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Design and implementation of digital closed-loop drive control system of a MEMS gyroscope

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Abstract: In order to effectively control the working state of the gyroscope in drive mode, the drive characteristics of the micro electromechanical system (MEMS) gyroscope are analyzed in principle. A novel drive circuit for the MEMS gyroscope in digital closed-loop control is proposed, which utilizes a digital phase-locked loop (PLL) in frequency control and an automatic gain control (AGC) method in amplitude control. A digital processing circuit with a field programmable gate array (FPGA) is designed and the experiments are carried out. The results indicate that when the temperature changes, the drive frequency can automatically track the resonant frequency of gyroscope in drive mode and that of the oscillating amplitude holds at a set value. And at room temperature, the relative deviation of the drive frequency is 0.624×10^{-6} and the oscillating amplitude is 8.0×10^{-6}, which are 0.094% and 18.39% of the analog control program, respectively. Therefore, the control solution of the digital PLL in frequency and the AGC in amplitude is feasible.

Key words: micro electromechanical system (MEMS) digital gyroscope; drive frequency; phase-locked loop (PLL); oscillating amplitude; automatic gain control (AGC)
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With the development of micromechanical technology, micro electromechanical system (MEMS) gyroscopes have become important inertial sensors, which have a broad application field including automobile, consumer electronics, control stabilization, and inertial navigation etc[1]. But the MEMS gyroscope has a serious defect: low precision. So many efforts have been made by researchers all over the world about how to improve the performance of MEMS gyroscopes.

Formerly, the MEMS gyroscope was controlled by some analog devices[2]. However, the control system of the gyroscope is easily influenced by the interference from bulk components, which leads to low precision and even works abnormally. In order to overcome these shortcomings, instead of the analog circuit, a digital circuit is starting to play an important role in the MEMS gyroscope signal control. Especially, the use of a field programmable gate array (FPGA) brings great convenience, which can flexibly deal with the complicated signals by many advanced algorithms. Therefore, gyroscope digital processing has become a promising research direction for improving the measurement precision.

As the gyroscope is sensitive to the external environment, it is essential to control the drive system on a closed-loop solution through adding the feedback branch. Traditionally, the closed-loop system directly detects the drive detection signal in the drive direction, and dominates the amplitude of the output signal by the automatic gain control (AGC) algorithm [3-6]. Due to the frequency characteristics of the drive signal which mainly depends on the structure of the gyroscope sensor, some deviations exist between the frequency of the drive signal and the resonant frequency in the drive mode of the MEMS gyroscope, as well as being affected by the temperature change [7]. For these problems, a novel closed-loop drive circuit is presented in this paper, which utilizes a digital PLL to track the resonant frequency and utilizes the AGC to make the amplitude constant.

1 Drive Characteristics of the MEMS Gyroscope

The gyroscope is a sensor for measuring the angular velocity based on the Coriolis force, and the basic working principle is described in Fig. 1(a). There are two orthogonal axes named x and y, representing the drive and the detection directions, respectively, and the direction perpendicular to the drive and the detection directions is sensitive to the angular velocity, which is the z axis. In the drive direction, the proof mass is electrostatically driven by a constant amplitude and frequency. If the sensor is rotated along the sensitivity direction, the Coriolis force will excite the proof mass oscillating in the detection direction, and the displacement of the proof mass can be

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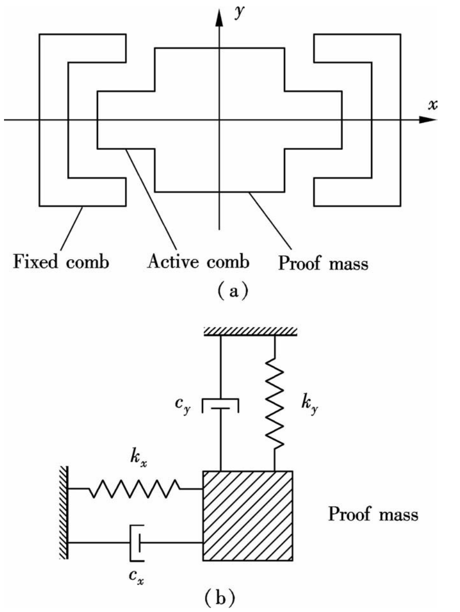

Fig. 1 Principle schematics of MEMS gyroscope. (a) Simple structure schematic diagram; (b) Equivalent schematic diagram

detected by a capacitance readout circuit [8]. Fig. 1(b) is the equivalent model of the gyroscope system.

From the model of the spring and mass, it is found that this system is, in fact, a classical second-order oscillating system. Without considering the quadrature error, the drive and the detection mode can be expressed by

$$\ddot{x}(t)+\frac{c_x}{m}\dot{x}(t)+\frac{k_x}{m}x(t)=\frac{F_e}{m} \tag{1}$$

$$\ddot{y}(t)+\frac{c_y}{m}\dot{y}(t)+\frac{k_y}{m}y(t)=-2\Omega_z\dot{x}(t) \tag{2}$$

where m is the mass of the proof mass; F_e is the electrostatic force; Ω_z refers to the input angular rate in the z axis; c_x, k_x and c_y, k_y are the damping coefficients and the spring stiffness coefficient in the x and y directions, respectively.

If the external drive force $F_e=A_F\sin\omega_d t$, where ω_d is the drive signal frequency, then the displacement of the proof mass in the drive direction can be expressed by the following equation under the stable working condition.

$$x(t)=A_xA_F\sin(\omega_d t+\varphi_x) \tag{3}$$

The amplitude A_x and the phase ϕ_x can be denoted as

$$A_x=\frac{1/m}{\sqrt{(\omega_x-\omega_d)^2+\omega_x^2\omega_d^2/Q_x^2}} \tag{4}$$

$$\varphi_x=-\arctan\frac{\omega_x\omega_d}{(\omega_x^2-\omega_d^2)Q_x} \tag{5}$$

where $\omega_x=\sqrt{k_x/m}$ and $Q_x=m\omega_x/c_x$ represent the angular frequency and the quality factor of the drive mode, respectively.

According to the above drive equations, the characteristic curves of the magnitude-frequency and the phase-frequency are drawn in Fig. 2 and Fig. 3. From the figures, it can be seen that the frequency is the main factor influencing the drive performance. When the frequency is equal to the resonant frequency of the drive mode, the amplitude has a maximum value and the phase is $-90°$. At this time the drive mode of the MEMS gyroscope is in the resonance state. Therefore, in order to make the MEMS gyroscope work stably and efficiently, it is necessary to ensure the drive frequency in accordance with the resonant frequency.

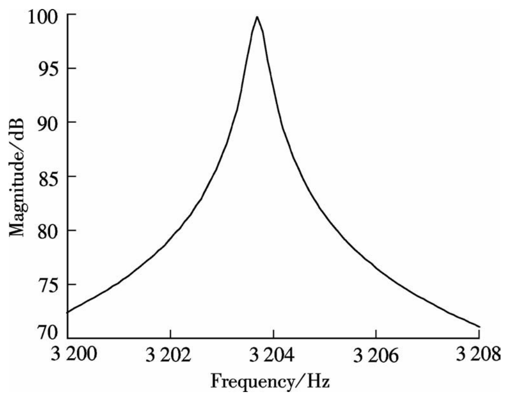

Fig. 2 Characteristic curve of magnitude-frequency

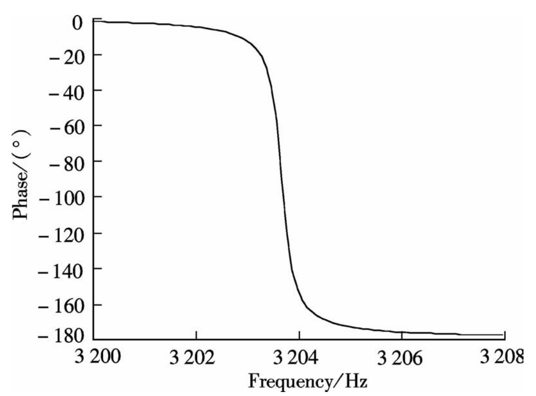

Fig. 3 Characteristic curve of phase-frequency

Based on the drive equation and the drive characteristics, the detection equation (2) can be solved, and in the steady state, the displacement of the proof mass in the detection direction can be represented as

$$y(t)=A_y\cos(\omega_d t+\varphi_x+\varphi_y) \tag{6}$$

where A_y and ϕ_y are the amplitude and the phase in the detection direction induced by the Coriolis effect, which can be represented as

$$A_y=A_xA_F\frac{2\omega_d\Omega_z}{\sqrt{(\omega_y^2-\omega_d^2)^2+(\omega_y\omega_d/Q_y)^2}} \tag{7}$$

$$\varphi_y=-\arctan\frac{\omega_y\omega_d}{(\omega_y^2-\omega_d^2)Q_y} \tag{8}$$

where $\omega_y=\sqrt{k_y/m}$ and $Q_y=m\omega_y/c_y$ represent the angular frequency and the quality factor of the detection mode, respectively.

From the solution of the detection equation, it can be seen that the detection output signal has the same frequency as the drive signal, and the amplitude is proportional to the amplitude of the drive signal and the input angular rate. Therefore, the drive frequency and the amplitude are two significant factors.

In conclusion, in order to drive the gyroscope to work at the maximum value, the drive frequency should be in accord with the resonant frequency of the drive mode. Moreover, to ensure that the detection output signal be in a stable state, it is crucial to ensure that the gyroscope oscillate with the resonant frequency and work on the constant amplitude.

2 Closed-Loop Control Method in Drive Mode

According to the importance of the drive frequency and the amplitude of the MEMS gyroscope, a control solution is presented in Fig. 4. The whole system includes the drive control and the detection output. In the drive control mode, a closed-loop solution is adopted, which is composed of the PLL module for tracing the resonant frequency and the AGC module for regulating the amplitude. The detection component utilizes an open-loop detection scheme, and the demodulation method employs the phase sensitive demodulation algorithm.

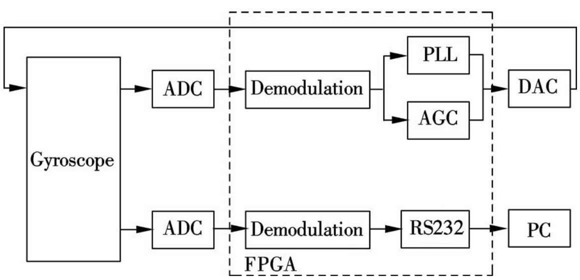

Fig. 4 Control solution of the MEMS gyroscope

2.1 Phase control based on PLL

The phase is an important parameter for the drive control of gyroscopes, and the drive frequency changes with the phase adjustment. In order to effectively control the drive phase, a digital PLL solution is designed, as shown in Fig. 5. The PLL consists of a phase detector (PD), a lower pass filter (LPF), a proportional integral control (PI) and a digital control oscillator (DCO). The whole control solution is implemented in a closed-loop control system [9].

The DCO is a signal generator, which simultaneously generates the digital quadrature cosine and sine signals, represented by u_{o1} and u_{o2}, respectively. And it is composed of the direct digital synthesizer (DDS) [10], whose frequency is controlled by the frequency control word M, and the basic principle is shown in Fig. 6.

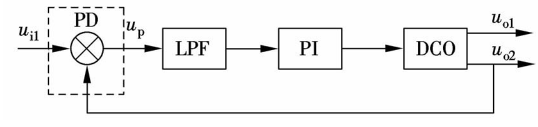

Fig. 5 Phase control schematics based on PLL

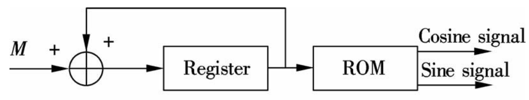

Fig. 6 Principle of the DCO signal generator

The PD is a phase comparator for obtaining the phase difference between the drive detection signal and the drive signal, which employs the phase sensitive demodulator achieved by a multiplier. After normalization processing in amplitude, the drive detection signal u_{i1} is demodulated by the quadrature signal from the DCO, and the phase error is achieved. The LPF is a low pass filter to filter out the high frequency signal after phase demodulation and then a direct current (DC) signal is obtained, which is an instantaneous phase error. To reduce the control error and improve the stability in the steady state, a PI controller is introduced.

In practice, when the resonant frequency of the gyroscope is changed by some environmental factors, according to the phase frequency characteristic in Fig. 3, a phase difference θ_p between the drive detection signal and the drive signal will appear, then the signal from the ADC can be demodulated by the orthogonal signal from the DCO.

$$u_p = u_{i1} u_{o2} = \cos(\omega_d t + \varphi_x + \theta_p) \sin(\omega_d t + \varphi_x) = \frac{1}{2}[\sin(2\omega_d t + 2\varphi_x + \theta_p) - \sin\theta_p] \tag{9}$$

The result of phase sensitive demodulation is divided into the double frequency signal and the DC signal. Through a PLF module, the double frequency signal is filtered out and the DC signal is obtained. Here, the angular θ_p is small enough to be approximately equal to the sine value. Consequently, the angular θ_p is obtained accordingly, which is the frequency control word. Because the angular θ_p is the instantaneous phase angular and it is regarded as the angular rate ω, it is necessary to control the value in an appropriate and stable state by the PI module.

$$\Delta\theta = k_p(1 + k_i \Sigma\omega) \tag{10}$$

where k_p and k_i are the coefficients of the proportion and the integral, respectively. When $\Delta\theta$ is determined, the current frequency control word θ_c can be obtained through the previous frequency control word θ_0.

$$\theta_c = \theta_0 + \Delta\theta \tag{11}$$

The θ_c will regulate the oscillation frequency of the DCO until it is in accord with the resonant frequency of the drive mode. The signal generated by the DCO will drive the gyroscope oscillating with the resonant frequency after it passes through a digital analog convertor (DAC) module.

Therefore, the PLL control system can ensure the drive frequency to automatically trace the resonant frequency of the drive mode.

2.2 Amplitude control based on AGC

The amplitude of the drive signal of the MEMS gyroscope is another significant parameter for achieving accurate control. To maintain the drive signal oscillating at a constant value all the time, it is necessary to detect the oscillating amplitude and compare it with the set value, then adjust the drive signal to an appropriate amplitude according to the error. Therefore, a closed-loop control scheme in the amplitude can be implemented by adding the amplitude feedback loop, which is called an AGC control solution (see Fig. 7).

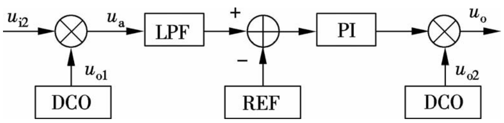

Fig. 7 Amplitude control schematics based on AGC

The AGC module is comprised of the amplitude demodulation, the LPF, the amplitude comparator, the PI control module and the DCO module. The amplitude demodulation is an essential approach through which the amplitude value of the drive detection signal can be acquired. For simplicity, amplitude demodulation also makes use of the phase sensitive demodulation. The LPF module is used to get rid of the high frequency component in the demodulation so that the DC signal is derived from the demodulation result. The amplitude comparator is a crucial component of the AGC control system, which is used to compare the amplitude value of the drive detection signal with the set value represented by the symbol REF in Fig. 7. The function of the PI module is to control the difference from the comparator in a steady state. Based on the deviation, the gain of the drive signal from the PLL will be regulated to an appropriate value, which is implemented by a multiplier.

When the amplitude of the vibration of the drive signal changes because of surrounding factors, the drive detection module will detect the displacement of the gyroscope oscillation. After the ADC sampling, the drive detection signal is changed into the digital domain. The digital signal is demodulated by the in-phase signal from the DCO.

$$u_a = u_{i2}u_{o1} = A_x\cos(\omega_d t + \varphi_x + \theta_a)\cos(\omega_d t + \varphi_x) = \frac{1}{2}A_x[\cos(2\omega_d t + 2\varphi_x + \theta_a) + \cos\theta_a] \qquad (12)$$

where A_x is the amplitude of the drive detection signal, and θ_a is an angular which is so small that cos θ_a is 1 approximately.

According to Eq. (12), the results of demodulation are divided into the alternating current signal and the DC signal. Through the LPF module, the DC signal is obtained and it is exactly the amplitude. Comparing the amplitude value with the set value in a comparator shows that the result is the instant deviation caused by the amplitude change.

$$\Delta A = \frac{1}{2}A_x - A_{REF} \qquad (13)$$

The PI control algorithm brings the gain error into the steady state, and the gain A is achieved.

$$A = k_p(1 + k_i\Sigma\Delta A) \qquad (14)$$

Then the gain is multiplied to the drive signal from the PLL output. The signal will drive the gyroscope oscillating at the amplitude equal to the set value. Hence, the oscillating amplitude of the drive mode can hold at the set value all along.

3 Experiment and Results

In order to further verify the validation in practice, a circuit with the FPGA digital processing is designed according to the control solution in Fig. 4, and the corresponding print circuit board is fabricated, as shown in Fig. 8. Here, the MEMS gyroscope adopts the structure-decoupled dual-mass gyroscope designed by Yin et al[11]. The digital process chip employs the FPGA from the Altera corporation with the Verilog HDL programming language, and both the ADC and the DAC make use of 24-bit high precise devices.

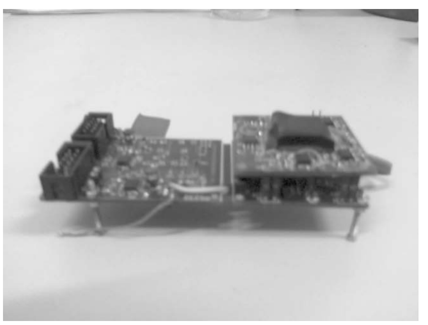

Fig. 8 Photo of the MEMS gyroscope system

3.1 Frequency and amplitude characteristics

Due to the fact that the MEMS gyroscope is sensitive to environmental temperature[12], an experiment is designed as follows. First, the MEMS gyroscope is placed in the temperature control box. Then, the temperature of the box is set and the temperature rises from −40 to 60 ℃ with a speed of 1 ℃/min. During the temperature change, the drive frequency and the oscillating amplitude are sampled using the ADC. Finally, the data are transmitted to the PC by the RS232 serial communication interface.

When the temperature increases, the resonant frequency of the MEMS gyroscope changes with the external environment. Through the phase demodulation, the change value of the frequency can be calculated. According to the change value, the PLL will actively adjust the drive frequency until it is consistent with the resonant frequency. Hence, the drive frequency can automatically track the resonant frequency under the control of the PLL. Fig. 9 describes the curve of the drive frequency changing with the temperature. For the amplitude, with the temperature rising, the quality factor (Q value) of the drive mode decreases and the drive amplitude increases. But under the control of the AGC, the oscillating amplitude is constant and equal to the set value. The oscillating amplitude from the drive detection signal is depicted in Fig. 10.

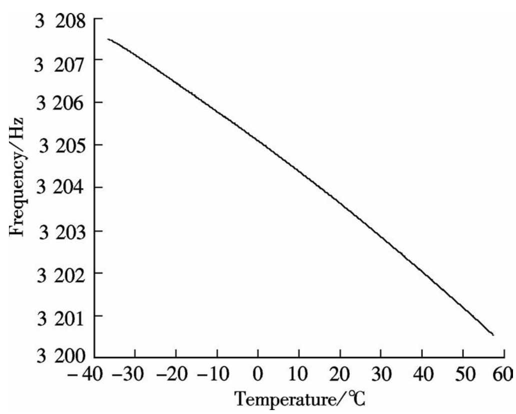

Fig. 9 Curve of frequency with temperature change

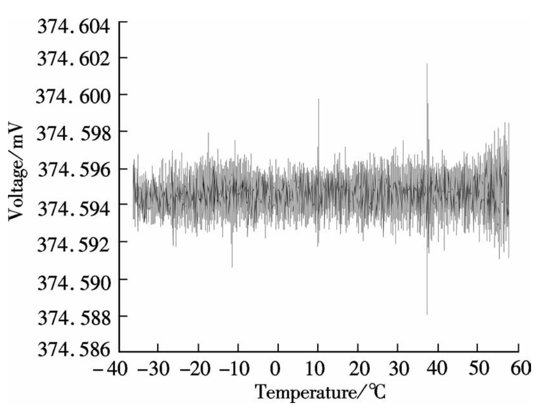

Fig. 10 Curve of amplitude with temperature change

3.2 Drive frequency and amplitude stability characteristics

To test the stability of the gyroscope, an experiment is arranged as follows. The test surroundings are at a constant room temperature of about 25 ℃. After the MEMS gyroscope works in a stable state, a set of test data are transmitted out by the RS232 (see Fig. 11 and Fig. 12).

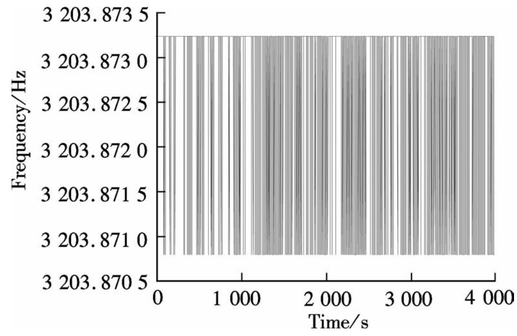

Fig. 11 Frequency characteristics at room temperature

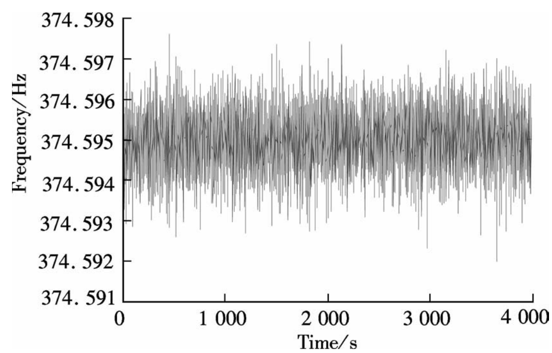

Fig. 12 Amplitude characteristics at room temperature

From the frequency characteristic diagram, it can be seen that the drive frequency has little fluctuation and the fluctuation scope is 0.624×10^{-6}, which is 0.094% of the analog PLL drive frequency [13]. It indicates that the drive frequency is in a stable state with high precision.

From the amplitude characteristic diagram, we can find that the oscillating amplitude has a ripple of 8.0×10^{-6}, which is 18.39% of the analog AGC amplitude control[13]. So we consider that the oscillating amplitude is under a stable control.

When the gyroscope works at the constant temperature, the resonant frequency maintains at an invariable value. Contrarily, when the resonant frequency changes, the phase error is obtained through the phase demodulation and the PLL will adjust the drive frequency according to the error and keeps it working in the resonant state. Under the control of the AGC, the oscillating amplitude will stay at a set value. The experimental results show that the drive frequency and the oscillating amplitude of the MEMS digital gyroscope have a good stability when they are under the control of the PLL and the AGC.

4 Conclusion

In order to maintain the MEMS gyroscope working in a stable state, a novel solution is proposed, which utilizes a digital PLL and an AGC control to control the drive frequency and the amplitude, respectively. A circuit with the FPGA is designed and the experiment is done under preset conditions. The results show that a digital PLL can trace the resonant frequency actively when the resonant frequency changes and the digital AGC can maintain the amplitude at a constant value all the time. Furthermore, the control solution has good stability and high precision at a certain temperature. Therefore, the novel closed-loop drive control system is feasible and reliable.

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MEMS 陀螺数字闭环驱动控制设计与实现

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摘要:为了有效控制陀螺驱动模态的工作状态,从原理上分析了微机械陀螺的驱动特性,提出了一个新型的微机械陀螺闭环驱动数字控制电路,即采用数字锁相环和自动增益控制方法分别控制驱动频率和振荡幅度.设计了带有现场可编程门阵列的数字处理电路,并进行了实验.结果表明:当温度变化时,驱动频率能够自动跟踪陀螺驱动模态的谐振频率,并且振荡幅值始终保持在设定值.在常温下驱动频率相对偏差为 0.624×10^{-6},振荡幅值相对偏差为 8.0×10^{-6},分别是模拟控制方案的 0.094% 和 18.39%.因此,基于数字锁相环和自动增益控制的频率和幅值闭环驱动控制方案是可行的.

关键词:微机械数字陀螺;驱动频率;锁相环;振荡幅度;自动增益控制

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