JMEMS Letters

Exclusion of Linear Acceleration Signal in the MEMS Thermal Gyroscope

Jamal Bahari* and Carlo Menon, Member, IEEE

Abstract—This letter identifies the source of linear acceleration signal in the microelectromechanical systems (MEMS) thermal gyroscope and provides a real-time solution to exclude it. The main culprit of the undesired acceleration signal is found to be lack of rotational symmetry due to Manhattan sensor topology. A higher level of symmetry is obtained by constructing a hybrid gyroscope using two individual devices operating in tandem but 180° out-of-phase. A precision rotary stage is used to test the duo. The experiments confirmed that higher symmetry is promising in excluding the acceleration signal. Compared with a single device, the hybrid gyroscope demonstrated 16-fold reduction in the acceleration signal and 5-fold improved acceleration to rotation sensitivities.

Index Terms—Acceleration, angular velocity, g-sensitivity, gyroscope, hybrid sensor, inertial sensor.

I. INTRODUCTION

Micromachined thermal inertial sensors are renowned for their unmatched shock resistance and low fabrication costs. The MEMS thermal accelerometer has been around for almost two decades [1] and has been commercialized [2]. In contrast, the MEMS thermal gyroscope (gyro) has not yet reached maturity and still is in the development stages [3]–[8]. The major setback in the development of thermal gyro can be attributed to lack of resolution between the linear acceleration and gyration signals [6]. Indeed, current versions of the thermal gyro [6], [7] have inherited the structure of the thermal accelerometer [9], making them more prone to detect acceleration. A remedy for suppression of the acceleration signal is data acquisition and post processing [10]; nonetheless, this approach may be computationally intensive and may not produce real-time output. In this article, we report a novel method for real-time elimination of the acceleration signal right at the device level.

II. BACKGROUND

The operating principle, design, fabrication process, and characterization of the MEMS thermal gyro used in this study are detailed in [6]. The thermal gyro is placed onto a circuit board on a programmable rotary stage. Fig. 1 shows the circuit schematic. The gyro’s two resistive microheaters, H1 and H2, are alternately activated setting the frequency f (50 Hz) and duty cycle D (50%). The heater powers are set to 5 mW by RH1 and RH2 and fine-tuned by RF. An instrumentation amplifier monitors the gyro’s resistive temperature detectors, TD1 and TD2, forming a Wheatstone bridge.

Manuscript received August 3, 2017; revised September 24, 2017; accepted October 14, 2017. Date of publication November 15, 2017; date of current version February 1, 2018. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada, in part by the Canadian Institutes of Health Research, and in part by the Canada Research Chairs program. Subject Editor A. Seshia. (Corresponding author: Jamal Bahari.)

The authors are with the Menrva Research Group, Schools of Engineering Science and Mechatronic Systems, Simon Fraser University, Burnaby, BC V5A 1S6, Canada (e-mail: jbahari@sfu.ca; cmenon@sfu.ca).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/JMEMS.2017.2764272

Fig. 1. The drive and signal conditioning circuit for testing the thermal gyro.

Fig. 2. Response of the thermal gyro obtained by a rotary stage and signal conditioning circuit when (a) acceleration $a = 0$ m/s$^2$, (b) $a = 9.81$ m/s$^2$.

with $R_1$ and $R_2$ and balanced by $R_b$. A polarity reversal module synchronized to $f$ and lowpass filters demodulate the response, followed by analog to digital conversion and Infrared transmission. The circuit’s cumulative amplification gain, $A_V$, is 40 940.

Fig. 2 shows the output voltage $V_{out}$ where the gyro experiences rotation speeds between ±1080 °/s, incremented by 360 °/s. $\Delta V_w$ and $\Delta V_a$ denote the voltage differences due to rotation $\omega$ and acceleration $a$, respectively. Fig. 2(a) shows $V_{out}$ when the gyro’s rotation axis, the $z$-axis, is parallel to gravity. Hence, no acceleration exists except the Euler acceleration imposed by the rotary stage. $\Delta V_a$ is measured 2.59 V between ±1080 °/s, and the gyro’s

$V_{out}$
sensitivity to rotation, \( S_\theta \), is calculated 1.20 mV/°/s. The voltage ripple at constant speeds is attributed to several phenomena such as vibration, un leveled device, and electromagnetic interference. Therefore, the maximum rotation equivalent ripple (at \( a = 0 \text{ m/s}^2 \)) is denoted by \( \Delta V_\theta \) and is measured 80 mV. When the rotating axis becomes perpendicular to gravity, the gyro’s output is affected by the acceleration \( g \), 9.81 m/s\(^2\). Fig. 2(b) shows this scenario where \( \Delta V_\theta \) drops to 1.83 V, resulting in an \( S_\theta \) of 848 \( \mu \text{V/°/s} \). The reduced sensitivity is attributed to lower heater temperature, due to cooling effect by natural convection which is pronounced along the larger cavity dimensions [11]. At 360 °/s, the maximum value of \( \Delta V_\theta \) is 340 mV. Subtracting \( \Delta V_\theta \) from \( \Delta V_a \), the gyro’s sensitivity to acceleration, \( S_a \), is calculated 130 mV/g (260 mV / 2g). The ratio of \( S_a \) to \( S_\theta \), g-sensitivity, indicates that the rotation signal is obscured by a comparable acceleration signal, equivalent to 722 \( \mu \text{V/°/s} \).

III. PROBLEM ANALYSIS AND PROPOSED SOLUTION

The two phase operation of the thermal gyro in conjunction with the polarity reversal mechanism should eliminate the acceleration signal [5]. Nevertheless, our geometrical analysis reveals that the sensor’s topology is the source of this incapability. To elaborate, Fig. 3 shows the superimposed phases of a thermal gyro whose plane is rotated by angle \( \theta \) relative to the direction of \( a \). The temperature rise at each TD can be resolved into two parts. The temperature rise due to rotation is illustrated by the dashed ellipses and denoted by \( T_{\theta i} \), where \( i \) identifies the actuated heater. The temperature rise due to acceleration is shown by the bold arrows resembling the natural convection currents and denoted by \( T_{ai} \). For simplicity, the bottom portion of these arrows and their cooling effects are neglected. \( T_{\theta i} \) and \( T_{ai} \) are identical in both phases of operation. However, the \( T_{\theta i} \) and \( T_{ai} \) are different as the convection currents generated by \( H_2 \) partially miss TD1 and hit a cavity wall. If \( V_{\theta i} \) and \( V_{ai} \) respectively denote the voltages induced by \( T_{\theta i} \) and \( T_{ai} \), the voltage difference at the TDs (or inputs of the Inst. Amp. in Fig. 1) is

\[
\Delta V = \begin{cases} 
V_{\theta i} + V_{ai} & I \\
-V_{\theta i} + V_{ai} & II.
\end{cases}
\]

Since the polarity of \( \Delta V \) is reversed during phase II, the rotation terms are maintained and the acceleration terms are only canceled at \( \theta \) where they are identical (i.e. 0°, 90°, 180°, and 270°). At \( \theta \) where the acceleration terms are different, their amplified difference appears at the output \( V_{out} \).

A remedy to this problem is to design the thermal gyro with higher order of symmetry, e.g. [8], such that the convection currents symmetrically affect the temperature detectors. An intuitive approach is to deviate from Manhattan geometries and suspend semicircular-shaped TDs over a circular-shaped cavity. However, it is prudent to seek alternative solutions that confirm higher symmetry improves performance. A subtle approach is to construct a hybrid-gyro by arranging multiple devices on a circle’s circumference similar to Fig. 4(a). As the number of devices is increased, the effective cavity shape and TD shape will be circular and semicircular, respectively. Also, special configuration of TDs is necessary to detect identical net \( V_\theta \)'s in both phases of operation. To avoid complications, we limit the scope of this work to two individual gyros put in the cross-series configuration shown in Fig. 4(b). The term cross-series implies that each TD of a device is in series with the opposite TD of the other device, e.g. TD1 is connected to TD3, and TD2 is connected to TD4. Although not shown in Fig. 4(b), the heater pairs \( H_1|H_3 \) and \( H_2|H_4 \) are mutually in series, as the red and gray colors imply. Unlike the shown configurations, alignment of the heaters of one device to those of the other is not necessary. However, the heaters’ line of symmetry must remain parallel to achieve best performance.

Similar to the operation of a single device, the hybrid-gyro is operated in two phases. As Fig. 4(b) illustrates, \( H_1|H_3 \) is activated in phase I, and the CCW rotation (\( \omega > 0 \)) creates \( T_{\omega i} \) at TD1 and \( T_{\omega a} \) at TD2. Also, the natural convection currents impose \( T_{\omega i} \) at TD1 and \( T_{\omega a} \) in the vicinity of TD4 and a cavity wall. Therefore, the voltage difference in phase I is

\[
\Delta V_I = V_{\omega i} + V_{3\omega a} + V_1a - V_{3\omega a}.
\]

In phase II, activation of \( H_2|H_4 \) and rotation create \( T_{\omega i} \) and \( T_{\omega a} \) at TD2 and TD4, respectively. The natural convection currents impose \( T_{\omega i} \) at TD4 and \( T_{\omega a} \) in the vicinity of TD1 and a cavity wall. The voltage difference in phase II is

\[
\Delta V_{II} = -V_{2\omega a} - V_{4\omega a} + V_2a - V_{4\omega a}.
\]

Knowing all \( V_{\omega i} \)'s are equal and substituting them by \( \Delta V_{\omega i} \), the voltage difference is concisely given as

\[
\Delta V = \begin{cases} 
2\Delta V_{\omega i} + (\Delta V_{\omega a} - \Delta V_{\omega a}) & I \\
-2\Delta V_{\omega i} - (\Delta V_{\omega a} - \Delta V_{\omega a}) & II.
\end{cases}
\]

where \( V_{\omega i} \) and \( V_{\omega a} \) are equal and substituted by \( \Delta V_{\omega i} \), and the equal \( V_{2\omega a} \) and \( V_{3\omega a} \) are replaced by \( \Delta V_{\omega a} \). Equation (4) implies that the cross-series configuration doubles the rotation signal and diminishes the acceleration signal during each phase. Note that this real-time performance is accomplished at the device level right before any amplification and signal conditioning. After polarity reversal and filtering, the doubled rotation signal \( \Delta V_{\omega i} \) is superposed by a minor acceleration difference \( \Delta V_a \) that is completely canceled if \( \Delta V_{\omega a} \) and \( \Delta V_{\omega a} \) are identical.
IV. Experimental Results

The hybrid-gyro is made on a prototype board. Table I lists the resistance $R$ of $H_i$ and $T_D$ of the constituent devices, G13 and G18. Performance of the hybrid-gyro is examined in the absence and presence of acceleration to be compared with that of the lower performance gyro, G13. The rotary stage is positioned according to the insets of Fig. 2, maintaining the same angular rates and increments. Fig. 5 shows the results where the “No Acc” plot is inverted about the time-axis, for annotation clarity. All the measured performance parameters of the hybrid and single gyros are summarized in Table II. Without acceleration, the $S_{\alpha}$ of the hybrid-gyro is 3.5 times smaller than that of G13. This expected reduction in $S_{\alpha}$ is attributed to the lower power density of the hybrid-gyro. In fact, the 5 mW heater power is maintained throughout the experiments. In the hybrid configuration, however, power is dissipated in two device cavities with a volume almost twice as that of a single gyro [6].

In the presence of acceleration, the hybrid-gyro demonstrates 7-fold smaller $\Delta V_a$ compared to G13. Eliminating $\Delta V_a$ in the $4^{th}$ row of Table II, this reduction is calculated better than 16-fold. Also, the $g$-sensitivity is improved to 30.1 °/s/g which is 5.1 times superior to that of G13 and 4.7 times enhancement over [10]. The residual $\pm 8$ mV ripple at 360 °/s infers a maximum difference of 195 nV (8 mV / $A_{\alpha}$) between the $\Delta V'_a$ and $\Delta V''_a$. This difference is partly attributed to the number of included gyros and partly to the less than perfect alignment explained in section III. Minor misalignment introduces differential errors between the acceleration terms in (4) that appear as voltage ripples at the output. Even if the device packages are perfectly aligned, the manually attached silicon dice usually have minor rotational misalignments. Consequently, output calibration is necessary to eliminate errors and further improve the performance.

V. Conclusion

We presented a hybrid MEMS thermal gyroscope comprised of two single gyros in a cross-series configuration that proved 16 times more effective in rejecting the linear acceleration signal. In spite of performing 2 to 3 orders of magnitude lower than the commercially available MEMS vibrating mass gyros, our hybrid concept enhanced the thermal gyro’s potential for adoption by the low-cost applications.

ACKNOWLEDGMENT

The authors express their gratitude to Dr. Albert M. Leung for lending the experimental setup and equipment.

REFERENCES
