High-Q and Wide Dynamic Range Inertial MEMS for North-Finding and Tracking Applications

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***Abstract*—We report high-Q and wide dynamic range MEMS gyroscopes and accelerometers for development of an IMU capable of north finding and tracking. The vacuum sealed SOI gyroscope utilizes symmetric quadruple mass architecture with measured quality factors of 1.2 million and proven sub–°/hr Allan deviation of bias. The true north detection was accomplished in conventional amplitude modulated (AM) rate mode and showed 3 milliradian measurement uncertainty. The north (azimuth) tracking necessitates a wide dynamic range, for which the same QMG transducer is switched to a frequency modulated (FM) modality. The test results for FM operation experimentally demonstrated a wide linear input rate range of 18,000 °/s and inherent self-calibration against temperature changes. Vertical alignment is possible using resonant accelerometers with a projected bias error of 5 μg and self-calibration against temperature variations, enabled by differential frequency measurements. We believe the developed low dissipation inertial MEMS with interchangeable AM/FM modalities may enable wide dynamic range IMUs for north-finding and inertial guidance applications previously limited to optical and quartz systems.**

I. INTRODUCTION

North-finding with milliradian (mrad) precision and azimuth tracking in a wide dynamic range is required for targeting, dead reckoning, and inertial guidance of fast spinning objects [1]. North identification is traditionally accomplished through the use of the magnetic field of the Earth; however, there are a number of spatial and temporal distortions in this field which limit the accuracy of this method. Moreover, practical limitations of geodetic, celestial, and GPS-based methods make high performance gyroscopes desirable for true north seeking (gyrocompassing). Although conventional fiber optic, ring laser, and macro-scale quartz hemispherical resonator gyroscopes can be used for precision gyrocompassing, they are not perfectly suited for man-portable and small vehicle applications. MEMS, in contrast, have a number of benefits when used as inertial sensors: they are light-weight, low-power, batch-fabricated, and are potentially capable of high performance operation, given the proper design.

Gyrocompassing typically requires better than 0.05 °/hr total bias error over temperature variations for repeatable measurements of the Earth's rate and 0.1 mg total bias error for vertical alignment. Several groups have reported silicon MEMS gyroscopes with sub–°/hr Allan deviation of bias [2]–[7]; however, single digit mrad north-finding and tracking over dynamic environment is often assumed unattainable by MEMS technology [8]. We propose to tackle this issue using the recently developed quadruple mass gyroscope (QMG) [9] and a new resonant accelerometer, with the resolution enhanced by high Q-factors and wide dynamic range provided by frequency modulated (FM) operation, which is also robust to temperature variations and shocks. Fig. 1 shows a photograph of a pyramid inertial measurement unit (IMU) prototype comprising MEMS quadruple mass gyroscopes and resonant accelerometers. This paper summarizes our recent publications [6], [7], [9]–[11] and reports new results on the resonant accelerometer.

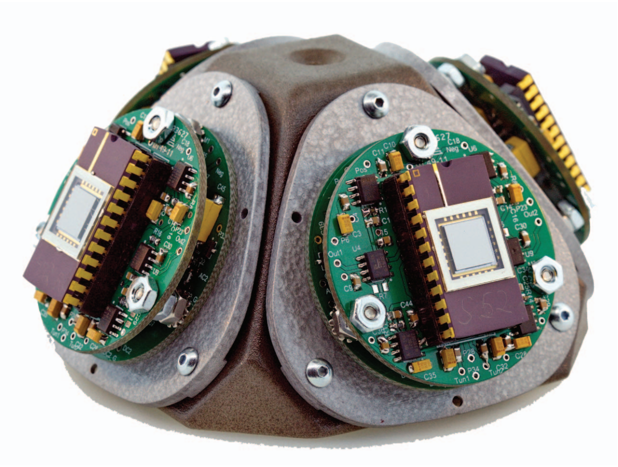
Fig. 1. Photograph of a pyramid inertial measurement unit (IMU) prototype comprising MEMS quadruple mass gyroscopes and resonant accelerometers.

II. QUADRUPLE MASS GYROSCOPE

The QMG transducer [9] was chosen for the IMU development due to its symmetric design with low energy dissipation and isotropy of both frequency and damping. Standalone QMGs were fabricated using an in-house silicon-on-insulator (SOI) process with a 100 μm device layer and a 5 μm sacrificial oxide. Singulated devices were vacuum sealed using a ceramic package technology with getters, providing a sub-mTorr vacuum sustainable over many years. Mechanical characterization of the packaged QMGs using ring-down tests

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This work was supported by the Office of Naval Research (ONR) and Naval Surface Warfare Center Dahlgren Division (NSWCDD) under grants N00014-09-1-0424 and N00014-11-1-0483.

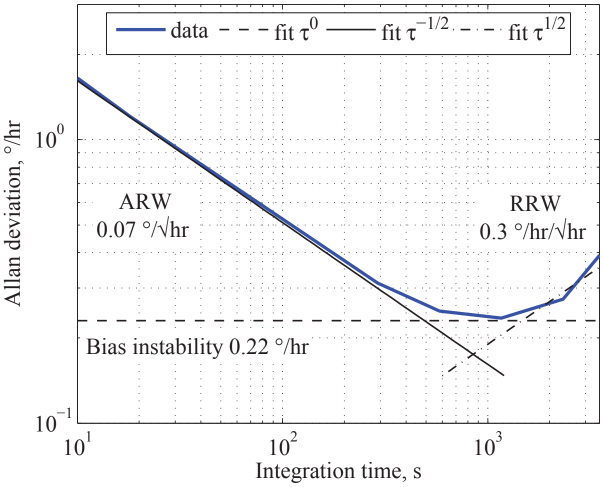

Fig. 2. Allan deviation of the QMG sensor used in this work, revealing a 0.07 °/$\sqrt{\text{hr}}$ ARW, and a 0.22 °/hr bias stability in rate measuring AM mode.

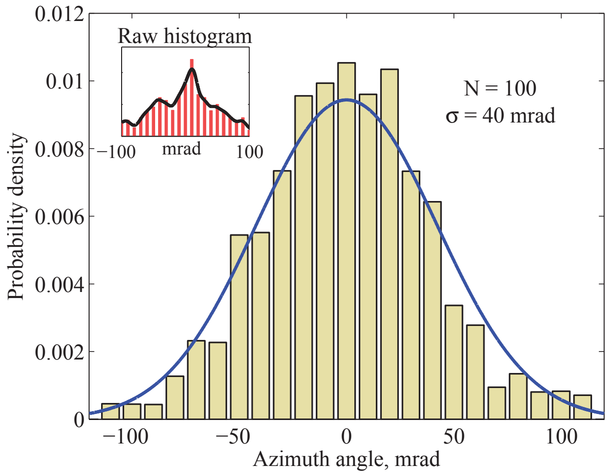

Fig. 3. Azimuth histogram with normal distribution fit after temperature self-compensation, showing a 40 mrad error of maytagging. Inset: raw histogram.

showed drive- and sense-mode Q-factors of 1.2 million, with ΔQ/Q symmetry of 1% [11]. The high Q-factor translates into an exceptional mechanical-thermal resolution limit of 0.0001 °/$\sqrt{\text{hr}}$ for mode-matched operation, suggesting feasibility of the sensor for gyrocompassing applications. Thermal cycling confirmed Q-factor above 0.7 million for temperatures up 100 °C (with Q of 1.7 million for –20 °C) [6].

The noise performance of the gyroscope used in this work was evaluated using the Allan deviation analysis. Fig. 2 shows current test results for the conventional amplitude modulated (AM) rate measuring mode [6], without temperature calibration. The QMG demonstrated angle random walk (ARW) of 0.07 °/$\sqrt{\text{hr}}$ (4.2 °/hr/$\sqrt{\text{Hz}}$), in-run bias of 0.22 °/hr, and rate random walk (RRW) of 0.3 °/hr/$\sqrt{\text{hr}}$ (0.005 °/hr×$\sqrt{\text{Hz}}$). Next, we demonstrate that the low level of noise the QMG allows north detection based on the Earth's rotation measurements.

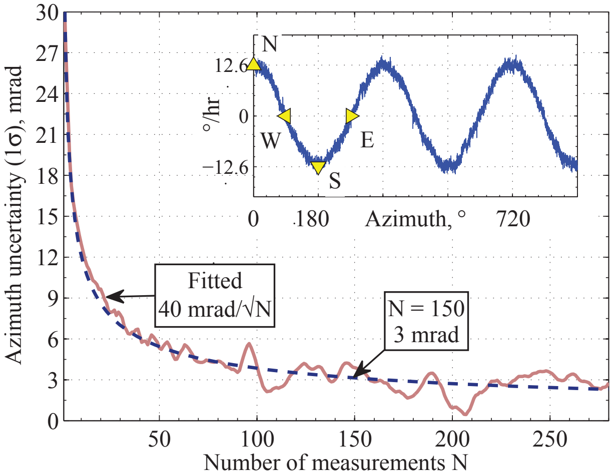

Fig. 4. Azimuth uncertainty as a function of filtered measurements. A 3 mrad error is achieved after 150 datapoints. Inset: Earth's rotation measurements.

III. NORTH-FINDING DEMONSTRATION

The true north orientation (as opposed to the magnetic north) is found by observing the horizontal component of the Earth's rotation vector. We implemented both "maytagging" and "carouseling" of a gyroscope on a rotary platform for north-finding.

A. *Maytagging for North-Finding*

"Maytagging" is discrete ±180° turning of the gyroscope sensitive axis, which allows for differential azimuth detection. Following this approach, we mounted the QMG with its input axis horizontal on a rotary platform and separated the Earth's rotation rate from the sensors bias by a virtue of 0° to 180° turns. By combining the east (0°) and west (180°) readings of platform heading, both azimuth (north direction) and the gyroscope bias were recovered.

The differential "maytagging" approach is effective for the constant bias. In practice, however, bias was time-varying and residues were still present in azimuth measurements, Fig. 3 inset. The detailed analysis confirmed temperature variations to be the primary drift source. Temperature self-compensation using the gyroscope frequency as an embedded thermometer resolved normal distribution of measurement errors. The azimuth uncertainty of 100 repeated measurements was 40 mrad before filtering or averaging [7], Fig. 3.

B. *Carouseling for North-Finding*

The continuous modulation of the constant Earth's rate for separation from the sensor bias is also possible as an alternative to the 2-point discrete azimuth measurement ("maytagging"). The continuous rotation or "carouseling" mechanization of the platform allows identification of azimuth angle, bias and scale-factor error. Specifically, the true north was detected by rotating the QMG sensitive axis in a horizontal plane with a 1 °/s rate, which modulates the Earth's constant rate with a 6 minute period, Fig. 4 inset. Every 6 minutes the azimuth was extracted from a sinusoidal fit.

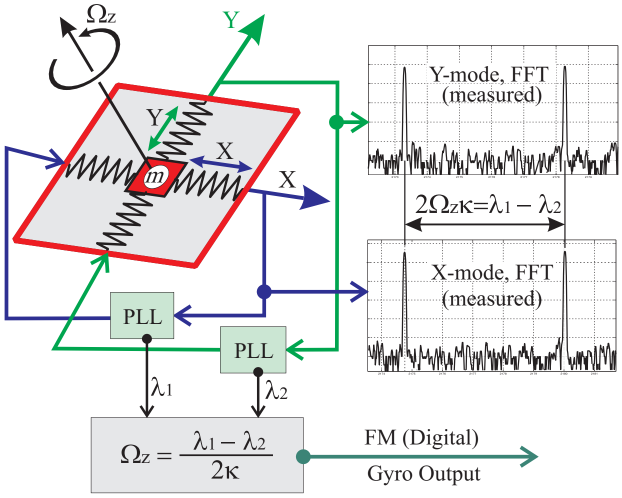

Fig. 5. Schematic of the gyroscope operation based on the mechanical FM of the input angular rate. Inertial rotation causes a split between the gyroscope's two vibratory modes, producing an FM measure of the input rate.

Probability analysis of the measurements revealed a Gaussian error model without any temperature calibration [7]. By filtering a sequence of multiple azimuth measurements, a progressively more precise azimuth was obtained (beyond the resolution of the gyroscope). The measurement uncertainty scaled down as the square root of the number of turns, Fig. 4. The experiment achieved a 3 mrad uncertainty by averaging of 150 azimuth datapoints. Ongoing improvements in the gyroscope layout and electronics are projected to reduce the 3 mrad gyrocompassing time down to one minute.

IV. NORTH-TRACKING CONCEPT

While north-finding necessitates a very low noise and narrow range sensor, north-tracking and navigation through fast motion adds the requirements for wide dynamic range and robustness. The QMG transducers addresse these challenges by switching between the high resolution AM and wide range FM measurement modalities [10].

A. *FM Gyroscope Operating Principle*

The frequency modulation (FM) approach tracks the resonant frequency split between two symmetric high-Q mechanical modes of vibration in the QMG transducer to produce a frequency based measurement of the input angular rate with inherent self-calibration against temperature variations, Fig. 5. The FM operation mode eliminates the gain-bandwidth and dynamic range trade-off of conventional AM gyroscopes and enable signal-to-noise ratio improvements by taking advantage of high-Q transducer without limiting the measurement range and bandwidth.

B. *Wide Dynamic Range Demonstration*

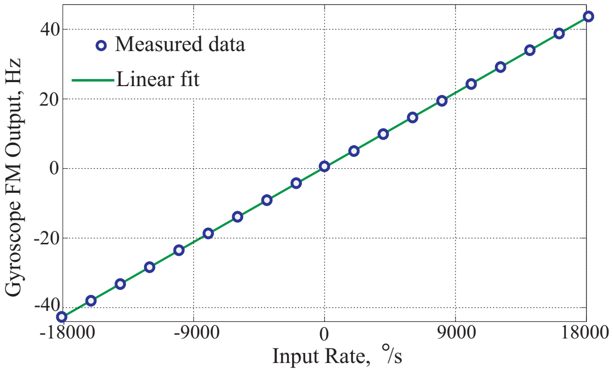

Fig. 6. Experimental characterization of the QMG in FM mode reveals less than 0.2% nonlinearity in a wide input range of 18,000 °/s.

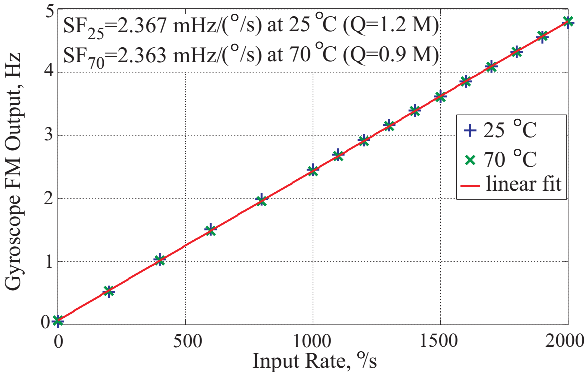

Fig. 7. Rate characterization of the QMG in FM mode shows no drift in the response for 25 °C and 70 °C despite a 30% reduction in Q-factor and a 5 Hz drop of nominal frequency (without any temperature compensation).

The proposed FM gyroscope operation provides a wide input rate range, limited only by the natural frequency of a mechanical element [11]. For the experimental validation, a vacuum packaged QMG was mounted on an Ideal Aerosmith High-Speed Position and Rate Table System 1571, and characterized from 0 to 18,000 °/s (50 revolutions per second). Without any compensation, the FM instrumented QMG demonstrated less than 0.2% nonlinearity throughout the entire range, Fig. 6.

Theoretical analysis of the proposed FM rate sensor also suggests immunity against the temperature-induced drifts by virtue of the differential frequency detection, i.e. by measuring the frequency split [10]. To experimentally investigate this concept, a vacuum packaged QMG sensor operated in FM mode was characterized on a temperature controlled Ideal Aerosmith 1291BR rate table. Without any active temperature compensation, experimental characterization of the FM instrumented QMG revealed less than 0.2% scale-factor change from 25 °C to 70 °C, Fig. 7. Despite a 30% reduction of the Q-factor and a 5 Hz change of the nominal frequency, the scale-factor sensitivity was less than 50 ppm/°C (limited by the experimental setup noise), demonstrating temperature robustness of the differential FM measurements.

The interchangeable AM/FM operation of the QMG sensor is expected to provide wide dynamic range for north-finding and north-tracking applications. The measured 0.22 °/hr bias instability of the AM mode combined with the measured

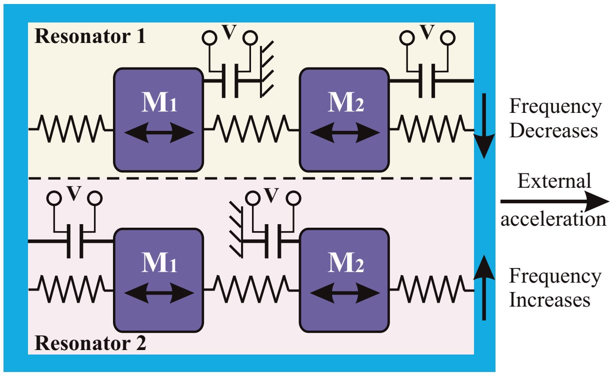

Fig. 8. Conceptual schematic of the accelerometer based on differential frequency measurement of the input acceleration.

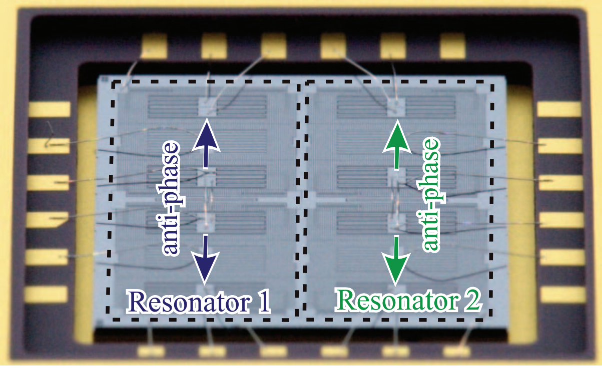

Fig. 9. An SOI prototype of the accelerometer based on frequency modulation of the input acceleration.

±18,000 °/s linear range of the FM mode enables the dynamic range of at least 170 dB. This makes a single high-Q MEMS transducer fitted for demanding high precision and wide input range applications.

V. VERTICAL ALIGNMENT

Alignment of the gyroscopes with respect to the gravity field is required for accurate north-finding and tracking. In this section we demonstrate proof of concept FM accelerometer for the vertical alignment.

A. Frequency-Based Acceleration Detection

The proposed resonant accelerometer comprises two MEMS vibratory tuning fork resonators, Fig. 8. Due to the applied electrostatic tuning, the input acceleration induces change in the natural frequencies of the resonators. Mirrored relative position of the two resonators ensures the identical frequency shifts, but with opposite signs, Fig. 8. The signal processing circuit tracks the frequency difference between the two resonant accelerometers, enabling the differential measurement. The proposed FM operation is expected to provide both inherently temperature-robust and quasi-digital measurement of the input acceleration.

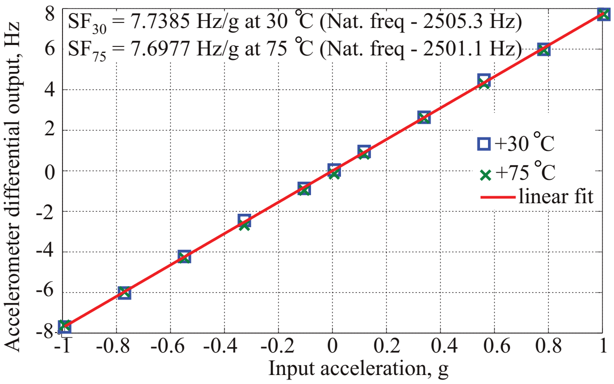

Fig. 10. Characterization of the differential FM accelerometer reveals a scale-factor change of less than 0.5% between 30 °C and 75 °C.

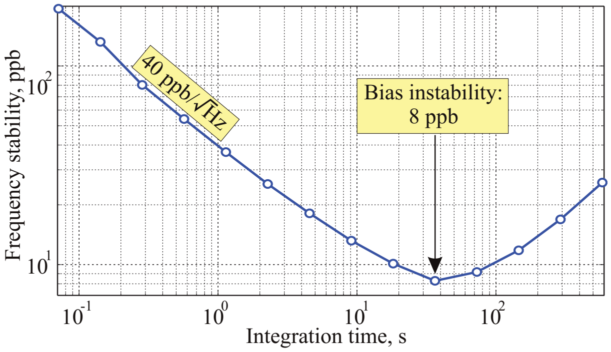

Fig. 11. Measured Allan deviation of the vacuum sealed high-Q tuning fork resonator, showing a 8 ppb frequency stability at 30 s time constant.

B. Accelerometer Demonstration

The approach validation was accomplished using a stand-alone silicon FM-based accelerometer fabricated in the 100 μm SOI process, Fig. 9. The device was tested by measuring response to the gravity field using an automated tilt stage. The natural frequencies of both resonators were recorded for each inclination. To investigate the temperature-robust concept of the proposed accelerometer, the same experiment was performed at the temperatures of 30 °C and 75 °C for the input range of ±1 g, Fig. 10. The measured split between the nominally equal natural frequencies was directly proportional to the input acceleration, Fig. 10. Experimental characterization of the differential FM accelerometer revealed less than 0.5% scale-factor change between 30 °C and 75 °C temperatures, Fig. 10. The noise performance of the FM-based accelerometer depends on the natural frequency stability of the anti-phase mode of the resonator. We demonstrated a 0.01 ppm frequency stability for the high-Q tuning fork resonator at 0 Vdc polarization voltage, Fig. 11. Using the measured scale factor of 4 Hz/g (at 28 Vdc), we project a bias instability of 5 μg and a velocity random walk of 25 $\mu g/\sqrt{Hz}$, after vacuum sealing.

VI. CONCLUSIONS

We demonstrated low dissipation silicon MEMS gyroscopes and accelerometers with interchangeable AM/FM modality for wide dynamic range IMU development. The current performance results for vacuum sealed quadruple mass gyroscope (QMG) showed Q-factors of 1.2 million and total bias error of 0.5 °/hr over temperature variations [7]. Continuous rotation ("carouseling") and discrete ±180° turning ("maytagging") were implemented for true north detection, demonstrating a 3 mrad azimuth uncertainty. Once north has been identified, it can be tracked by the same transducer using FM method of detection with a proven 170 dB dynamic range. Vertical alignment is enabled by the proposed resonant accelerometers, with precision ensured by differential frequency measurements of the acceleration. We project a 5 μg bias error for FM accelerometer after vacuum sealing.

Inspired by the progress on the low dissipation inertial MEMS, we are currently developing a multi-axis MEMS-based IMU with inherently quasi-digital FM operation. Currently we are developing a single-die system comprising a gyroscope and two resonant accelerometers in a shared vacuum package. Due to the inherent FM nature of the system, it is expected to provide dynamic range and stability unprecedented in conventional inertial MEMS, while simultaneously reducing the power consumption of the analog-digital interface.

ACKNOWLEDGMENT

Authors thank Brent Simon and Dr. Gunjana Sharma for aid with layout design and fabrication of the accelerometers.

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