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Digital Closed-loop Controller Design of A Micromachined Gyroscope Based on Auto Frequency Swept

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***Abstract*- This paper describes the design of a digital signal processing system for a MEMS vibratory gyroscope. It focuses on automatically obtaining the parameters of the gyroscope and ensure it vibrate at the resonance frequency through auto frequency swept. A closed-loop control method based on phase locked loop (PLL) and the automatic gain control (AGC) [1-3] with a proportion-integral (PI) controller. The angular rate demodulation is realized by adaptive filter algorithm. The whole closed-loop system is implemented on a field-programmed-gate-array (FPGA) platform with a Z-axis tuning fork gyroscope. The sensitivity is 3.7mv/deg/s with non-linearity 0.075% and the bias stability is 0.02°/s (1σ).**

I. INTRODUCTION

With the development of the micro-electronics technology [4], Micro-machined gyroscope, which is a sensor for measuring angular displacement, has been paid much attention in recent years due to its miniature size and batch production. It has a significantly increasing usage in automobile, biomedical equipment, consumer applications, industrial applications and other fields. Since 1990s, there has been a limited amount of research on the digital control system design of MEMS gyroscopes. Some achieved good performance of the gyroscope using the FPGA platform [5, 6]. For better linearity, closed-loop control must be used to ensure the vibration of the gyroscope with constant amplitude. Resonant frequency of the gyroscope is a key parameter of the closed-loop control system, which is usually obtained by a frequency sweeper as different gyroscopes vibrate with different frequency. It is rather time-consuming and takes too much effort to test the resonant frequency manually. Furthermore, the resonant frequency would drift with temperature, as shown in Fig.1. And parameters of the vibration of the gyroscope would change every time the gyroscope starts working.

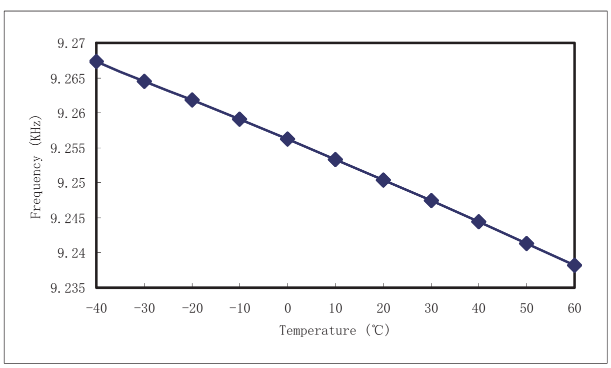

Fig.1. Resonant frequency & temperature

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Thus, this paper introduces the auto-sweep module to get parameters of the gyro's vibration for closed-loop control. Traditionally, these functions have been implemented by analogue circuits. But digital electronics are widely used as they can hardly be affected by temperature and are more flexible as various kinds of algorithms can be tried, the parameters can be adjusted conveniently.

In this paper, The whole digital signal processing system based on FPGA is introduced. A practical solution， based on the quadrature demodulation， is applied to the gyroscope's close-loop control to keep the vibration amplitude of the drive mode constant. The quadrature demodulation，which has been successfully used in telecommunication area，is to use a sine wave and a cosine wave to multiply the input signal respectively. Then the amplitude and phase information of the input signal，which are used to control the PID algorithm and PLL，can be obtained. A high-pass filter is used to filter out the low-frequency noise from the gyroscope's structure after ADC. The direct digital frequency synthesizer (DDS) has been introduced to generate drive signal with high signal-noise-ratio.

II. DEVICE DESCRIPTION

A. THE PRINCIPLE OF MEMS GYROSCOPE

Vibratory gyroscopes are designed to measure the angular rate of a rotating object. Its simplified model can be shown in Fig.2.

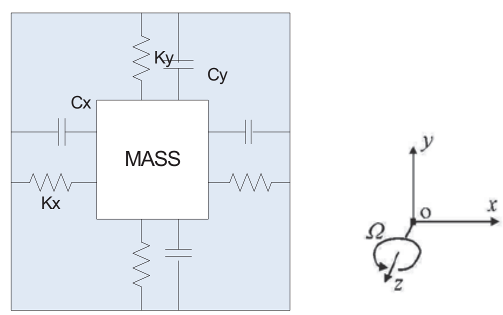

Fig.2. A simplified model for a vibratory gyroscope

The gyroscope has a mass suspended on the silicon framework, and two springs with stiffness coefficient K_x, K_y and damping coefficient C_x, C_y in each direction. The proof-mass is driven by electrostatic force to carry on a vibratory movement along x-axis. The operating principle of a resonant gyroscope is based on coupling the vibratory movement of driven mode to the sense mode by the Coriolis force which is an inertial force exerted on a moving body in a rotating reference platform and according to the following equation:

$$F_c(t) = -2m\Omega\ (t) \times \dot{x}(t) \tag{1}$$

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Where m is the effective mass of the drive mode, Ω is the angular rate around the z-axis, $\dot{x}(t)$ is the velocity of the central mass in the drive direction.

Usually, the gyroscope can be abstractly modeled as a secondary mass-spring-damping system and a set of equations can describe it as follows:

$$m_x\ddot{x}(t)+c_x\dot{x}(t)+k_x x(t)=F_{drv}+2m_x\Omega(t)v_y \quad (2)$$

$$m_y\ddot{y}(t)+c_y\dot{y}(t)+k_y y(t)=F_{sen}+2m_y\Omega(t)v_x \quad (3)$$

Where m_x, m_y are the effective mass in each mode, F_{drv}, F_{sen} are the external forces in each direction, the second term in the right of each equation is the coriolis force. Because the gyroscope is highly decoupled, velocity of the sense mode is too small, its affection can be omitted.

When, $F_{drv} = F_e \sin(\omega_d t)$, $F_{sen}=0$, and the drive signal frequency is equal to the drive ,sense resonant frequency, the final displacement can be obtained as:

$$y(t)=\frac{2F_e Q_x Q_y m_y \omega_d \Omega(t)\cos\omega_d t}{k_x k_y} \quad (4)$$

Where Q_x, Q_y are the quality factor of each mode. From the equation above, it reveals that the output can be enlarged by increasing the driving force, the Q factor, the proof-mass and decreasing the stiffness. And it can also shows that the angular rate is modulated by the signal of driving forces, so in order to get the angular rate, the hybrid signal must be demodulated through the frequency of driving signal.

The schematic figure of the gyroscope is shown in Fig.3.

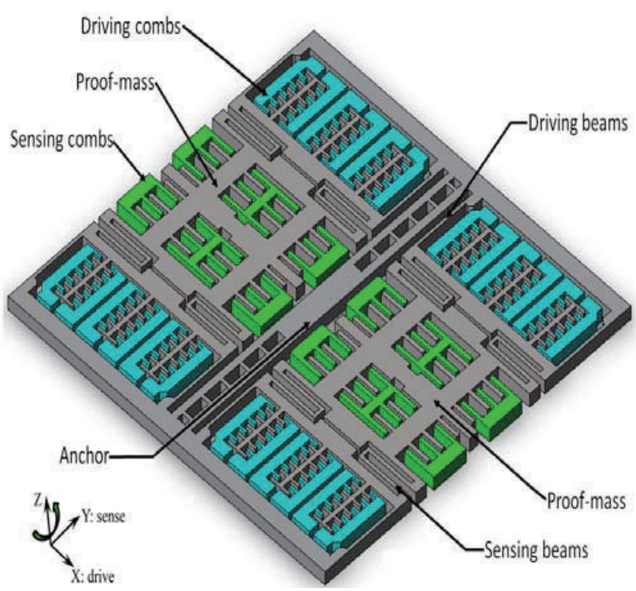

Fig.3. Schematic figure of the gyroscope

It is a symmetric structure with two proof-masses. The proof-masses, which are connected with the framework through the driving beams, are connected to the moveable combs. The framework is rigidly connected to the anchors. When the driving beams are driven by the Static electricity, the two proof-masses will vibrate in opposite directions along x axis. When there is a rotation along z axis, the induced Coriolis forces will force the proof-masses to vibrate relatively along y axis.

B. Device Description

Fig.4 shows the closed loop control scheme based on auto frequency swept.

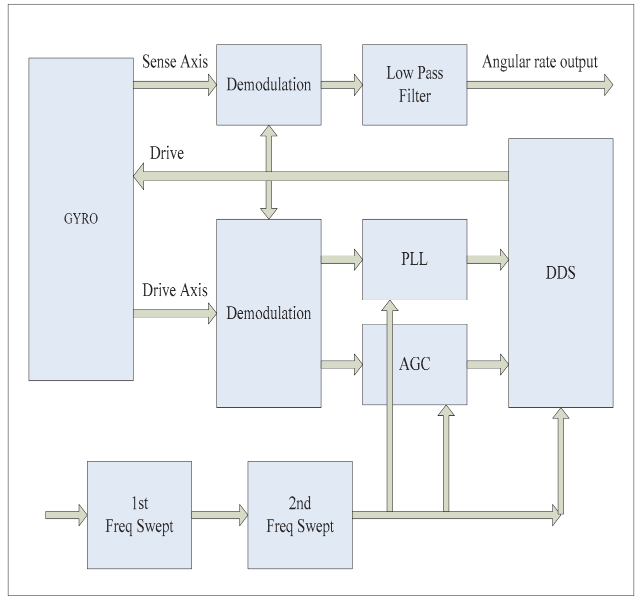

Fig.4 Close loop control with frequency swept

The whole digital signal processing system consists of three parts. The first part demodulates the signal of the sense mode. The second part is used to ensure the vibration of the gyroscope with constant amplitude and phase. And the third part obtains the parameters of the gyroscope and ensure it vibrate at the resonance frequency through auto frequency swept.

The part of demodulation performs the multiplication and low-pass filtering of the detection signal of the sense axis to generate an angular rate signal. A high-pass-filter is added before the module to filter out low-frequency noises. The rate signal is demodulated after the multiplication demodulation. A low-pass-filter performed by a decimation filter is used to reduce the doubled-frequency noise.

The closed loop is based on PLL and AGC with a PI controller to keep the movement stable which meets the requirement of constant amplitude. In this paper, the qurdrature demodulation, which has been successfully employed in telecommunication area, is adopted to get the amplitude and phase to respective close-loop control.

Detect signal of the sense axis is sent to demodulation part to generate the test angular rate. Another demodulation module will provide vibration amplitude and phase for AGC circuit and PLL respectively for closed-loop control. The target reference of the controller is get from the two sweeping process. The direct digital synthesizer (DDS) module generates the drive signal for the gyroscope.

The DDS provides a sine signal and a cosine signal in the same frequency, consistent with the resonant frequency of the drive mode. Then use the two signals to multiply the input signal respectively, which can be shown as follow:

$$
\begin{aligned}
S_1(t) &= A_1 \cdot \sin\left(w_n t + \phi\right) \cdot \cos\left(w_n t\right) \\
S_2(t) &= A_1 \cdot \sin\left(w_n t + \phi\right) \cdot \sin\left(w_n t\right)
\end{aligned}
\tag{5}
$$

After filtering out the $2w_n$ component with a low-pass filter with cut-off frequency of less than w_n. The results are shown as follow:.

$$
\begin{aligned}
I &= \frac{A_1}{2} \cdot \sin\phi \\
Q &= \frac{A_1}{2} \cdot \cos\phi
\end{aligned}
\tag{6}
$$

I and Q include the phase component and amplitude component of the signal. After some mathematical calculation, the amplitude and the phase can be obtained as:

$$
\begin{aligned}
AMP &= 4 \times \left[I^2 + Q^2 \right] \\
\tan\phi &= \frac{I}{Q}
\end{aligned}
\tag{7}
$$

When the system is power on, a rough frequency sweeping is started first to search the resonant frequency using DDS. The obtained frequency is not precise because of a large sweeping range and big step size but the rough sweeper would take short time. This motivates a second fine sweeping that employs the first searched frequency as the central point with a range of about 10Hz and step size being 0.01Hz in order to get more precise resonant frequency, vibration amplitude and phase. All these parameters are considered as the target reference for the controller. Then other modules of the system, such as demodulation, AGC circuit and PLL would start work to control the vibration of the gyroscope through DDS. This method has the advantage of convenient self-calibration, ensured vibration parameters of gyroscope and adaptation to environment temperature change.

III. EXPERIMENTS AND RESULTS

A printed circuit board is manufactured mounted with a Z-axis tuning fork gyroscope and relevant peripheral circuits are illustrated in Fig.5. To improve the signal-noise-ratio, the gyroscope is packaged in high vacuum.

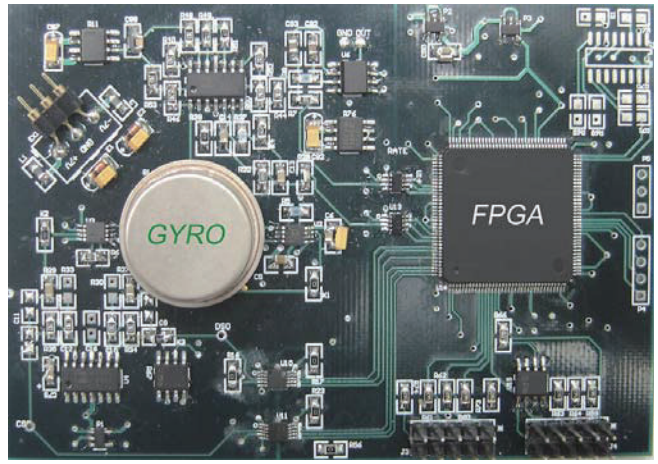

Fig.5. FPGA platform for the MEMS gyroscope.

Fig.6 shows the sweeping process which indicates that it took about 100s to fulfill the sweeping and get the resonant frequency. When the system is power on, a rough frequency sweeping is started first to search the resonant frequency using DDS. The first peak in the picture represents the resonant point by the rough sweeping process while the second peak is by the fine sweeping process. After that, the gyroscope vibrates with fixed reference value.

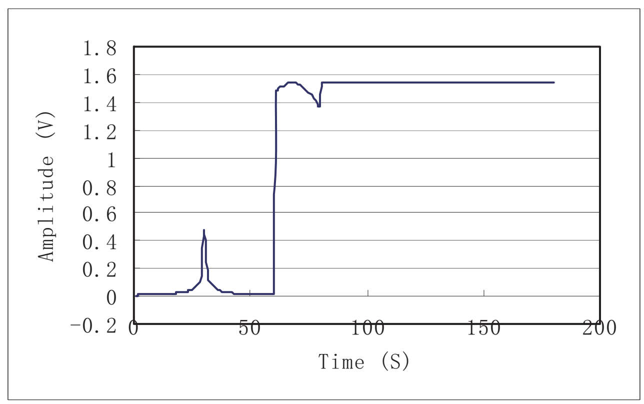

Fig.6. Velocity output when frequency swept

The test fluctuation of the vibratory velocity of the drive mode is 15.2ppm for an hour, as shown in Fig. 7.

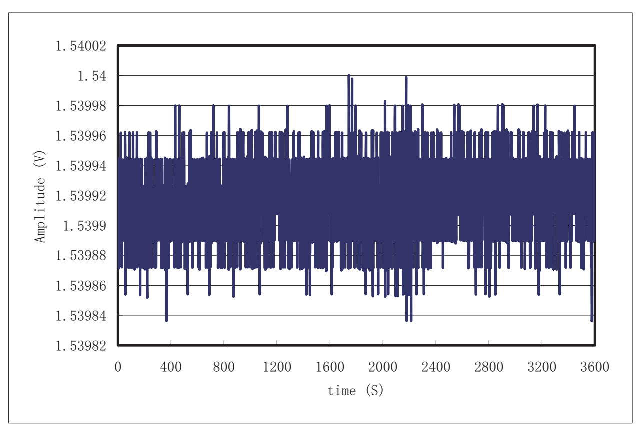

Fig.7. Stability of the vibratory velocity

Fig.8. shows the measured gyroscope output for the different angular input with the dynamic range of 600deg/s. The scale factor is 3.7mv/deg/s and the non-linearity is 0.075%.

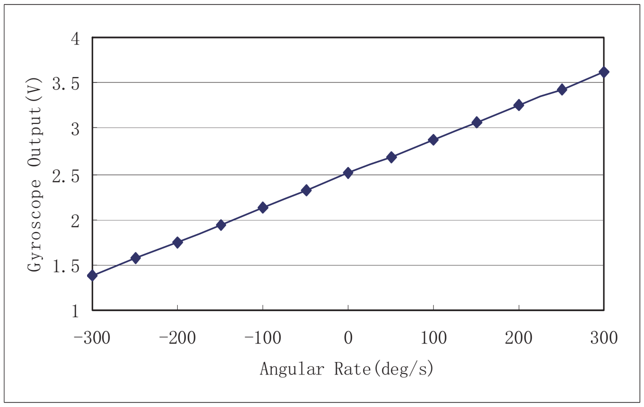

Fig.8. Gyroscope output for reference rate input

IV. CONCLUSION

In order to obtain the parameters of the MEMS vibratory gyroscope, a new digital signal processing system with auto frequency swept is designed in this paper. It took about 100s to fulfill the sweeping, including a rough frequency sweeping and a fine sweeping. Frequency accuracy is greater than 0.01Hz.

A digital closed-loop control method, which is based on PLL and AGC with a PI controller, is described. The angular rate demodulation is realized by adaptive filter algorithm. The whole closed-loop system is implemented on a FPGA platform with a Z-axis tuning fork gyroscope. The scale factor is 3.7mv/deg/s and the bias stability is 0.02°/s (1σ). Using the closed-loop control, the non-linearity is less than 0.075% with the dynamic range of 600deg/s

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