Thermal Calibration of Silicon MEMS Gyroscopes

I.P. Prikhodko, S.A. Zotov, A.A. Trusov, A.M. Shkel

MicroSystems Laboratory, Mechanical & Aerospace Engineering, University of California, Irvine, CA

ABSTRACT

We report our progress on the development of thermal calibration and stabilization for silicon MEMS gyroscopes with high quality (Q) factors. The temperature-induced drifts of most MEMS limit their potential applications in real-world missions. To address this limitation, we investigated a long-term bias drift compensation algorithm using the silicon MEMS quadruple mass gyroscope (QMG) with signal-to-noise ratio enhanced by 1.2 million Q-factor. The thermal calibration using an external temperature sensor removed a 99% temperature correlation between the temperature and the gyroscope output. The calibration stabilized the QMG output subject to temperature variations during a 24 hr run, resulting in Allan deviation bias instability improvement from 0.6 °/hr to 0.35 °/hr. Most importantly, this method removed a temperature ramp and resolved a 1 °/hr/$\sqrt{\text{hr}}$ rate random walk, indicating and improved long-term stability.

Keywords: MEMS, gyroscope, calibration, quality factor.

1 INTRODUCTION

In recent years several groups have reported silicon MEMS gyroscopes with sub-deg/hr Allan deviation bias instability [1]–[3]. However, long-term bias drifts limit their potential applications in real-world missions. The drift source for most MEMS is their inherent sensitivity to temperature variations. An uncompensated bias sensitivity of 500 (°/hr)/°C is typical for MEMS gyroscopes [4], [5], and requires temperature calibration to enable long-term measurements of small angular rates. While quartz oscillators [6] and MEMS resonators [7] have significantly advanced in compensation methods, the temperature stability of gyroscopes is still inferior, and requires new approaches. In this paper we investigate temperature sensitivity and propose compensation algorithms for the vacuum packaged silicon MEMS quadruple mass gyroscope (QMG) with measured quality (Q) factors of 1.2 millions [1], [2], Fig. 1. The calibration of QMG sensor using an external thermistor removed temperature-dependant drifts and enabled a sub-deg/hr bias instability over environmental changes.

2 THERMAL CALIBRATION

The gyroscope's voltage output relative to the nominal null offset is a measure of the input rotation rate. This offset value (bias) is thus contributes to the overall accuracy of angular rate measurements. The initial bias is determined experimentally by averaging the zero rate (static) output. However, bias is temperature dependent, and the calibration is necessary prior to gyroscope operation. The calibration takes advantage of the temperature sensitivity coefficient of bias, which in turn depends on the temperature coefficient of frequency (TCF). The TCF defined by the material's elastic properties is linear for silicon (near room temperature), and thus bias dependence is also linear. Provided instantaneous gyroscope temperature readings, the real-time compensation of the gyroscope output using the sensitivity coefficient of bias is feasible.

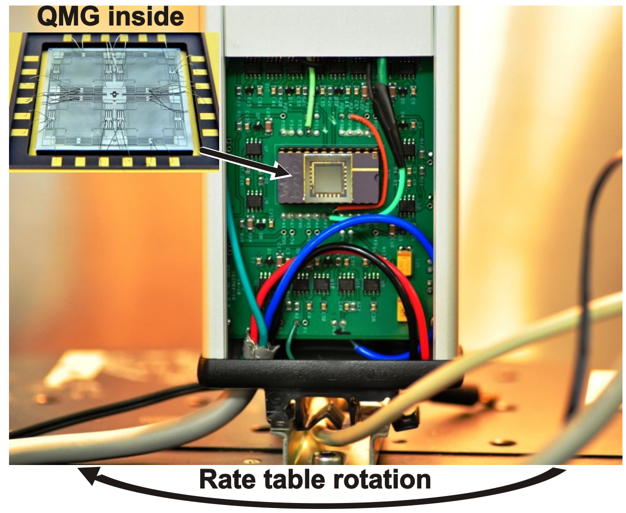

Figure 1: Photo of the experimental setup, showing the vacuum packaged QMG rate sensor, PCB electronics, and the rate table located inside a thermal chamber.

3 EXPERIMENTAL RESULTS

Temperature sensitivity is significantly reduced by the QMG transducer design symmetry [8], [9], which ensures frequency and damping isotropy over wide temperature range. Nevertheless, fabrication and packaging imperfections, as well as electronic components drifts contribute to the temperature sensitivity of the gyroscope output. The thermal calibration was accomplished by a stand-alone silicon QMG, with the performance enhanced by the Q-factors of 1.2 million [1], [2], Fig. 1.

All experiments were performed using a custom PCB connected to a LabView programmable, FPGA-based, HF2 lock-in amplifier from Zurich Instruments. The vacuum packaged sensor was mounted on a PCB with front-end electronics and installed on a 1291BR Ideal Aerosmith rate table inside the thermal chamber. The drive-mode was operated closed-loop, while the sense-mode remained open-loop. The PLL-based drive-loop sustained

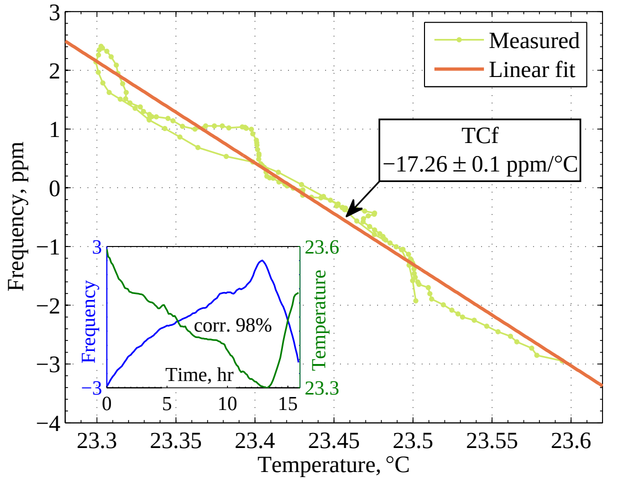

Figure 2: Linear frequency-temperature dependence, revealing a −17 ppm/°C temperature coefficient of frequency. Inset: measured 98% temperature and frequency correlation.

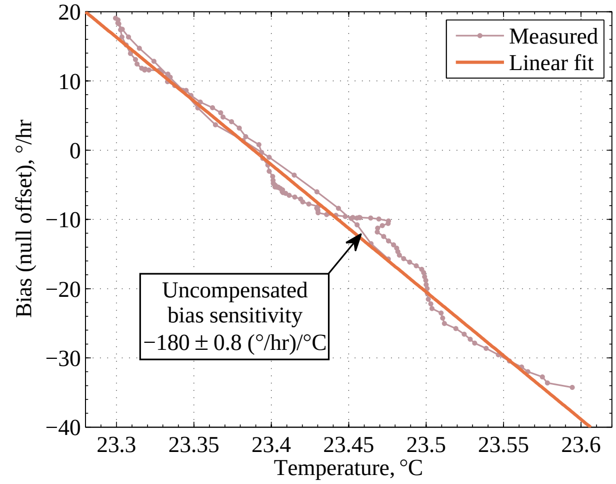

Figure 4: Uncompensated temperature dependence of a QMG output, revealing a −180 °/hr/°C bias sensitivity.

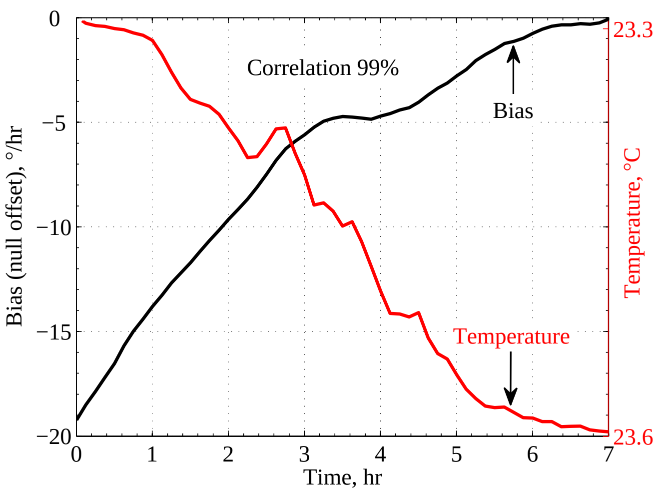

Figure 3: Measured 99% correlation of a QMG bias (null offset) and room temperature during a 7 hr run.

oscillation at resonance and provided reference for the signal demodulations. The AGC stabilized the amplitude of drive-mode motion. The gyroscope output proportional to the angular rate was detected by demodulating the sense-mode signal. The experiments were conducted using the vacuum sealed QMG at 0.16 Hz frequency mode-matching condition. The room temperature was logged using a 10^{-4} °C resolution thermistor from GEC Instruments.

The room temperature and resonant frequency recorded over a 16 hr run showed a strong 98% correlation, Fig. 2 inset. As shown in Fig. 2, the resonant frequency changes linearly with the temperature as −17±0.1 ppm/°C. Similarly, the strong correlation between the gyroscope bias and the temperature was observed during a 7 hr run. The measured 99% correlation confirmed the environmental changes to be a primary drift source, Fig. 3. As predicted, linear relationship is observed for bias values plotted as a function of the on-chip gyroscope temperature, Fig. 4. The temperature sensitivity coefficient of −180 ±0.8 (°/hr)/°C was found by linear least squares fitting. The measured sensitivity coefficient is then used to perform temperature compensation.

To perform calibration, the temperature from the external thermistor is converted to bias units using −180 (°/hr)/°C coefficient and subtracted from the gyroscope output. Fig. 5 compares the time history of raw and compensated zero rate (static) outputs recorded during a 24 hr run with day/night temperature variations. The compensation of sense-mode drifts reduced the apparent long-term drift and reduced the temperature correlation from 97% to below the measurement error, indicating that the gyroscope output was no longer affected by the temperature fluctuations Fig. 5.

To further analyze the noise performance of the QMG, the Allan deviation method was applied to the Fig. 5 data. Allan deviation allows to determine the random processes present in the gyroscope output, Fig. 6. Fit to the $\tau^{-1/2}$ slope (white noise) at the short integration time revealed a 0.1 °/$\sqrt{}$hr angle random walk. The flicker noise reached for integration times of approximately 3 min indicated a 0.6 °/hr bias instability. For times longer than 200 s the output was dominated by the temperature ramp with the τ^1 slope. The thermal calibration allowed to improve the bias instability by two fold and remove temperature ramp, reaching 0.36 °/hr at 10 minutes time constant, Fig. 6. The longer time constant also indicates the improved long-term stability of the gyroscope output. Fit to the $\tau^{1/2}$ slope at larger time intervals ($>$ 600 s) revealed that the output is limited by the random walk process of 1 °/hr/$\sqrt{}$hr (as opposed to the output dominated by temperature-induced drifts).

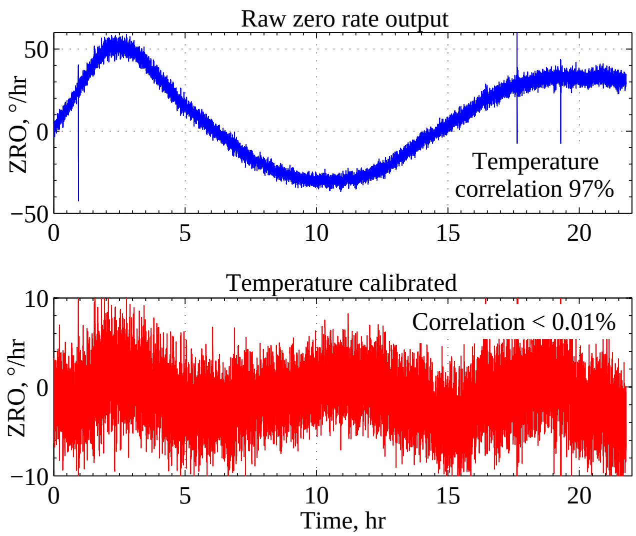

Figure 5: Time history of a QMG zero rate output over day/night temperature changes during 24 hr. Thermal calibration removes temperature correlation.

4 CONCLUSIONS

We demonstrated a thermal calibration algorithm for high-Q silicon MEMS gyroscopes. The thermal calibration using a precision thermistor removed a 99% temperature correlation between the temperature and the QMG rate sensor output. The calibration stabilized the gyroscope output subject to temperature variations during a 24 hr run, resulting in Allan deviation bias instability improvement from 0.6 °/hr to 0.35 °/hr. Most importantly, this method removed a temperature ramp and resolved a 1 °/hr/$\sqrt{}$hr rate random walk. These efforts effectively allowed to reach long-term stability of the QMG rate sensor, providing a path for inertial-grade MEMS gyroscopes.

ACKNOWLEDGEMENTS

This work was supported by the ONR/NSWCDD grants N00014-09-1-0424 and N00014-11-1-0483. Authors would like to thank Zurich Instruments AG and SST International.

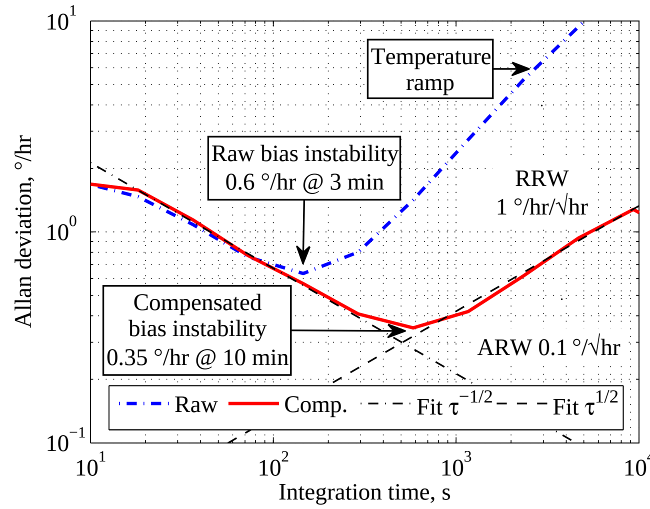

Figure 6: Allan deviation of the Fig. 5 data, showing a 0.35 °/hr bias instability after thermal calibration.

REFERENCES

[1] I.P. Prikhodko, S.A. Zotov, A.A. Trusov, A.M. Shkel, "Sub-degree-per-hour silicon MEMS rate sensor with 1 million Q-factor," Proc. 16th Int. Solid-State Sensors, Actuators and Microsystems Conf. (Transducers'11), Beijing, China, June 5–9, 2011, pp. 2809–2812.

[2] I.P. Prikhodko, A.A. Trusov, A.M. Shkel, "North-finding with 0.004 radian precision using a silicon MEMS quadruple mass gyroscope with Q-factor of 1 million," Proc. 25th IEEE Int. Conf. Micro-Electro-Mechanical Systems (MEMS'12), Paris, France, Jan. 29 – Feb. 2, 2012, pp. 164–167.

[3] F. Ayazi, "Multi-DOF inertial MEMS: From gaming to dead reckoning," Proc. 16th Int. Solid-State Sensors, Actuators and Microsystems Conf. (Transducers'11), Beijing, China, June 5–9, 2011, pp. pp. 2805-2808.

[4] K. Shcheglov, C. Evans, R. Gutierrez, and T. K. Tang, "Temperature depedent characteristics of the JPL silicon MEMS gyroscope," in Proc. IEEE Aerospace Conf., 2000, pp. 403–411 vol. 1.

[5] M. Weinberg, A. Kourepenis, "Error sources in in-plane silicon tuning-fork MEMS gyroscopes," IEEE J. Microelectromech. Syst, vol. 15, pp. 479-491, 2006.

[6] J.R. Vig, "Temperature-insensitive dual-mode resonant sensors - a review," IEEE Sensors Journal, vol. 1, no. 1, pp. 62–68, 2001.

[7] E. J. Ng, H.K. Lee, C.H. Ahn, R. Melamud, T.W. Kenny, "Stability measurements of silicon MEMS resonant thermometers," Proc. IEEE Sensors Conf., Limerick, Ireland, Oct. 28–31, 2011, pp. 1257–1260.

[8] A.A. Trusov, A.R. Schofield, A.M. Shkel, "Micromachined tuning fork gyroscopes with ultra-high sensitivity and shock rejection," U.S. patent application 20 100 313 657 (2010b).

[9] A.A Trusov, I.P. Prikhodko, S.A. Zotov, A.M. Shkel, "Low-Dissipation Silicon Tuning Fork Gyroscopes for Rate and Whole Angle Measurements," IEEE Sensors Journal, vol. 11, no. 11, pp. 2763–2770, 2011.

CONTACT

A.A. Trusov, tel: +1-949-824-6314; atrusov@uci.edu.