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Development of a Single-Chip MEMS Gyrocompass

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This presentation will discuss the gyrocompass-on-a-chip with built-in vibration isolation and compensation currently being developed at the University of California, Irvine under a grant from the Navy. The objective of this program is self-leveling, ultra-high performance Micro-Electro-Mechanical-Systems (MEMS) gyroscope capable of azimuth detection with 0.001 radian accuracy and amenable to standard silicon wafer batch fabrication and vacuum packaging. Relatively low Quality (Q) factors caused by small size, fabrication imperfections, design and packaging drawbacks are widely recognized as the main performance limiting factors for silicon MEMS gyroscopes. In contrast to the quartz precision machined, navigation-grade Northrop Grumman Hemispherical Resonator Gyroscope (HRG) with a Q-factor of several millions, best MEMS gyroscopes reach Q-factors of only 0.1 million. Our group has developed and demonstrated a new silicon Quadruple Mass Gyroscope (QMG) with Q-factor above 1 million and sub-deg/hour performance. Due to the unique design, with mechanical energy dissipation time constant in excess of 1 minute, the same sensor element is capable of interchangeable operation in three different modes of inertial measurement: precision rate mode, rate integrating (whole angle) mode, and inherently frequency modulated (FM) modes. We believe the developed ultra-high Q-factor QMG sensor element with 3 interchangeable modes of operation may enable low SWaP silicon MEMS devices for north finding and inertial guidance applications previously limited to high-cost, power hungry optical and quartz sensors.
The presentation will report detailed characterization of the high resolution silicon micromachined QMG sensor with measured sub-degree-per-hour bias stability enabled by a Q-factor above 1 million. The gyroscope sensor utilizes proprietary, dynamically balanced Quadruple Mass Gyroscope (QMG) architecture, which suppresses substrate energy dissipation and maximizes Q-factors. Dissipation of energy through the substrate is minimized by the means of complete anti-phase operation, facilitated by an integrated mechanical lever mechanism. Operation at low frequencies (on the order of 1 kHz) decouples the mechanical resonance and thermal relaxation time constants, thereby increasing the fundamental thermoelastic Q-factor limit above 1 million, which is an order of magnitude improvement compared to previous state-of-the-art silicon MEMS. Characterization of a stand-alone, sub-mTorr vacuum sealed QMG prototype confirmed the ultra-high, drive- and sense-mode symmetric Q-factor of 1.1 million, which translates into a 0.01 deg/hour /rt-Hz fundamental mechanical-thermal noise limit.

Ultra-high sensitivity silicon MEMS rate sensors are desired for the multiple inertial navigation and north-finding applications. An optimal architecture of a high resolution vibratory rate gyroscope should comprise a symmetric mechanical structure with a combination of high Q-factors, high Coriolis coupling, drive- and sense-mode degeneracy, and frequency tuning capability. Usually these requirements are addressed by using continuous structures such as disks and rings operated in balanced wineglass modes. However, the limited design space of continuous structures inherently couples Q, drive-amplitude, and operational frequency, limiting the achievable performance. In comparison to the precision machined, axisymmetric HRG, previously investigated silicon MEMS gyroscopes suffered from aniso-elasticity, aniso-damping, and short energy dissipation constants less than 1 second. The frequency trimming and tuning is also more challenging for continuous structures as both mass and stiffness are collocated. An alternative approach proposed in this paper is to use a lumped, dynamically balanced, 4-quadrant symmetric QMG architecture. It comprises four symmetrically decoupled tines synchronized by anti-phase levers, providing a unique combination of low energy dissipation and isotropy of both the resonant frequency and damping. Due to the symmetry of the device, the drive- and sense-modes are degenerate and provide identical temperature coefficients of frequency for increased robustness to the temperature-induced drifts. At the same time, the QMG is expected to provide ultra-high Q-factors and enable high precision angular rate measurements.

Stand-alone prototypes of the QMG were fabricated using an in-house 100 um SOI process and packaged using custom technology for robust vacuum sealing of high-Q gyroscopes. Mechanical characterization of the vacuum sealed prototype using ring-down tests revealed symmetric drive- and sense-mode Q-factors of 1.11 and 1.06 million, approaching the device thermoelastic limit of 1.3 million. The ultra-high Q-factor translates into the fundamental mechanical-thermal resolution limit of 0.01 deg/hour/rt-Hz for mode-matched operation, suggesting feasibility of the QMG sensor for gyrocompassing applications. Rate characterization was performed under a 0.2 Hz frequency mismatch in the input range of 45 deg/hour. The noise performance measured from a zero rate output of the QMG prototype revealed 0.06 deg/hour ARW, 0.88 deg/hour bias stability, and 0.01 deg/hr*rt-Hz ARRW. For preliminary analysis of the north-finding application, the long-term bias drift was compensated by carouseling on a rate table, which results in frequency modulation of the input angular rate. A sinusoidal modulation of the Earth´s rotation was produced by changing the orientation of the QMG relative to the Earth´s rotation axis. The gyroscope output was 15 deg/hour when the sensitive axis was pointing to the true north. The azimuth error of the sinusoidal fit was computed for different averaging times, revealing a 150 mrad accuracy for 5 minutes at 33 deg latitude. Our experimental results and modeling suggests feasibility of the QMG sensor for gyrocompassing applications.

Inspired by the successful development of the silicon micromachined QMG angular motion sensor, we are currently investigating a multi-axis MEMS IMU for self-contained gyrocompassing by developing a single-die, completely FM-based, quasi-digital architecture. A proof of concept implementation is being developed as a single-chip solution, combining an ultra-high Q-factor, quasi-digital QMG gyroscope co-fabricated with two complementary resonant tuning fork, high-resolution, quasi-digital accelerometers. Embedded accelerometers enable self-alignment of the gyro axis to the gravity field and feedback compensation of vibrations and shock. Toward this goal, we have developed and demonstrated complementary resonant MEMS accelerometers with 0.05 ppm frequency stability and sub-mg bias. Due to the inherent FM nature of the proposed system, it is expected to provide resolution and stability unprecedented in conventional inertial MEMS devices.

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