A Digital Control System for Micro-comb Gyroscope

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Abstract *–Vibratory gyroscope exploit a coriolis force coupling between two degree of freedom internal to the sensor for detection of the sensor's angular rotation rate. The peripheral circuit is the key part to realize the function of the gyro system. The peripheral circuit traditionally adopts pure analog circuit. However, the analog circuit has some inherent shortcomings. These limit the accuracy of the gyro. In this paper, a digital control system for micro-comb is introduced. According to testing the gyro performance is much improved by means of the digital control system.*
Keywords :MEMS, micro-comb gyroscope, angular velocity sensor, capacitive sensor, DSP, weak signal detection, C/V conversion, self-exited drive

I. INTRODUCTION

With the development of MEMS, the micro gyroscope has become a research focus. Because the micro-gyro has many advantages compared to traditional gyroscope, it has good application prospect in many area, such as advanced automotive safety and comfort systems, robotics, virtual/augmented reality, medicine, military and space applications, and so on. Many countries have invested a large amount of human and material resources to develop the micro-gyro.

A micro-gyro system to be able to work properly, no matter what the micro-gyro structure is, there not only must be a high-performance inertial sensor as a core device, but also the needs of its control system (mainly the external signal processing and detection circuit) co-operation. The high- performance of gyro system relies on the performance indicators, but also depends on the control system.

According to the working principle of micro-comb gyroscope, its control system is mainly composed of two parts: self-excited drive mode control and testing mode demodulation. Both parts of the traditional method are the use of analog circuits to achieve. However, with the micro-gyroscope further enhancing performance, the increasingly complex structure, as well as self-calibration, analog circuit is very difficult to meet the gyro development demand in complex, flexible, and error characteristics of compensation. As everyone knows, the analog circuit has the following inherent shortcomings:

- Each individual device will introduce additional noise and temperature drift;
- Development of control loop is very time-consuming process;
- Some mathematical methods or functions, which will be used to improve the gyro performance, are almost impossible to be integrated based on analog circuits.

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In addition to the points listed above, when the arithmetical calculation is realized by pure analog circuit, it is based on the op-amp circuit and analog multiplier circuit. Because the volume of input and output operations is instantaneous voltage or current signals, and the analog devices has temperature drift and non-linear features, the computing accuracy will be relatively low.

For the above problems, a digital control system for micro-comb gyro is introduced in this paper. The control system bases on DSP, and the analog circuits are used as little as possible in the system in order to improve the performance of the gyro system.

Working Principle of Micro-comb Gyro

The micro-comb gyro is a vibratory gyroscope based on Coriolis Effect. The structure of micro-comb gyro is of many kinds, but the basic structure and working principle is identical. A principle structure of the gyro is showed in Fig1. The basic structure of the gyro includes three elements: Drive comb, Sense comb and Mass. The drive comb and mass make up a resonator, which is called the primary resonator. The Sense comb and Mass make up another resonator, which is called the secondary resonator. The primary resonator can vibrate with velocity amplitude v_x in the x direction by a driving force, which is called a driven mode of the gyro. If the structure shown in Fig1 is now considered in a rotating frame of reference, and it is further assumed that the applied angular velocity Ω is about the *z*-axis with a magnitude Ω_z (in rad/s), the Coriolis force will act on the structure in *y* direction. The force can be described as:

$$F_c = 2mv_x \times \Omega_z \qquad (1)$$

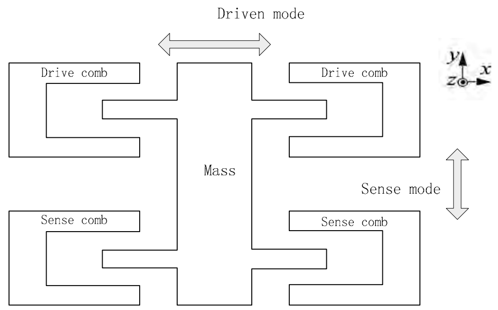


Fig1. Schematic diagram of micro-comb gyro

The mass will move Δy distance in *y* direction under the F_c, which is called a sense mode. The relation of Δy and F_c can be described as:

$$\Delta y = f_1(F_c) \tag{2}$$

Then the capacitance between the Sense comb and the mass will be changed Δc, which has a relation with Δy:

$$\Delta c = f_2(\Delta y) \tag{3}$$

So it can be get an equation from the equations (1), (2) and (3):

$$\Delta c = f(\Omega_z) \tag{4}$$

So it is obvious that the Ω_z can be get if the Δc can be detected. The micro-comb gyro works on this principle.

II. DIGITAL CONTROL SYSTEM

According to the working principle of the micro-comb gyro, there are two important elements to realize the gyro function. They are driving system and detecting system. These two systems compose the control system for gyro. There a digital method realizing the control system is introduced in this paper. A block diagram of the digital control system is showed in Fig2.

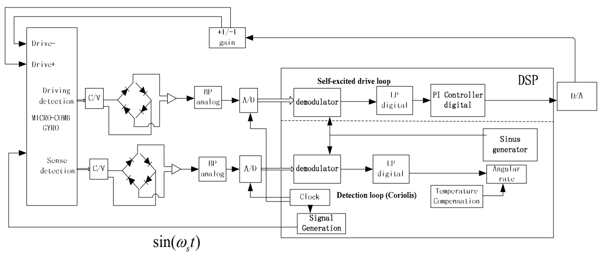


Fig2. Block diagram of the digital control system

This system is based on DSP, and includes two parts: self-excited drive loop and detection loop (Coriolis).

According to the working principle of the micro-comb gyro, it detects the angular velocity by detecting the capacitance changes caused by Coriolis force. The capacitance changes is very small which is at the range of attoFarad [3,4]. An amplitude modulation technique similar to the readout of the surface micro-machined accelerometer presented in Ref. [5] is used to detect these small changes. In the Fig.2 the Signal Generation block controlled by the clock in the DSP is used to generate a high frequency carrier($\sin(\omega_s t)$) at the range of in the hundreds kHz, which is applied to the gyro structure to modulate the capacitance changes signal.

A. Self-excited drive loop

This micro-gyro is an electrostatic driving vibratory gyroscope. To drive the micro-gyro, there are two methods to be chosen which are open loop driving and closed loop driving. According to the working principle of the gyro, the frequency of the driving signal must equal to the natural frequency of the driving modal. It mainly applies RC oscillation circuit or voltage-controlled oscillation circuit to tune the driving frequency and the natural frequency of the driving modal coincides in the open loop driving, as showed in the figure 3.

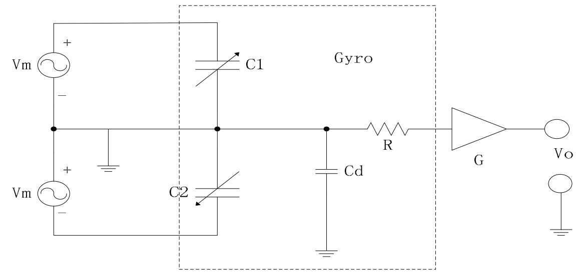


Fig3. Schematic diagram of open loop driving

There is residual stress in the gyro structure and the ambient temperature is always changing, which will cause the natural frequency to drift. The open loop driving can not detect this change, so it is not able to drive the gyro reliably.

In order to overcome the drawback of the open loop, the closed loop is a good choice to drive the gyro. There is a digital closed loop driving employed in this paper, which is showed in the Fig2. The main functional modules of this loop include: C/V conversion, diode peak detector ring, A/D convertor, demodulator, PI controller, D/A convertor. Its working principle is described as follows.

When the gyro vibrated under the drive force, the capacitance of driven mode will be changed. The C/V conversion converts the change of the capacitance into a voltage signal that is modulated by the carrier $\sin(\omega_s t)$. The signal will be fed through the diode peak detector ring firstly to get the harmonic vibration signals reflecting the actual situation of the gyro vibratory. Then the harmonic signals will be filtered by a BP filter in order to filter out low frequency disturbances and high-frequency carrier signal. After that, this signal will be converted into a digital signal by the A/D convertor under the controlling of the clock in the DSP. After digitalized the signal will be fed through the DSP, and be demodulated to get the driving amplitude and phase. These two values can determine the gyro vibratory waveform. Then the driving voltage applied to the gyro will be calculated by the PI controller, which next will be converted to analog control voltage by D/A, and applied to the drive comb showed as in Fig2. By this control the amplitude and phase are stabilized.

The method described as above is simulated by EDAlink and SYNPLE in IntelliSuite, the simulating result is showed in Fig4.

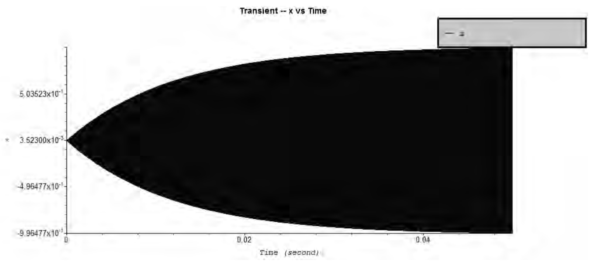


Fig4. The time-amplitude relation of o the gyro start-up

It can be seen that the gyro (a research sample) will stably vibrate about 0.04s after power on. So it is proved that the digital self-excited is feasible.

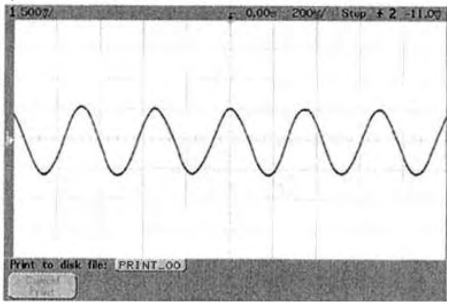
B. Detection loop

The detection loop is used to readout the angular velocity Ω_z. The front-end of the loop is same to the driving loop showed in Fig2. In addition it includes demodulator, filter, and so on. When the gyro is subject to Coriolis force, the capacitance between sense comb and the mass will change. The C/V conversion transforms the capacitive change into voltage signal, and which is modulated by a high-frequency carrier as described in the first of this part. Then the modulated signal is fed through the diode peak detector and A/D convert as same as the front-end of the driving loop. After that the signal will be demodulated and filtered in the DSP, and the angular velocity is get. In addition there is a temperature compensation to compensate the drift caused by the temperature changing.

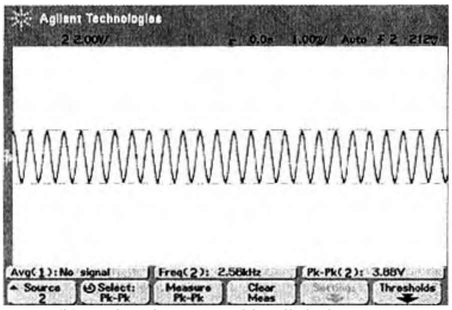
The signals including driving detection and sense detection are demodulated in DSP as showed in the Fig2. A demodulation algorithm for the least mean square demodulation (LMSD) is used in DSP, which is similar to the reference [7]. The LMSD is a method that uses the characteristic of random signal to demodulate signal. It simultaneously applies two demodulating signals that are in-phase and quadrature signals, which cause the demodulation result is better than traditional multiplication demodulation. The demodulation results are assured optimally at minimum mean square error.

III TESTING AND CONCLUSION

In order to verify the digital control system, some tests are executed. There an analog system and a digital system are used to the same gyro separately, and the results are compared. In the paper, the digital control system is compared with the analog system in two aspects: drive system and detection system. For drive system, the compare is implemented by means of testing and comparing the drive signal. In the figure 5, the driving signal generated by analog system and digital system are given separately. In the figure 5, (a) is the driving signal generated by analog system. When we observe this signal on oscilloscope, it can be found that the signal is not a perfect sinusoidal wave. There are more clutter and the harmonic interference, and the amplitude stability is not good. If A represents the peak-peak value and ΔA represents the change of peak value, we define $\Delta A / A$ is the amplitude stabilization. The amplitude stabilization of the signal generated by analog system is about 12%.



(a) Signal generated by analog system



(b) Signal generated by digital system

Fig5. Driving signal generated by two system

But in the Fig5 (b), we can find that the signal generated by digital system is better than the signal generated by analog system in frequency purity and amplitude stabilization. Its amplitude stabilization is about 1.2%.

For the detection system, the output data is compared by level of noise. The figure 6 is the MSE figure of output data.

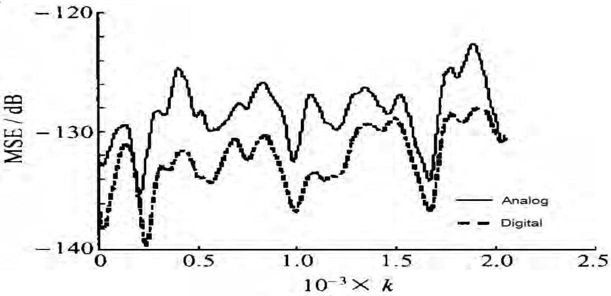


Fig6. MSE compare of output data of digital system and analog system

From the figure, it can be found that the MSE of digital system is lower than analog system's by about 30%.

According to these results, the gyro performance is much improved by means of digital control system.

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