NEW CLOSED-LOOP DRIVING CIRCUIT OF SILICON MICROMACHINED VIBRATORY GYROSCOPE

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Abstract: A new closed-loop driving scheme for the silicon micromachined vibratory gyroscope (SMVG) is proposed. The push-pull driving is adopted and in-phase AC and reverse-phase DC voltages are applied in the driving electrodes placed in both sides of the active combs, respectively. Driving performance analyses show that the frequency spectrum between driving moments and noise signals is separated. Therefore, the model of the closed-loop control is set up with the phase lock loop (PLL). The requirements for phases and gains of the sinusoidal self-drive-oscillation are met by PLL, thus the closed-loop circuit reaches the self-drive-oscillation. Phase conditions of the sinusoidal self-drive-oscillation and the characteristic of phase discrimination of the PLL are used to eliminate the coupling between driving and sense signals, and noise signals. Finally, experimental results show that the variations of both the driving frequency and the amplitude are all under 0.02%. The precision and the reliability of the gyroscope are greatly improved.

Key words: phase lock loop; closed-loop; silicon micromachined vibratory gyroscope; self-drive-oscillation

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INTRODUCTION

Silicon micromachined vibratory gyroscopes (SMVGs) are small in volume, light in weight and low in cost. Their production technics is compatible with that of the micro-electronics. Production in great numbers is possible to be used whenever the precision is not strictly required, so the potential application of SMVGs is promising[1-3]. But SMVGs cannot meet the practical application in terms of the precision and reliability. One reason is that the precision of the frequency and the amplitude of SMVG driving is low, thus resulting in poor reliability. When open-loop driving is adopted, the frequency and the amplitude stability of the driving signal source affect the stability of the SMVG directly. Meanwhile, it is influenced by the temperature variation. Even if there is a driving signal source of high performance, the driving signal cannot automatically adjust itself according to the gyroscope driving condition because of open-loop driving[4,5]. When closed-loop driving is adopted, sense signals are usually fed back as driving signals. But the driving signal will be coupled into the sense signal[6]. The coupled signal is of the same frequency as the sense signal. Therefore, the interference cannot be eliminated in conventional filtering ways. Furthermore, sense signals are weak and the signal-to-noise ratio of the circuit is low, so the driving of the SMVG is not satisfactorily effective.

In this paper, a new closed-loop driving scheme is introduced. PLL technique is adopted to satisfy the requirment of the phase angle and the gain of the sinusoidal self-drive-oscillation. In this way, self-drive-oscillation of the loop is set up and closed-loop control is realized. PLL traces the sense signals instead of the coupled driving ones, which eliminate the interference of the shared frequency. PLL itself can be regarded as a narrow band filter. Noise signals of the majority of frequency channels are filtrated in the circuit. Besides, PLL can trace the variations of the

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closed-loop frequency and the closed-loop phase angle, and adjust them. Then the amplitude and the frequency of the driving circuit are stabilized, and the precision and the reliability of the SMVG are raised.

1 DRIVING STRUCTUCE AND CONTROL PRINCIPLE

The structure of the SMVG is shown in Fig. 1. The scheme adopts the push-pull driving, i. e. , in-phase AC and reverse-phase DC voltages are applied in the driving electrodes which are placed in both sides of the active combs, respectively as shown in Fig. 2. The motion equation of the driving mode is

$$I\ddot{\theta} + D\dot{\theta} + K\theta = M \tag{1}$$

where I, D and K refer to the moment of the inertia, damping constant and the stiffness coefficient, respectively. They are decided by the driving structure. M refers to the electrostatic moment of the driving axis and θ the vibratory angle displacement. When driving voltages

$$V_1 = V_d + V_m \sin\omega t \quad V_2 = - V_d + V_m \sin\omega t$$

are applied to the driving electrodes, we have

$$M = 2\frac{\varepsilon hR}{d} V_d V_m \sin\omega t \tag{2}$$

where ε is the dielectric constant; d the distance between the fixed comb and the active comb; h the thickness of the comb; and R the equivalent semidiameter of the gyro driving by electrostatic moment. V_d, $V_m \sin\omega t$ are the dc-bias voltage and AC driving voltage. According to the motion equation, we have

$$\theta = \theta_0 \sin(\omega t - \varphi) \tag{3}$$

under the vacuum condition, φ equals to 90°.

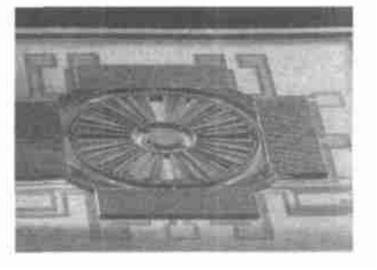

Fig. 1 SEM picture of SMVG

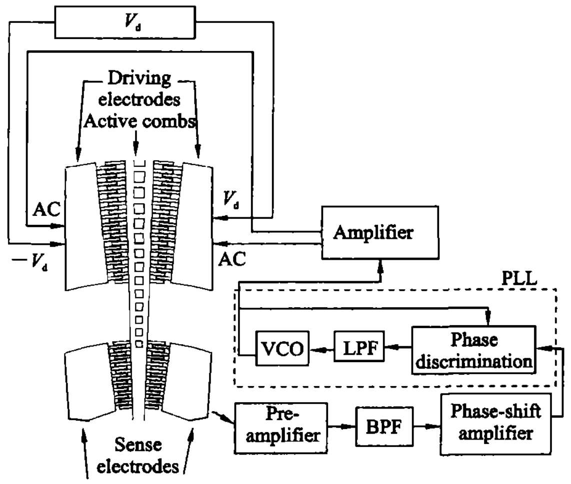

Fig. 2 Principle diagram of closed-loop control

2 DRIVING ANALYSIS

The driving voltages applied to the driving electrode always contain noise signals. To analyze the influence of the noise signals on the driving performance, driving voltages can be expressed as follows

$$V_1 = V_d + V_m \sin\omega t + n_1(t) \tag{4}$$

$$V_2 = - V_d + V_m \sin\omega t + n_2(t) \tag{5}$$

where $n_1(t)$ and $n_2(t)$ are noise signals of the driving voltage. The experiments show that $n_1(t)$ and $n_2(t)$ are mainly $1/f$ low frequency noises. The driving moment can be expressed in the following

$$M = \frac{\varepsilon hR}{2d}[4V_d V_m \sin\omega t + 2V_d(n_1(t) + n_2(t)) + 2V_m \sin\omega t(n_1(t) - n_2(t)) + n_1^2(t) - n_2^2(t)] \tag{6}$$

The dc-bias voltage is supplied by the precision voltage source, therefore, the noise signals can be neglected. The majority of the noise signals resulted from the AC, and the ACs applied to the driving electrodes are the same. $n_1(t)$ and $n_2(t)$ can be equal to each other

$$M = 2\frac{\varepsilon hR}{d}[V_d V_m \sin\omega t + V_d n_1(t)] \tag{7}$$

where the first item of Eq. (7) is the driving moment, which is of the same frequency as the inherent driving frequency of the gyro. It drives the gyro to oscillate harmoniously; the second item the noise moment. It is mainly $1/f$ low frequency noises, which is much different from that of the driving frequency and has no effects on the driving.

3 CLOSED-LOOP CONTROL PRINCIPLE

Fig. 2 illustrates the closed-loop control principle. Firstly, signals detected from the sense electrodes are pre-amplified. Secondly, the useful AC signals are chosen by the bandpass filter (BPF). Thirdly, these signals are rectified by the phase-shift amplifier. The target signals will be traced by the PLL. Finally, AC signals will be amplified and applied to the driving electrodes with the dc-bias voltage. The dotted frame is the PLL. The theories of the PLL are as follows: firstly, instantaneous phase angles of output and input signals are contrasted by the phase discriminator (PD). Then the high frequency signals are filtrated by the low pass filter (LPF). Finally, the driving signals are exported by the voltage controlled oscillator (VCO). When the tracing is locked, the input signals are of the same frequency as the output signals, and the phase difference is invariable. This closed-loop control circuit is equivalent to a sinusoidal self-drive-oscillation circuit. To realize the self-drive-oscillation, two requirements must be met: (1) The phase angle of the circuit should be $\theta = 2n\pi$ (n should be an integer). (2) The gain of the whole circuit should be $A > 1$. Fig. 3 is the transfer function frame of the closed-loop control system. In Fig. 3, K_c is the proportion factor of the capacitance C, that is transferred from the angular displacement θ K_v the proportion factor of the voltage that is transferred from the capacitance. K_0 and K_2 are the gain factors of the AC. Inside the dotted frame is the phase model of the PLL circuit. ϕ_1 and ϕ_2 are the input and output phase angles

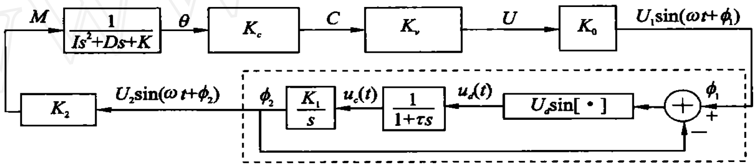

Fig. 3 Transfer function frame of closed-loop control system

4 CLOSED-LOOP CONTROL ANALYSIS

Sense checking is weak signal detection. The gain range of the circuit is wider. The surrounding signals are coupled into sense signals and the useful signal is influenced. The most important coupling signals are those input driving ones[6].

Assuming that the sense signal is

$$u_g = U_g \cos \omega t \tag{8}$$

and the total noise is

$$u_n = U_q \cos(\omega t - \theta_0) + n(t) \tag{9}$$

where $n(t)$ is the low frequency noise, and θ_0 the phase shift of the sense signal to the input driving ones.

The input driving signals and the sense signals are of the same frequency. Therefore, the interference cannot be filtrated by the normal filter. This kind of interference is restrained by satisfying the phase angles of the self-drive-oscillation.

Fig. 4 is the phase model of the whole circuit. If $\theta_0 + \theta_1 + \theta_2 = 360°N$ (N is an integer), the phase angle of the self-drive-oscillation is satisfied, and the circuit oscillates. As to the coupled signals, they cannot realize the self-drive-oscillation of the circuit for a lack of phase angle θ_1. Under the vacuum condition $\theta_0 = 90°$, if we choose the PLL with the phase shift $\theta_1 = 0°$, the interfering signals in the succeeding circuit of the PLL will be restrained after being locked. It can be analyzed as follows[7].

The voltage of input signals is

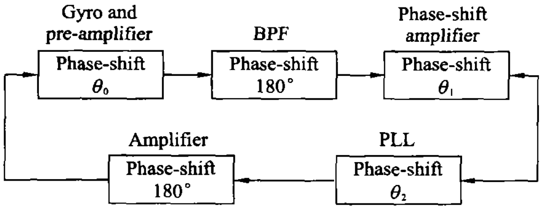

Fig. 4 Phase model of closed-loop circuit

$$u_{in}(t) = K_0[U_g\cos(\omega t + \theta_1) + U_q\cos(\omega t - 90° + \theta_1) + n(t)] \qquad (10)$$

the voltage of output signals after being locked is

$$u_{out}(t) = K_A K_0 U_g\cos(\omega t + \theta_1) \qquad (11)$$

where K_A is the gain coefficient of the PLL.

Through the phase discriminator (multiplicator)

$$u_d(t) = u_{in}(t) \cdot u_{out}(t) = \frac{K_A K_0^2 U_g}{2}[U_g\cos(2\omega t + 2\theta_1) + U_g + U_q\cos(2\omega t - 90^0 + 2\theta_1) + \cos(\omega t + \theta_1)n(t)] \qquad (12)$$

through the filter

$$u_c(t) = \frac{K_A K_0^2 U_g^2}{2} \qquad (13)$$

From the abovementioned equations, we can conclude that whether there are interfering signals or not, the signal frequency and the phase angle output by the VCO is not changed when the circuit is locked. And the interfering signals in the succeeding circuit of the PLL are restrained. Besides, the tracking capacity of the frequency and the phase of the PLL can sense the driving variations of the SMVG. The feedback signal can adjust the driving signals of the SMVG. If the input signals disappear, the PLL can maintain the output of the signals for some time. It has certain quality of robustness. It can be applied even there is too much noises.

5 EXPERMMENTAL RESULTS

Figs 5, 6 are the frequency and the amplitude of AC signals for 1 h in the closed-loop driving circuit. From Fig. 5, we can see that during 1 h, the frequency variation is no higher than 1 Hz. From Fig. 6, we can see that in 1 h the AC signal variation is no more than 1.3 mV. The precision of the SMVG is greatly improved.

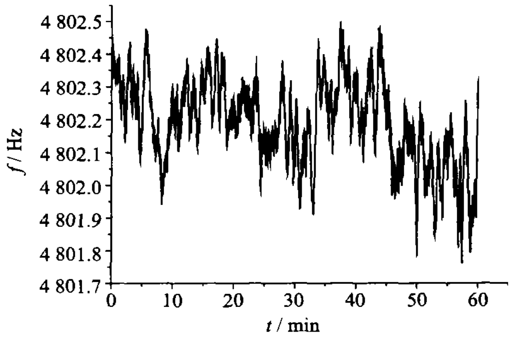

Fig. 5 Frequency curve of driving signal for 1 h

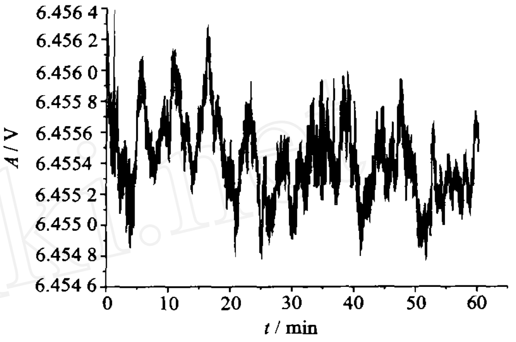

Fig. 6 Amplitude curve of driving signal for 1 h

6 CONCLUSION

The closed-loop control realized by the PLL can effectively eliminate the interference of the driving signal to the sense signal, and restrain the low frequency noises to a certain degree, by which the driving is of stable amplitude and frequency. Experimental results show that the project is feasible because the circuit is simple.

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硅微陀螺仪的一种新型闭环驱动方案

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摘要: 介绍了一种新的硅微陀螺仪闭环驱动方案。该方案采用推挽驱动方式, 即在陀螺仪活动梳齿两边的驱动电极上分别施加同相交流电压和反相直流电压。对驱动性能进行了分析, 结果表明驱动力矩的频段与噪声信号频段是分离的。在此基础上, 利用锁相技术满足正弦自激振荡的相角和增益条件, 建立环路的自激振荡, 实现了闭环控制。同时在闭环回路中利用正弦自激振荡的相角条件和锁相环的鉴相特性, 消除了驱动信号对驱动检测信号的同频干扰, 抑制了环路中的噪声干扰。试验结果显示, 驱动电压的频率和幅度的变化量均在0.02%以下, 实现了驱动稳幅稳频的目的, 陀螺仪精度和可靠性得到了显著提高。

关键词: 锁相环; 闭环; 硅微陀螺仪; 自激振荡
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