A Method for Real-Time Suppression of In-Phase Error of Silicon Micro Gyroscopes

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Abstract. This paper reports a method to suppress the in-phase error of silicon micro gyroscopes in real time, which can realize long-term stability, without significantly affecting the sensor noise. The in-phase error suppression is by periodically changing the polarity of the drive mode, and the bias (zero rate output) decreases from -7.8 deg/s to -3.9 deg/s, attenuation amplitude of which is about 3.9 deg/s. By sampling the output using information fusion technology, low short-time noise and bias instability can be obtained without cutting off the gyroscope and adding additional sensors, the bias instability of which is reduce from 35.0 deg/hr to 10.8 deg/hr. The feasibility of the approach was experimentally evaluated using a MEMS gyroscope with the algorithm implementation on FPGA in real-time.

1. Introduction

In previous work, some methods were implemented to improve the long-term stability of the gyroscopes. Tsinghua University conducted a fixed-point temperature experiment on silicon micro gyroscopes and used neural network algorithms to identify the temperature characteristics of silicon micro gyroscopes \cite{1}. The temperature drift after temperature compensation is reduced by 5\% over the entire temperature range. The Boeing Company reported a dish gyroscope with zero bias self-compensation technology \cite{2}. The study proposed that the zero drift error introduced by the damping asymmetry is related to the driving angle. By periodically driving the axial direction between 0° and 90°, the periodic inversion of the damping error can be realized, and the long-term drift resulting from the error term is eliminated by data smoothing. Berkeley University proposed a continuous time domain damping error self-compensation method \cite{3}. The study realized the continuous variation of the driving axis in the plane by adjusting the amplitude and phase of the feedback force, avoiding the problem of noise aliasing and bandwidth limitation caused by sudden change of the driving axis. With this technique, the zero-bias instability of the MEMS gyroscope is reduced from 9°/h to 2°/h. Another adopts the Dual Ramp method, however, due to the intermittent sampling, the bandwidth is reduced and the noise is increased \cite{4}.

This study intends to use the momentum moment vector commutation theory to understand the gyro in-phase error mechanism, and realize the online self-compensation of the in-phase error by drive mode period inversion method. Compared with the previous methods, our method can achieve real-
time error suppression and is insensitive to environmental factors, which can achieve long-term stability of the output without significantly affecting the sensor noise.

2. Methodology

The mechanical structure of the gyro mainly includes two masses, a drive beam, a sense beam, an anchor beam, a drive comb, a sense comb etc. In the figure 1, PM1 and PM2 represent two masses, which are connected to the anchor point through the sense beam, the drive beam and the anchor beam. The Driver Element represents a drive comb, and the closed-loop driving circuit of the silicon micro-gyro applies a driving signal on the comb to generate an electrostatic force to drive the two masses in the driving direction (X-axis) for the opposite vibrating motion. When an angular velocity is input along the Z-axis, due to the Coriolis Effect, Coriolis force will be generated in the direction of the detection axis (Y-axis), so that the two masses generate vibration in the Y direction.

Since the detected voltage is proportional to the angular velocity, the angular velocity input in the Z-axis direction can be calculated [5].

2.1. The In-phase Error Caused by Force Imbalance

Bias (zero rate output) is the average over a specified time of gyro output measured at specified operating conditions that has no correlation with input rotation [6]. The machining deviation will cause the gap of the internal drive comb fingers electrode plate of the gyro to be asymmetric, thereby generating an electrostatic force in the direction of the sense axis. This error term is in phase [7] with the wanted signal at the same frequency, which seriously affects the signal output, causing the gyro's bias and reducing the gyroscope performance [8].

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**Figure 1.** Structure of dual-mass silicon micro gyroscope

**Figure 2.** Schematic diagram of the mechanism of in-phase coupling error
As shown in Figure 2, the stress generated during processing or installation changes the internal comb spacing of the gyro. At this time, the drive force applied in the X-axis direction must leak to the Y-axis detection direction. Suppose the force in the X-axis direction is $F_x$, the force in the Y-axis direction is $F_y$, there are $F_y = F_x \sin \alpha \propto F_x \alpha$, and is the coupling coefficient from drive to sense. The comb capacitance gap is $g$, the amount of change is $\Delta g$, $L$ is the length of the overlapping portion of the dynamic and static comb teeth, and the width is $h$.

According to the theorem of conservation of energy and the principle of virtual work, the interaction between the combs of the drive direction is [9]:

$$F_x = -\frac{\partial W_g}{\partial X} = \frac{1}{2} \frac{\partial C}{\partial \alpha} V^2 = \frac{1}{2} \left( \frac{\varepsilon h}{g + \Delta g} + \frac{\varepsilon h}{g - \Delta g} \right) V^2 \tag{1}$$

In the formula, $W_g$ is the energy storage between the combs, $C$ is the capacitance between the combs, $V$ is the driving voltage applied to the comb finger, and $\varepsilon$ is the dielectric constant. When the stress is introduced into the comb gap change $\Delta g$, the resultant force in the Y direction is not zero, and the coupling force in the sense direction is:

$$F_y = \frac{1}{2} \frac{\partial C}{\partial Y} V^2 = \frac{1}{2} \left( -\frac{\varepsilon l h}{(g + \Delta g)^2} + \frac{\varepsilon l h}{(g - \Delta g)^2} \right) V^2 \tag{2}$$

Therefore, the coupling coefficient $\alpha$ drive to the sense is:

$$\alpha = \frac{F_x}{F_y} = \frac{g^2}{2\Delta g L} \tag{3}$$

2.2. Method of Drive Mode Inversion

The method of inhibition for the in-phase error is realized by drive force periodic inversion. Since the silicon gyro has a high quality factor, the oscillation of the resonator does not disappear immediately but gradually decays during a period of inversion of the driving force, so the polarity of the gyro scale factor does not change [10]. At this time, the polarity of the in-phase error in the segment changes. Therefore, it is only necessary to periodically alternate the driving force polarity, and the angular velocity detection can be performed in the time interval of the driving force inversion to achieve self-compensation of the in-phase coupling error.

![Figure 3. Drive force polarity inversion and error elimination timing diagram](image)

As shown in Figure 2, the stress generated during processing or installation changes the internal comb spacing of the gyro.
Figure 3 shows a timing diagram for the proposed error cancellation algorithm. Resonator amplitude rises from A to C, the time of which is 7/8 of the entire cycle. At this time, the error polarity is +. Correspondingly, Resonator amplitude rises from C to D, the time of which is 1/8 of the entire cycle, and the error polarity is -. But to cancel out the errors, the sense-mode is only sampled just equal time interval around point C, that is to say, from B to D.

However, this sampling method limits bandwidth and increases noise, due to lower amplitude and sampling more slowly. Obviously, discontinuous sampling can result in “dead-times” from A to B.

2.3. Method of Drive Mode Inversion

In order to reduce the noise and increase the bandwidth of the driving modal inversion method, we propose a signal fusion technique as shown in the figure 4.

As discussed in the previous section, the gyro data acquisition is only 1/4 of the full period (from B to D). Since the drive mode inversion output has good low frequency characteristics, and the establishment process has good high frequency characteristics such as larger bandwidth and lower noise, this study combines the two signals through a low pass filter and a high pass filter. Continuous monitoring of angular velocity can be achieved to compensate for bandwidth loss and improve RRW characteristics.

3. Experiments Result

We have experimented to verify the feasibility of the above method, which can improve the long-term stability of the gyro without adding extra noise (Figure 1). The evaluation board comprising the silicon gyroscopes and a FPGA for implementation of real-time fusion algorithm, as shown in Figure 5.
3.1. Drive Mode Inversion Validation

In order to prove that our method indeed cancels out the error, the gyro output for normal operation and drive modal inversion is sampled, as shown in Figure 6. Bias with drive mode inversion method is reduced by 3.9 deg/s, compared to normal condition, both of which is tested under the same environmental conditions. So, it is obvious that drive mode conversion is able to reduce bias.

![Figure 6](image)

**Figure 6.** Zero rate drift with drive mode inversion method is reduced by 3.9 deg/s, compared to normal condition.

As shown in Figure 7, the analysis of the gyroscope output in drive mode inversion revealed a bias instability of 10.76 deg/hr, which is much more excellent than normal mode, 41.81 deg/hr. Therefore, the gyroscopes with drive mode inversion will achieve long-term stability. However, as far as noise performance is concerned, the conclusion is that the short-term noise of drive mode inversion is twice larger than normal mode, as shown in Figure 8. All in all, we certificate that long-term stability can be achieved and zero rate drift is limited, but the short-term noise is worse by the method of drive mode inversion.

![Figure 7](image)

**Figure 7.** ALLAN variance of two modes
In order to demonstrate the improvement in short-term noise while ensuring the similar long-term stability, we adopt this new fusion technology. We guarantee real-time operation on only one gyroscope, reducing application complexity. The fusion technique uses a low-pass filter to calibrate samples from B to D, and a high-pass filter to calibrate non-calibrated samples (from A to B), which make full period into one output.

For this experiment the high-pass and low-pass filters were 3rd order Butterworth IIR digital filters, getting the parameters by designing the filter in MATLAB, and then implement it in an INTEL’s FPGA. Due to the two lines on the Figure 8 meet at this point in 5s, so set the cutoff frequency of the filter to 1/5 Hz. As is shown in Figure 9, low short-time noise and bias instability can be obtained without cutting off the gyroscope and adding additional sensors, the bias instability of which is reduced from 35.0 deg/hr to 10.8 deg/hr.

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4. **Conclusion**

To sum up, we demonstrate the feasibility of the novel in-phase error suppression method based on the drive mode inversion without obviously worsening sensor noise. It eliminates bias caused by force imbalance. Our method is applicable to a wide range of gyro structures, and it does not need to cut off
the normal operation of the gyroscopes, so real-time compensation can be achieved. Further improvements to the method can eliminate bias caused by other factors.

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