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New digital drive phase control for improving bias stability of silicon MEMS gyroscope

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Abstract: In order to improve the bias stability of the micro-electro mechanical system (MEMS) gyroscope and reduce the impact on the bias from environmental temperature, a digital signal processing method is described for improving the accuracy of the drive phase in the gyroscope drive mode. Through the principle of bias signal generation, it can be concluded that the deviation of the drive phase is the main factor affecting the bias stability. To fulfill the purpose of precise drive phase control, a digital signal processing circuit based on the field-programmable gate array (FPGA) with the phase-lock closed-loop control method is described and a demodulation method for phase error suppression is given. Compared with the analog circuit, the bias drift is largely reduced in the new digital circuit and the bias stability is improved from 60 to 19 °/h. The new digital control method can greatly increase the drive phase accuracy, and thus improve the bias stability.

Key words: silicon micro-electro mechanical system (MEMS) gyroscope; bias drift; drive phase control; field-programmable gate array (FPGA)

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The silicon MEMS gyroscope (SMG) has the advantages of small volume, light weight, low cost and batch fabrication, which makes it a suitable angular-rate sensor. It is also a basic sensor in the micro inertial measurement unit (MIMU) and can have both military and civilian uses, such as in attitude flight control systems, the automobile industry and so on[1-2]. The sensitivity of the MEMS gyroscope has been greatly improved due to the achievements in vacuum package technology and the DDSOG (deep dry silicon on glass) deep etching technology. But the existence of bias drift has greatly reduced the precision of the gyroscope. For example, in navigation applications, the attitude signal is obtained by integration of the angular rate, so the bias drift error can be accumulated in the integration which leads to remarkable attitude signal drift errors.

The use of digital signal processing and the advanced algorithm in gyroscope circuits can lead to higher flexibility and reliability[3-4]. In this paper, the gyroscope signal is processed as much as possible in the digital domain.

By analyzing the principle of bias production, we find that the drive phase stability is the primary factor affecting the bias stability. A FPGA-based digital signal processing circuit with additional drive phase control is presented. Experiments confirm that the improved drive phase control can greatly improve the bias stability.

1 Factors Affecting Bias Stability

The quadrature error of the sense mode is an unavoidable mechanical error caused by the coupling from the drive mode to the sense mode[5]. It is the main factor affecting the bias stability. The phase of quadrature error is the same as the phase of the drive mode vibration (see Fig. 1), so the drift of the drive phase can lead to a drift in the quadrature error phase.

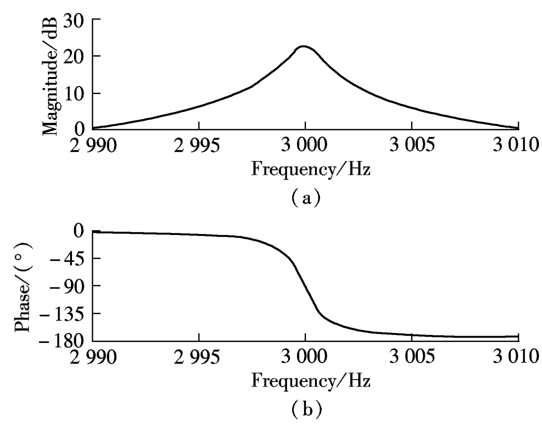

Fig. 1 Drive mode bode diagram. (a) Amplitude-frequency response curve; (b) Phase-frequency response curve

The output of a gyroscope comes from the phase sensitive demodulation which is achieved by the multiplication of the sense mode signal with the drive mode signal. Assume that the phase of the external drive force is $\cos(\omega_d t)$, which is the same as the phase of the drive signal, then the sense mode signal can be expressed as $K_1 + K_2$, where $K_1 = A_2 \sin(\omega_d t + \varphi)$ is the Coriolis force signal, and $K_2 = A_3 \cos(\omega_d t + \varphi)$ is the quadrature error signal.

$$\varphi = -\arctan \frac{\omega_x \omega_d}{Q_x(\omega_x^2 - \omega_d^2)} \tag{1}$$

where φ is the phase of quadrature error, which is the same as the drive mode displacement signal; ω_d is the external drive force frequency; ω_x and Q_x are the resonant frequency and quality factor of the drive mode; A_2 is the amplitude of the Coriolis force signal; and A_3 is the amplitude of the quadrature error signal.

When the input angular signal is zero, $K_1 = 0$. The demodulation signal of the sense mode can be expressed as

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$$V_{\mathrm{dmod}} = \sin(\omega_{\mathrm{d}} t) A_3 \cos(\omega_{\mathrm{d}} t + \varphi) A_3 \frac{\sin(2\omega_{\mathrm{d}} t + \varphi) - \sin\varphi}{2} \quad (2)$$

The bias signal is obtained after filtering the quadric harmonic signal,

$$V_{\mathrm{bias}} = -\frac{A_3}{2}\sin\varphi \quad (3)$$

So the bias signal is mainly affected by the amplitude and the phase of a quadrature error. The amplitude of quadrature error varies with the fabrication error and its influence on the bias signal can be expressed as

$$\frac{\partial V_{\mathrm{bias}}}{\partial A_3} = -\frac{\sin\varphi}{2} \quad (4)$$

When the drive mode works near the resonant frequency, the phase φ is small, so sin φ should be close to zero. The drift of the quadrature amplitude has a smaller effect on the bias drift.

$$\frac{\partial V_{\mathrm{bias}}}{\partial \varphi} = -\frac{A_3}{2}\cos\varphi \quad (5)$$

But the drift of quadrature phase can cause a much greater effect on the bias drift. As shown in Eq. (5), the bias signal is mainly affected by the stability of the phase of quadrature error. The effect is proportional to the amplitude of the quadrature error. As the amplitude of the quadrature is mainly determined by fabrication error, the stability of the quadrature phase needs to be improved so as to improve the stability of bias.

2 Digital Closed-Loop Control of Drive Mode with Additional Phase Optimization Control

2.1 Basic closed-loop control circuit

The silicon MEMS gyroscope with vacuum packaging has a very high quality factor (above 10^4), which means that the external drive force frequency should be as close as possible to the resonant frequency of the drive mode to obtain a large vibration amplitude response with limited driving force. Besides, the resonant frequency of the drive mode changes linearly with temperature. When the temperature rises by 100 ℃ (from −40 ℃ to 60 ℃), the resonant frequency accordingly decreases by about 10 Hz. This requires a closed-loop frequency control system to make sure that the external drive force frequency follows the change in the resonant frequency.

The drive mode control circuit diagram is shown in Fig. 2. The gyroscope mechanical structure and the analog readout circuit are simplified in a transfer function. All the control processing is in the digital domain.

The digitally controlled quadrature oscillator (DCQO) is one of the key parts in the control circuit. It produces two digital orthogonal sine-wave signals with the same frequency controlled by the phase control loop, which are set as phase standard to obtain phase and amplitude information of the drive mode displacement. The principle of the DCQO is based on complex multiplication[6] and the phase precision is determined by the length of the complex multiplicand. In this case, the output phase resolution can reach 0.000 1°.

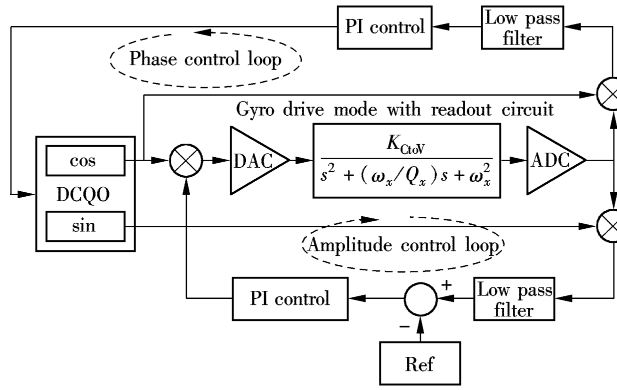

Fig. 2 Basic diagram of drive mode control circuit

There are two control loops: the phase control loop and the amplitude control loop. The phase control loop is set to control the drive force frequency by using the phase-lock method[7-8]. The amplitude control loop is set to control the vibration amplitude of the drive mode with the AGC (automatic gain control) method.

Suppose that the two orthogonal signals from the DCQO are $\cos(\omega_{\mathrm{d}} t)$ and $\sin(\omega_{\mathrm{d}} t)$, and the drive signal has the same phase as $\cos(\omega_{\mathrm{d}} t)$. So the drive mode output signal should be $A_{\mathrm{d}}\cos(\omega_{\mathrm{d}} t + \varphi)$, where A_{d} is the amplitude of the drive mode vibration, and φ is the drive phase. As shown in Fig. 1, the increase in driving frequency will cause a decrease in the drive phase. When the external drive frequency equals the resonant frequency, the drive phase $\varphi = -90°$.

The drive phase signal V_φ is obtained by filtering the product of the DCQO cosine signal and the drive mode output with the low pass filter to remove the quadric harmonic signal. The amplitude of the drive mode output signal may change and can cause an error to phase detection, so it is normalized to avoid the error.

$$V_{\mathrm{mulp}} = \cos(\omega_{\mathrm{d}} t)\cos(\omega_{\mathrm{d}} t + \varphi) = \frac{\cos(2\omega t + \varphi) + \cos(\varphi)}{2} \quad (6)$$

$$V_\varphi = \frac{\cos\varphi}{2} = \frac{\sin(\varphi + 90°)}{2} \quad (7)$$

When φ is near −90°, $V_\varphi \approx (\varphi + 90°)/2$. A PI controller is introduced to control the voltage signal V_φ to zero by adjusting the DCQO output signal frequency. When the frequency is equal to the resonant frequency of the drive mode, φ should be −90° and V_φ be zero.

The acquisition of the drive amplitude also uses the multiplication and the filtering method. The multiplier is a DCQO sine signal and the multiplicand is the drive mode output signal.

$$V_{\mathrm{mulA}} = \sin(\omega_{\mathrm{d}} t) A_{\mathrm{d}} \cos(\omega_{\mathrm{d}} t + \varphi) = \frac{A_{\mathrm{d}}[\sin(2\omega t + \varphi) - \sin(\varphi)]}{2} \quad (8)$$

After filtering the quadric harmonic signal, Eq. (8) can be simplified as $V_{\mathrm{A}} = -A_{\mathrm{d}}\sin\varphi/2$, where φ is near −90°, $V_{\mathrm{A}} \approx A_{\mathrm{d}}/2$. A PI controller is introduced to make the typical AGC control.

A simulation based on Fig. 2 is done to confirm that the drive control system works properly. Considering the individual differences in fabrication, packaging and working temperature ranges, the maximum error of the resonant frequency value between the actual and the designed is in the range of 100 Hz. So in the simulation, the initial value between the drive force frequency and the drive mode resonant frequency is set to 100 Hz. For example, the initial frequency of the DCQO is set to 100 Hz higher than the resonant frequency.

The simulation results are shown in Figs.3 to 5. Fig. 3 shows that the DCQO frequency automatically decreases by 100 Hz and meets the resonant frequency. Fig. 4 and Fig. 5 show the input and output of the drive mode, respectively. At first, the drive signal frequency is much higher than the resonant frequency, so the drive signal saturates to the maximal and just obtains a small output. As the drive frequency approaches the resonant frequency, the output amplitude begins to increase quickly. When the amplitude reaches the reference value, the drive signal amplitude gets smaller so that it can reduce the output amplitude. Finally, all the signals become stable. This simulation indicates that the phase control loop and amplitude loop can remain stable.

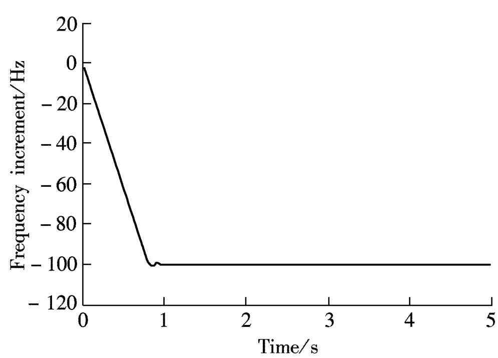

Fig. 3 Simulation result of phase control output

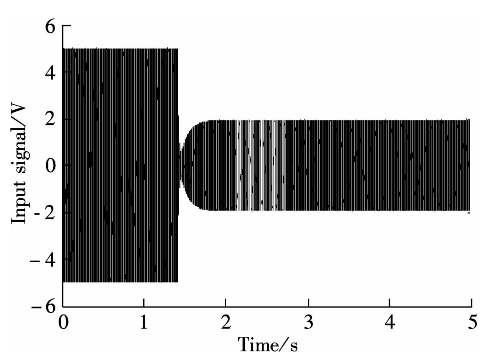

Fig. 4 Simulation result of drive signal

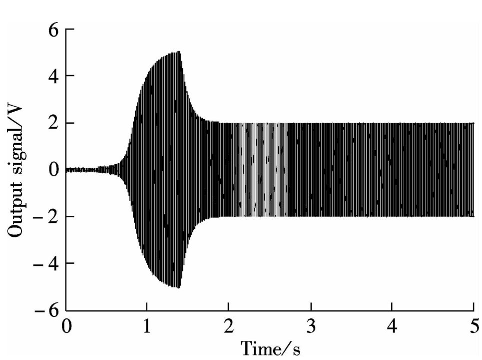

Fig. 5 Simulation result of drive mode output signal

2.2 Phase error by zero-order hold effect and treatment

In the analog-to-digital conversion, the zero-order hold effect can produce additional phase error. This phase error changes with the drive frequency and cannot be controlled in the phase control loop. A phase shift multiplication method is introduced to correct the error.

f is the frequency of the drive mode output signal shown as the analog signal in Fig. 6. f_s is the ADC sampling frequency and $f_s > 10f$. Because of the zero-order hold effect, the sampled signal delays the time of $1/(2f_s)$ than the analog signal. So the phase between the two signals is $f/(2f_s) \times 360°$.

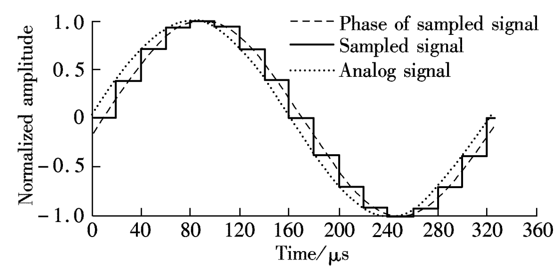

Fig. 6 Diagram of zero-hold effect error

As shown in Eq. (6), a multiplication is introduced to obtain the phase information. In digital signal processing, it is in a discrete time form,

$$V_{\mathrm{mulp}}(k) = \cos(\omega_d t_k)\cos(\omega_d t_k + \varphi) \qquad k = 1, 2, \ldots \tag{9}$$

As shown in Fig. 7(a), the signal from the DCQO and the sampled drive mode output signal in the same sample period makes multiplication. The DCQO signal is a digital signal, but the drive mode output signal is from the analog signal being sampled, thus it has a sample phase error. The phase error can change the production result and affect drive phase stability.

To correct the phase error, the DCQO signal should delay the same time of $1/(2f_s)$, then the two signals can make synchronization again. The demodulation method is as follows:

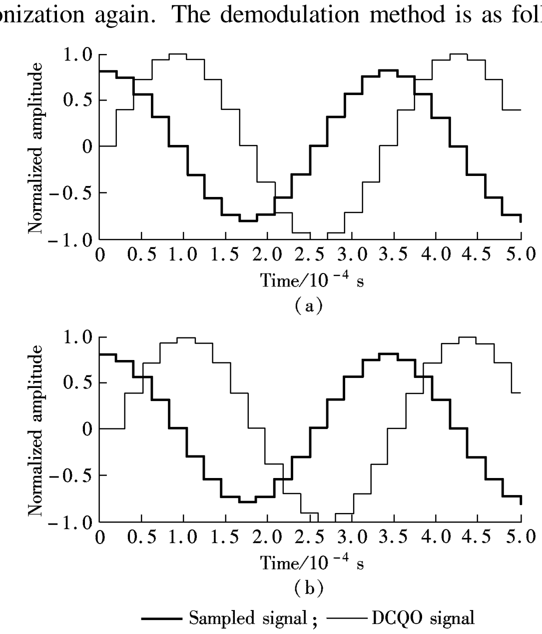

Fig. 7 Multiplication schematic for demodulation. (a) Normal multiplication; (b) Signal delay in multiplication

$$V_{\mathrm{mulp}}(k)=\frac{\cos(\omega_{\mathrm{d}}t_{k-1})\cos(\omega_{\mathrm{d}}t_{k-1}+\varphi)+\cos(\omega_{\mathrm{d}}t_{k-1})\cos(\omega_{\mathrm{d}}t_{k}+\varphi)}{2} \tag{10}$$

As shown in Fig. 7(b), the thick line is the sampled signal with delay and the thin line is the DCQO signal.

3 Experiments

3.1 Identifying the main factor affecting bias stability

An analog circuit with notable bias drift verifies that the drive phase is the main factor affecting bias stability. The bias signal and the sense mode amplitude signal are measured for 70 min at room temperature after a cool-down time of more than 10 h.

The result of the bias output signal is shown in Fig. 8. The bias stability is 60 °/h. The amplitude of the sense mode signal is shown in Fig. 9.

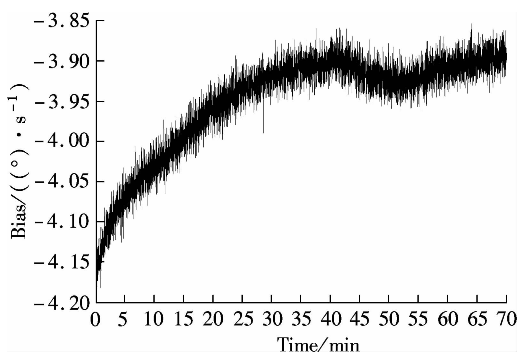

Fig. 8 Bias output signal of analog circuit

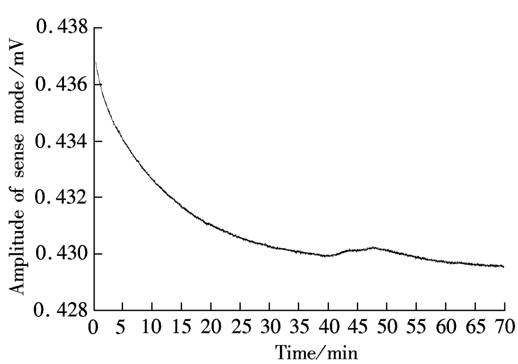

Fig. 9 Amplitude of sense mode signal of analog circuit

The drive phase signal can be obtained by calculating the transformation of Eq. (3), $\phi=\arcsin(-2V_{\mathrm{bias}}/A_3)$, as shown in Fig. 10.

As shown in Fig. 9 and Fig. 10, both the drive phase and the amplitude of the sense mode have a significant drift with time. To identify the primary factor affecting the bias output signal, two more calculations are given as follows:

1) Make the amplitude of the sense mode signal stable, for example, $A_3=0.432$, and the drive phase remains unchanged as shown in Fig.10, so the bias can be calculated (see Fig. 11).

2) Make the drive phase stable, for example, $\phi=91.24°$, and the amplitude signal remains unchanged as shown in Fig. 9. The bias result is shown in Fig. 11.

As shown in Fig. 11 and Fig. 12, to keep the drive phase stable has more effect on bias drift than to keep the amplitude of the sense mode stable. However, the stability of the amplitude of the sense mode signal is important for the scale factor of the gyroscope, and the details can be seen in Ref. [7−8]. So the drive phase is the primary factor affecting the bias drift.

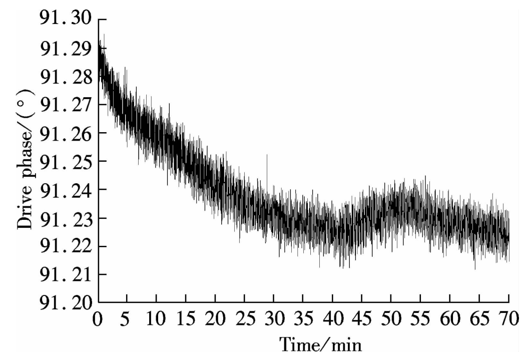

Fig. 10 Drive phase signal of analog circuit

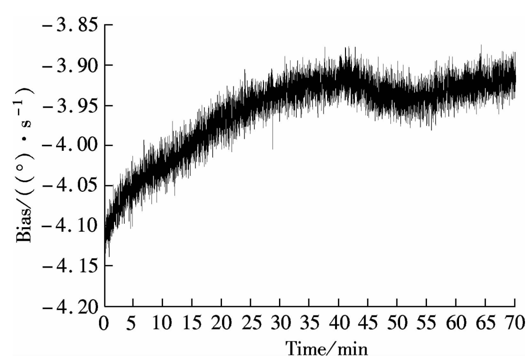

Fig. 11 Bias signal with stable amplitude of sense mode

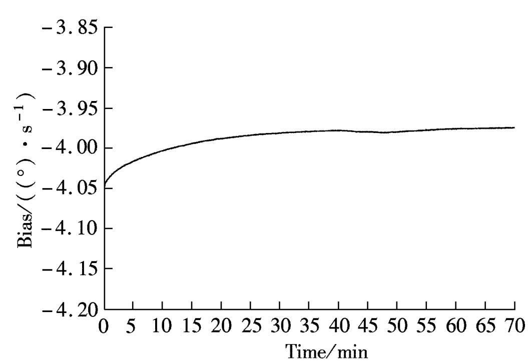

Fig. 12 Bias signal with stable drive phase

3.2 Experiment of digital circuit bias output

A MEMS gyroscope with a digital control circuit (see Fig. 13) is made to verify the phase correction method. The bias output is measured at room temperature, with a cool-down time for more than 10 h. The result with phase correction is shown in Fig. 14. The bias stability is 19 °/h which is mostly caused by noise and not by the drift. The drive phase is also calculated and the drift is within 0.01°, which is greatly improved compared with Fig. 10. So the improvement in the drive phase indeed improves the bias stability.

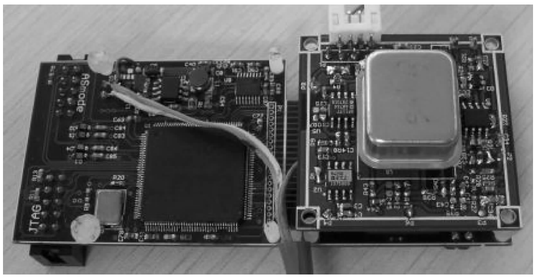

Fig. 13 Gyroscope and digital control circuit

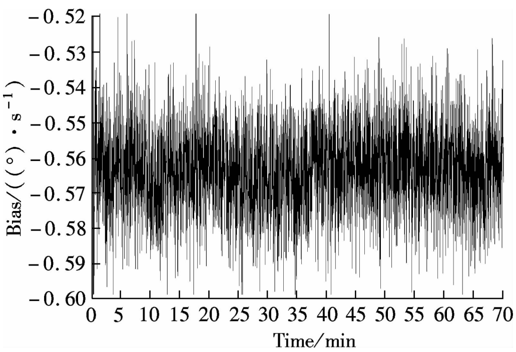

Fig. 14 Bias output of new digital control circuit

4 Conclusion

The bias stability is greatly related to the quadrature stability. A method of improving the quadrature error stability by improving the driving phase stability is proposed. With the method, the bias stability has greatly improved. Analyses and experiments prove the effectiveness of the method.

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新型驱动相位控制技术提高硅微机械陀螺仪稳定性的方法

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摘要:为了增强硅微机械陀螺仪的零偏稳定性,减少其受温度的影响,从数字信号处理的角度提出了一种提高驱动模态驱动相位精确度的方法. 通过零偏信号生成的原理,分析出驱动相位的偏差是影响其性能的主要因素. 采用基于 FPGA 数字信号处理实现方式的锁相环闭环控制原理,实现了对驱动相位的精确控制. 给出了一种抑制相位误差的解调方法. 对比模拟电路,新型数字电路很好地抑制了零偏的漂移,零偏稳定性由 60 °/h 提高到 19 °/h. 新的数字控制方法显著提高了对驱动相位的控制精度,达到了增强零偏稳定性的目的.

关键词:硅微机械陀螺仪;零偏漂移;驱动相位控制;现场可编程门阵列

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