

Improving the Temperature Stability of MEMS Gyroscope Bias with on-chip Stress Sensors

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Abstract—Temperature calibration is commonly used to suppress the bias drift of MEMS inertial sensors. Temperature compensation reduces the bias drift but cannot eliminate it. We report a compensation technique for temperature-induced drifts by incorporating temperature and on-chip stress, for the first time. Adding on-chip stress to the temperature captures the offset behavior with hysteresis more accurately. Our open and closed-loop sense mode temperature sweep results demonstrate almost three-fold offset stability improvement over only temperature calibration for a wide (65°C) temperature range. Temperature and stress sensors provide data about thermal stress and stress mismatches in the sensor stack, respectively. We validate the calibration concept with a MEMS ring gyroscope integrated with eight capacitive stress sensors. We perform the temperature tests with an on-PCB heater that only heats the MEMS die and front-end amplifiers.

Keywords—MEMS gyroscope, temperature calibration, stress calibration, stress sensor

I. INTRODUCTION

Environmental temperature and stress are the main factors responsible for the bias drift [1]. Temperature and stress variations affect the dynamics of a MEMS gyroscope and cause undesired offset shifts. Even though the exact mechanisms behind the offset shifts are not precisely known, the shifts can be attributed to stress and temperature dependence of resonance frequencies, quality factors, and alignment of the drive and sense modes [2]. The sensor stack includes multiple materials, i.e., Silicon MEMS sensor, die-attach, package, solder, and printed circuit board (PCB) with orders of magnitude different mechanical properties. Epoxies are used as the die attach and the epoxy properties are not well defined, might change orders of magnitude over temperature, and are not repeatable [3]. Among the properties Coefficient of Thermal Expansion (CTE) and Young's Modulus (E) are of special interest. Significantly different CTEs and Es lead to unavoidable stress on the MEMS die upon temperature cycling since individual stack materials expand and contract at different rates.

Temperature calibration is widely utilized to minimize the bias drift with the fundamental assumption that the temperature-bias drift relation is linear [4]. Temperature calibration reduces the bias drift, [5] uses the drive resonance

frequency as an accurate temperature sensor instead of external measurements but cannot eliminate the bias variations against temperature. Temperature is a major source of the drift but while correlating with temperature to the first order, the drift dynamics are complicated. Constant temperature testing of state of the art gyroscopes still exhibited long-term drift [6]. The studies mentioned above suggest the need for new bias calibration methods in addition to temperature.

Stress calibration has been shown to suppress the long-term drift of the gyroscopes [7]. The MEMS device interacts with the environment through the anchors, and stress provides a more accurate assessment of the device state. The drift is due to anchor displacements; temperature is a scalar average measurement and might not be a direct anchor state indicator. In [8], distributed CMOS stress sensors on the ASIC die have been used to compensate humidity-induced scale factor drifts. 64 devices were tested, and three times improvement has been achieved on the sensitivity stability with on-chip stress sensors. The effect of PCB bending stress on the performance of mode-split gyroscopes has been studied in [9]. We think both temperature and stress should be employed for an effective bias compensation. Towards that end, our recent work showed the suppression of long-term, days to weeks long, MEMS gyroscope drift at room temperature with integrated capacitive stress sensors [10]. We analytically modeled the stress effects to understand the fundamental drift mechanisms and verified the model with experiments [2]. In this work, we focus on temperature calibration and show that on-chip stress sensing and temperature can cancel the temperature-induced drifts more effectively than only temperature, for the first time. Our approach differs from [8] since our stress sensors are on the MEMS layer instead of the ASIC. We can directly measure the MEMS stress.

II. RING GYROSCOPE, STRESS SENSORS, AND TEST SETUP

Figure 1 presents the SEM photo of the ring gyroscope with on-chip stress sensors (left) and the overall architecture of the MEMS die (right). Eight stress sensors are evenly distributed outside the ring. The ring gyroscope has 1.6mm radius, a drive frequency of 58,740Hz, and operates in $n=2$ wineglass modes. The main idea behind the choice of a ring structure is due to the anchor locations. The ring gyroscope has the mechanical anchors on the center and electrodes on the periphery. This configuration lets us to integrate stress sensors in the close vicinity of the device anchors. So, we can accurately capture the stress state of the mechanical structure.

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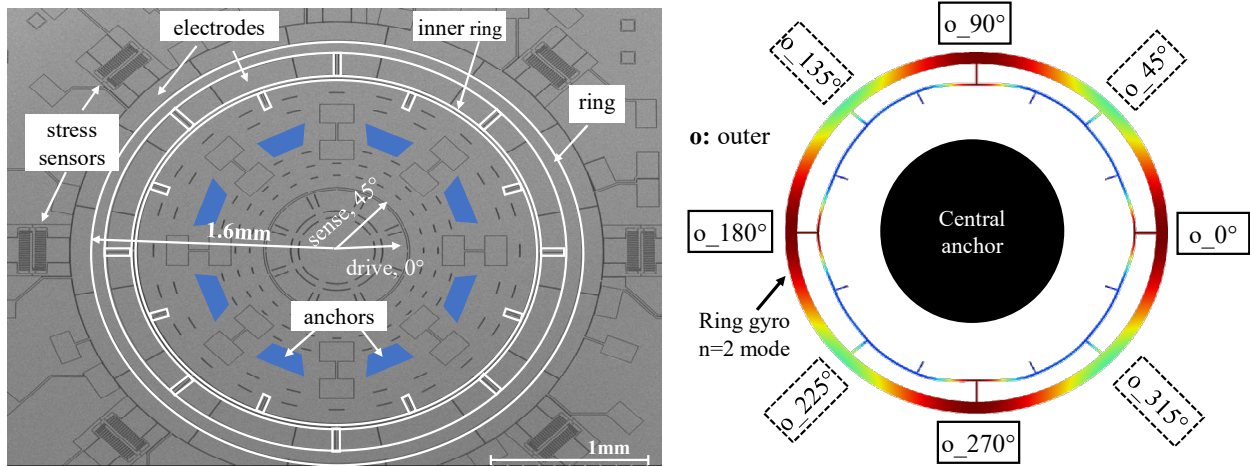


Fig. 1: SEM image of the ring gyroscope with on-chip stress sensors (left), and the overall architecture of the MEMS die. Eight stress sensors are evenly distributed outside the ring.

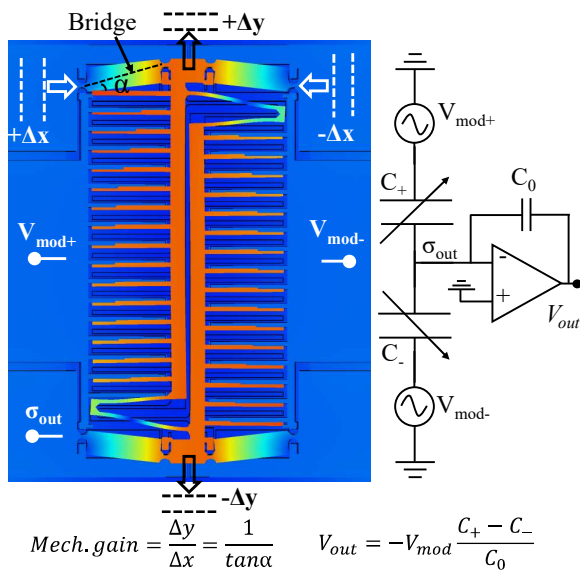


Fig. 2: Capacitive stress sensor and the readout, the strain in the x-direction is amplified and converted into capacitance variations in the y-direction by the imbalanced bridge. A transimpedance amplifier is used as the electronic readout.

Figure 2 illustrates the capacitive stress sensor and its front-end. Unlike piezoresistive stress sensors [7], capacitive stress sensors do not consume DC power, preventing additional heating of the MEMS die. The capacitive stress sensor amplifies the substrate strain in the orthogonal direction with an imbalanced bridge [11]. The imbalance angle sets the gain ($1/\tan(\alpha)$). The stress is measured by the capacitances attached to the mid-point of the bridge. The stress sensor operates far from its mechanical resonance ($\sim 300\text{kHz}$). Differential modulation clocks ($V_{mod\pm}$) at 10kHz are applied, and a transimpedance amplifier converts the capacitance variations to voltage. A digital lock-in amplifier demodulates transimpedance amplifier output. The eight stress sensors share the same differential clocks, and each sensor has its own transimpedance amplifier. The amplified stress sensors are then multiplexed and demodulated by a single digital demodulator. We rely on the

fact that stress is a slowly varying physical variable, and we have a single demodulator for the eight stress sensors.

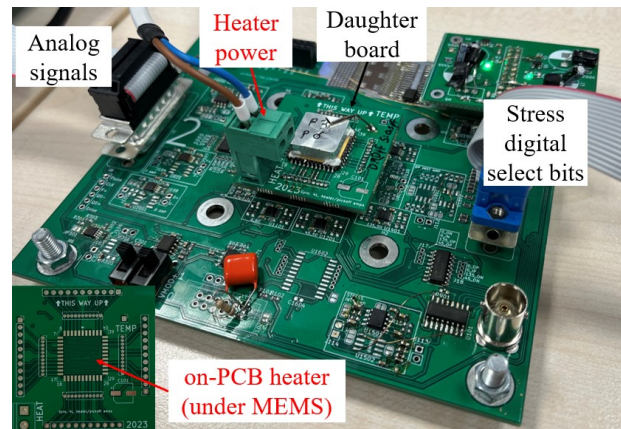


Fig. 3: Test-PCB with on-PCB heater.

Figure 3 shows our test PCB with the on-PCB heater (bottom left). The wafer level vacuum packaged MEMS gyroscope is mounted on a 44-pin ceramic leadless chip carrier (LCC) which is then soldered to a daughter board. The daughter board houses the on-PCB heater on the top side (under the LCC). A proportional to absolute temperature (PTAT) temperature sensor along with the gyroscope drive and sense mode front-end amplifiers are located on the bottom side of the daughter board (not shown) to minimize the parasitic capacitances. Even though closed-loop temperature control could be implemented, we gradually ramp the heater voltage in open-loop and monitor the temperature during the experiments. Only the MEMS die and gyroscope front-ends are heated with this setup. All the stress sensor front-ends, multiplexers, and the signal conditioning circuitry are on the main PCB and not heated.

The gyroscope control loops, stress sensor output demodulation, digital control for the stress sensor multiplexing, and the data recording are handled by the digital PLL. The gyroscope output is recorded continuously, and each stress sensor output is recorded $\sim 2\text{s}$ in each cycle.

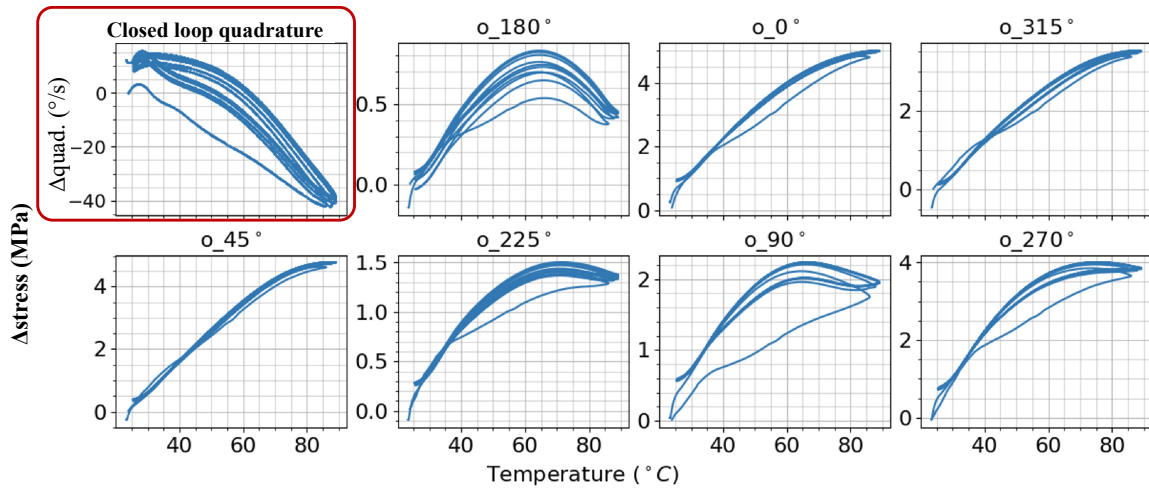


Fig. 4: The recorded stress sensor outputs, the stress sensor outputs generate positive output for tensile stress. While the stress across the chip is generally tensile, it is not uniform and difficult to predict.

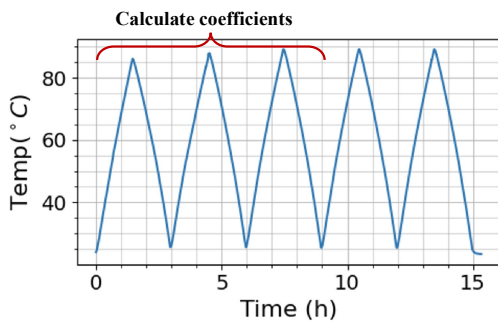


Fig. 5: Applied temperature profile. The temperature was swept 65°C for five cycles with a ramp rate of 1.5°C/min.

III. TEMPERATURE TESTS AND CALIBRATION RESULTS

Figure 5 presents the applied 5 cycle temperature profile to observe hysteresis possible effects. The temperature tests covered ~25°C-90°C. The temperature ramp rate was relatively slow at 1.5°C/min to allow temperature settling across the sensor stack. Figure 4 shows the distributed stress sensor outputs and the quadrature signal. Our stress sensors generate positive output for tensile stress. Measuring the sensitivity of the stress sensors is not straightforward, so we use the calculated sensitivity for the stress sensors. The maximum measured stress is ~5MPa. The MEMS gyroscope is made from silicon, a low CTE material. Silicon is surrounded by high CTE materials, i.e., die attach, solder, and PCB. As a result, we expect to measure tensile stress with temperature. The distributed stress sensors in Fig. 4 exhibited tensile behavior consistent with the intuition. However, we did not observe uniform tensile stress across the chip. The nonuniform stress distribution across the chip cannot be predicted with straightforward methods and simulations. We believe the stress distribution varies from sensor to sensor based on the final die attach and soldering configuration. So, measurement of on-chip stress is required to obtain the accurate stress distribution of the MEMS die.

Our stress sensors do not capture the thermal stress directly. Assume that all the sensor stack materials have the same CTE, then all the materials expand and contract together, and the sensors do not measure any stress variations. The stress sensors also expand with temperature,

and if both sides of the bridge in Fig. 2 move the same amount with the bridge expansion, no stress is induced on the sensor. The sensors capture the induced stress on the MEMS die due to the mismatches of the expansion and contraction of the sensor stack materials. Temperature provides the thermal data, so both stress and temperature measurements are required to characterize the state of the MEMS device comprehensively.

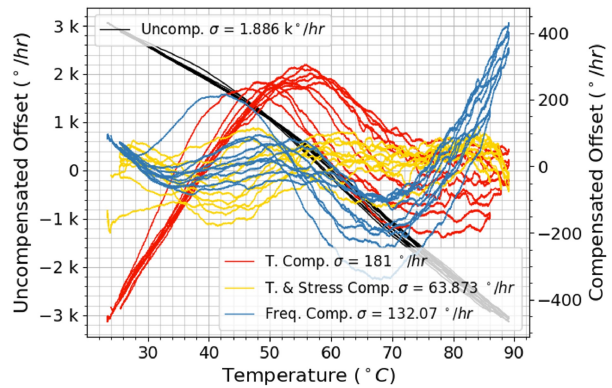


Fig. 6: Uncompensated and compensated gyroscope output vs. temperature for open-loop operation. Stress and temperature calibration yield the best results. Note that the y axes are different for uncompensated and compensated cases.

The main goal of this work is to study the effects of stress and temperature on the gyroscope performance. Figure 6 shows the zero-rate output (ZRO) variation of the gyroscope and different calibration results with temperature. The gyroscope operates in open-loop mode with 120Hz frequency split. There is quadrature control loop, we plot the quadrature in Fig. 4 from the closed loop output. The quadrature varies by ~50°/s. The quadrature is nulled by a control loop, so we don't expect quadrature leakage into the ZRO. The raw ZRO changes by 6000°/h for 65°C temperature difference with a temperature coefficient of 92.3°/h/°C. There is a relatively small hysteresis in the ZRO. We then utilize a least error squares linear line fit between the ZRO and temperature and stress outputs. We use the first three temperature cycles to calculate the calibration coefficients and apply the coefficients to the entire data set (5 cycles). We report the standard deviation to compare the fit residues.

ZRO – temperature relation is linear to the first order and temperature calibration removes most of the drift as expected with a standard deviation of $\sigma_{\text{Temp.}}=181^\circ/\text{h}$. However, temperature calibration cannot remove the hysteresis effects. Temperature and stress calibration yield the best results, $\sigma_{\text{stress\&Temp.}}=64^\circ/\text{h}$, 2.8X times improvement over only temperature calibration. The hysteresis effects can be observed in the stress plots, leading to the improvement in calibration. These results support the idea that both temperature and stress should be employed for calibration, they provide complementary data about the gyroscope.

We also performed temperature sweeps for closed-loop sense mode. Figure 7 presents the uncompensated and compensated ZRO. The results are close to the open-loop operation presented in Fig.6.

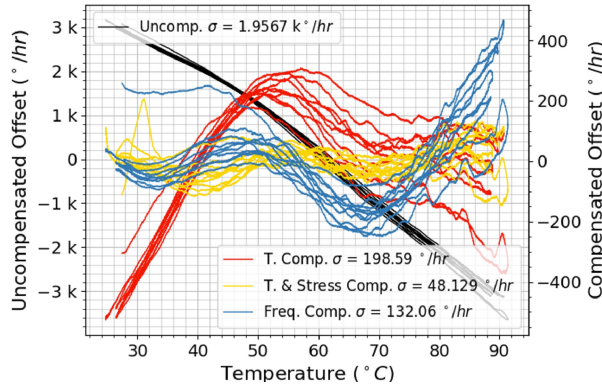


Fig. 7: Uncompensated and compensated gyroscope output vs. temperature for closed-loop operation. The results are close to the open-loop operation.

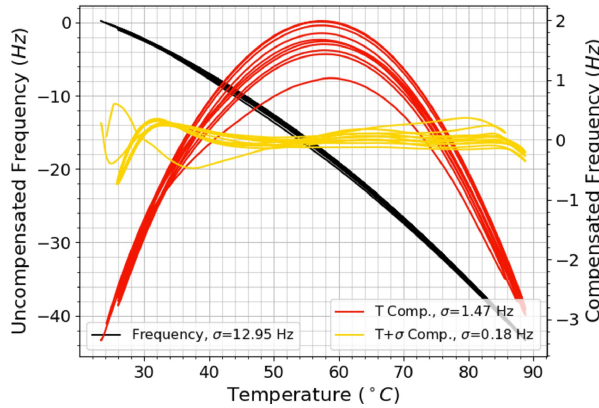


Fig. 8: Variation of gyroscope drive frequency vs. temperature, and the fit residues. Inclusion of stress results in 8X better residues. Note that y axes are different for the uncompensated and compensated cases.

Our temperature sensor is underneath the daughter board and we don't measure the on-chip temperature. As suggested by [5], drive frequency can be utilized as an on-chip temperature sensor. Compensating the ZRO with the drive frequency yielded slightly less drift than the temperature with $\sigma_{\text{freq.}}=132^\circ/\text{h}$ for both open and closed loop operation. We analyzed the frequency variation with temperature and stress in Figure 8. The drive frequency develops hysteresis over temperature cycles and cannot be fully predicted with temperature. Temperature and stress

together can predict the drive frequency variation almost 8 times better than the frequency.

IV. CONCLUSIONS

Bias drift is a fundamental problem for MEMS gyroscopes and the mechanisms behind the drift are not completely understood. We know that environmental stress and temperature variations lead to drift. Commonly utilized temperature calibration cannot eliminate the drift since it tries to suppress the drift with a single scalar temperature measurement. In this work we showed that the distributed stress measurements and temperature can suppress the drift more effectively than just temperature. The stress and temperature measurements are required because each captures a different aspect of the drift. The stress sensors do not detect the thermal stress directly, they rather measure the stress mismatches in the system and temperature is an indicator of material property changes and thermal stress.

REFERENCES

- [1] E. Tatar, "On-chip compensation of stress, temperature, and nonlinearity in a MEMS gyroscope," *PhD Thesis*, Carnegie Mellon University, Feb. 2016.
- [2] M. Hosseini-Pishrobat, D. Erkan, and E. Tatar, "Analytical and experimental study of stress effects in a MEMS ring gyroscope," *Sensors and Actuators A: Physical*, vol. 362, pp. 1-15, Nov. 2023.
- [3] A. Misrak *et al.*, "Impact of die attach sample preparation on its measured mechanical properties for MEMS sensors applications," *J. of Microelectronics and Electronic Packaging*, vol. 18, no.1, pp. 21-28, 2021.
- [4] M. Vujadinovic, T. Hiller, L. Blocher, T. Northemann, and B. Choubey, "Towards a better understanding of offset changes across temperature in mode-split open-loop MEMS gyroscopes," *Proc. IEEE 2023 Int. Symp. On Inertial Sens. Sys. (INERTIAL '23)*, Lihue, HI, USA, March 28-31, 2023.
- [5] I.P. Prikhodko, A.A. Trusov, and A. Shkel, "Compensation of drifts in high-Q MEMS gyroscopes using temperature self-sensing," *Sensors and Actuators A: Physical*, vol. 201, pp. 517-574, Oct. 2013.
- [6] R.L. Kubena, R.J. Joyce, and A.D. Challoner, "Correlation of frequency, temperature, and bias stability of a Si ring gyro," *Proc. IEEE 2016 Int. Symp. On Inertial Sens. Sys. (INERTIAL '16)*, Laguna Beach, CA, USA, Feb. 22-25, 2016.
- [7] E. Tatar, T. Mukherjee, and G.K. Fedder, "Stress effects and compensation of bias drift in a MEMS vibratory-rate gyroscope," *J. of Microelectromechanical Sys.*, vol. 26, no.3, pp.569-579, June 2017.
- [8] J. Jurgschat, F. Roewer, I. Toth, T. Ohms, and A. Zimmermann, "Integrated stress sensors for humidity performance drift analysis and compensation in inertial measurement units," *J. of Microelectromechanical Sys.*, vol. 31, no.6, pp.918-926, Dec. 2022.
- [9] W. Mayer, A. Küster, P. Tristchler, T. Hiller, D. Radovic, and A. Zimmermann, "Modeling and experimental analysis of low-cost MEMS gyroscopes under PCB bending stress," *Proc. IEEE 2023 Int. Symp. On Inertial Sens. Sys. (INERTIAL '23)*, Lihue, HI, USA, March 28-31, 2023.
- [10] B.E. Uzunoglu, D. Erkan, and E. Tatar, "A ring gyroscope with on-chip capacitive stress compensation," *J. of Microelectromechanical Sys.*, vol. 31, no.5, pp.741-752, Oct. 2022.
- [11] T. Veske, D. Erkan, and E. Tatar, "Characterization of packaging stress with a capacitive stress sensor array," *Proc. IEEE MEMS2023*, Munich, Germany, Jan. 15-19, 2023, pp. 909-912.