uncertainties on the order of 10 deg/h. In Class II CVGs, typically implemented as vibrating bars or axisymmetric shells, the two modes are identical, allowing for arbitrary positioning of the drive axis or pattern angle. This unique feature enables whole angle and self-calibration mechanizations in addition to the rate measuring force rebalance mode. This paper reports a successful realization of the approach using a recently developed Quad Mass Gyro (QMG) – a MEMS Class II CVG with lumped architecture.

II. Gyroscope System

The QMG is a silicon MEMS based on four proof masses coupled with anti-phase lever mechanisms [2, 3] providing two dynamically balanced vibration modes spatially separated by 90 degrees, Fig. 1. While the gyro has been previously demonstrated with $Q>10^6$ when packaged with a getter [4], a gyro packaged without getter and a Q of 10^3 was used here.

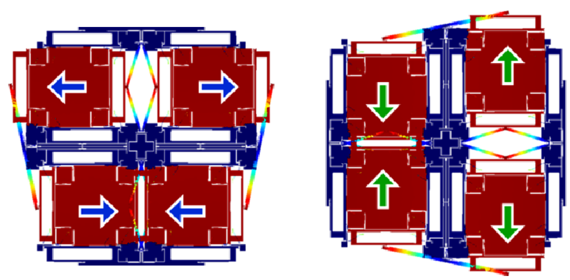

Fig. 1. Quad Mass Gyroscope resonator finite element modeling, showing two identical mode-shapes characteristic of a Class II CVG.

Fig. 2. Photograph of the standalone CVG controls suite fully compatible with the DARPA PALADIN test platform. The bottom card is a flexible DSP/FPGA unit; the top card has analog signal conditioning. QMG in a ceramic DIP-24 with a glass lid is in the center of the top card.

An electronics suite was developed to support standalone operation of the QMG, Fig. 2. The suite integrates a packaged MEMS device with an analog signal conditioning card and a digital control card in a single system electrically and mechanically compatible with DARPA PALADIN platform.

CVG control firmware running on the digital board implements the four primary servo loops: (1) drive amplitude, (2) drive frequency PLL, (3) sense Coriolis force rebalance, (4) sense quadrature. Additionally, the drive axis or the pattern angle can be (1) locked to a prescribed location for force rebalance operation, (2) allowed to precess in response to rotation for whole angle operation, or (3) commanded to slew at a prescribed rate for virtual carouseling or self-calibration.

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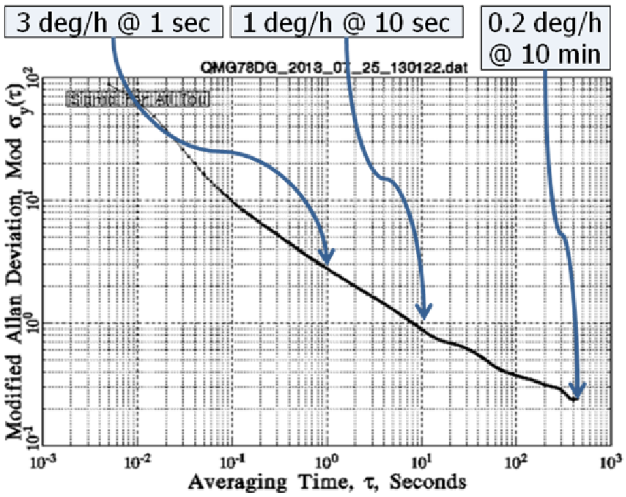


Fig. 3. Allan Deviation characterization of force rebalance operated QMG (sealed without getters at a Q=10^3) showing 0.05 deg/rt-hr ARW and <0.2 deg/hr bias instability. Both values are expected to improve proportionally to the increase of Q from 10^3 to 10^6 using getters. The gyroscope full scale is 1350 deg/s, providing a dynamic range of 147 dB.

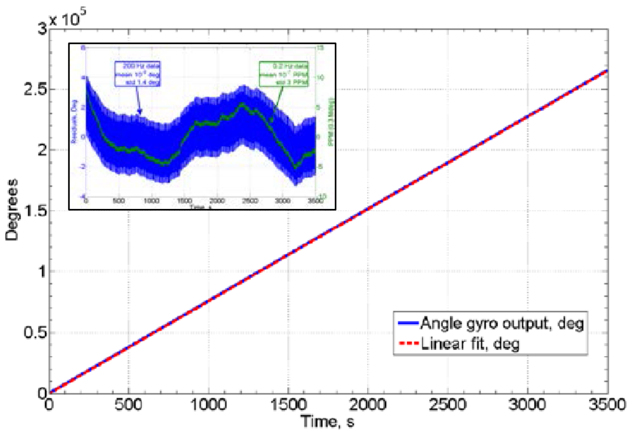


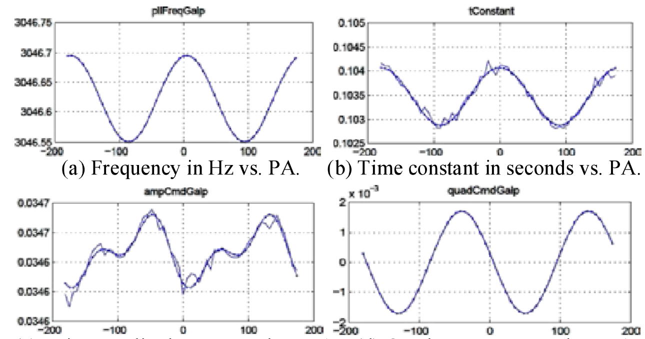
Fig. 4. Whole angle demonstration. The gyroscope was rotated at a 100 deg/s for 1 hr, showing excellent 3 ppm scale factor instability (inset).

III. CHARACTERIZATION RESULTS

A QMG with an operational frequency of 3047 Hz, as-fabricated frequency mismatch of 0.15 Hz, and a Q of 10^3 was integrated and characterized in all three mechanization modes. Switching between the modes is done through a computer GUI and does not require any hardware changes or adjustments.

Experiments in the force rebalance rate measuring mode demonstrated a full scale of 1350 deg/s, an ARW of 0.05 deg/rt-hr, and a bias instability of 0.2 deg/hr or 0.05 ppm of the full scale, Fig. 3. Characterization over power and temperature cycles showed excellent bias and scale factor repeatability.

To characterize operation of the whole angle mode, the gyroscope system was rotated at constant rates of ±100 deg/s for 1 hour at several different temperatures. The data, shown in Fig. 4, revealed a constant angle gain of 0.75 which agrees well with analytical modeling of the effect of the shuttle mass [2, 3]. Analysis of the linear fit to the angle data showed a scale factor instability of only 3 ppm, showcasing one of the inherent advantages of the whole angle mechanization of Class II CVG.



(a) Frequency in Hz vs. PA. (b) Time constant in seconds vs. PA.

(c) Drive amplitude command vs. PA. (d) Quadrature command vs. PA.

Fig. 5. Demonstration of self-calibration using virtual carouseling of the Pattern Angle (PA). Mismatches and misalignments in frequency, damping, and gains are made observable as functions of PA, enabling elimination of their bias contributions according to D.D. Lynch models.

Self-calibration mechanization uses virtual carouseling, i.e. slewing of the pattern angle and monitoring of control signals in the gyroscope servo loops, Fig. 5. As a result, mismatches and misalignments of stiffness and gains are identified in the nominally symmetric gyroscope. In addition, a ringdown measurement is automatically conducted at multiple equally spaced pattern angle orientations, making the damping mismatch and misalignment observable. Self identification of these imperfections enables elimination of their respective bias contributions using the math models developed by D.D. Lynch.

IV. CONCLUSIONS

We have shown practicality and benefits of force rebalance, whole angle, and virtual carouseling mechanizations in a standalone QMG system. Measured performance is expected to improve furthermore with the currently ongoing testing of a getter packaged QMG. The approach may enable orders of magnitude improvement in noise and stability of MEMS gyros.

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