The Design and Test of the Single Chip Integration Accelerometer Gyroscope

LIU JUN, TANG JUN, SHI YUNBO

National Key Lab for Electronic Measurement and Technology,

North University of China,

Department of Electronic Science and technology, Taiyuan, Shanxi, 030051,

P.R. CHINA,

Tel +86 -351 -3920397, Fax +86 -351- 3922131, E-mail: lj@ime.pku.edu.cn ,

Abstract: A single chip integration accelerometer is designed in this paper. By means of a silicon mass, it integrated the measurement of the two kinds of the inertial parameter on a single chip. The paper analyzed the measurement theory of the accelerometer gyroscope. And then some experiment to test the characteristics of the accelerometer gyroscope is introduced. The results show that this design can successfully detect the acceleration and angle velocity at the same time.

Key Words: accelerometer gyroscope, design, single chip integration,design, test

1 Introduction

The single chip integration accelerometer gyroscope is a kind of inertial sensor which integrates the accelerometer and gyroscope on a single chip [1]. It can measure the acceleration and angle velocity at the same time.

As the development of the semiconductor fabrication technology, the research of the accelerometer gyroscope has made a rapid progress. Some companies like Northrop and Endevco has already not only developed the single axis accelerometer gyroscope, but also the dual axis accelerometer gyroscope has already been developed [2][3]. The characteristics of the accelerometer gyroscope designed by Northrop are shown in Table1:

Driving frequency		4KHz
Acceleration	Range	±60g
measurement	Nonlinearity	<0.1%
	Scale factor	0.2V/g
Angle	Range	3000°/s
velocity	Random drift	100°/h
measurement	Nonlinearity	<0.1%
	Stability	15°/h

Table1 The characteristics of the accelerometer designed by Northrop [2]

Considering the problems of the accelerometer gyroscope design, a single chip integration accelerometer gyroscope is introduced in the paper. The test results of this accelerometer gyroscope show that it can get a good performance by means of a single mass.

2 The structural design

The structure of the accelerometer gyroscope can be seen in Fig1. It is composed of mass, driving comb fingers, measurement fingers, springs, anchors and so on. The whole structure is absolutely symmetry to the X axis and Z axis. In this design, X is the driving direction of the gyroscope, Y is the measurement direction of the

accelerometer, Z is the input direction of acceleration and angle velocity and is also the measurement direction of the acceleration.
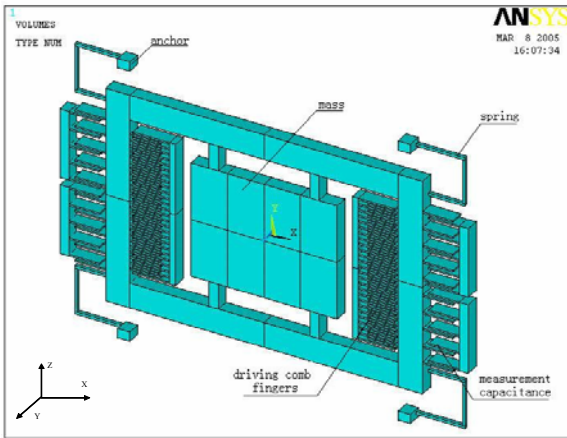

Fig1 The structure of the accelerometer gyroscope

3 Mechanics computation and simulation

The spring is the key component of the sensor to transform the input inertial parameters to the mechanical deformation. As we can see in Fig1, the accelerometer has a symmetry structure of four U-springs. We can divide each U-spring into three cantilevers, so the stiffness matrix of a single cantilever in its own coordinate can be calculated. By means of some arithmetic, we can get the stiffness matrix of the whole structure in the overall coordinate. The detailed calculated method can be seen in reference [4][5].

The parameters of the spring structure was set: beam width: $b = 12\mu m$; beam thickness: $h = 18\mu m$; length of beam1: $l_1 = 160\mu m$; length of beam2: $l_2 = 220\mu m$; length of beam3: $l_3 = 240\mu m$;

Youngs Module: $E = 1.9 \times 10^{11}$; Shear Module: $G = 1.9 \times 10^{11}$.

Set the origin of coordinates in the middle of the cantilever (l/2). Set the reference coordinate OXYZ as we can see in Fig2. According to the related theory of mechanics, we can calculate out the stiffness matrix C of a single cantilever:
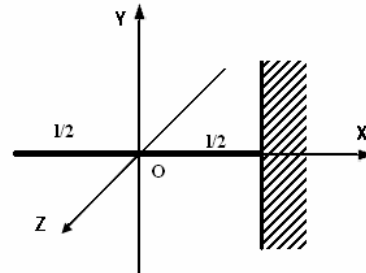

Fig2 The sketch of a single beam

$$C = \begin{bmatrix} k_1 & 0 & 0 & 0 & 0 & 0 \\ 0 & k_2 & 0 & 0 & 0 & 0 \\ 0 & 0 & k_3 & 0 & 0 & 0 \\ 0 & 0 & 0 & k_4 & 0 & 0 \\ 0 & 0 & 0 & 0 & k_5 & 0 \\ 0 & 0 & 0 & 0 & 0 & k_6 \end{bmatrix}$$

Where
$$\begin{cases} k_1 = \dfrac{Ebh}{l} \\ k_2 = (\dfrac{12l}{Gbh} + \dfrac{l^3}{Ebh^3})^{-1} \\ k_3 = (\dfrac{12l}{Gbh} + \dfrac{l^3}{Ehb^3})^{-1} \\ k_4 = \dfrac{Gbh^3}{3l} \\ k_5 = \dfrac{Eb^3h}{12l} \\ k_6 = \dfrac{Ebh^3}{12l} \end{cases}$$

By means of coordinate transformation, and the springs series connection and parallel connection arithmetic [4][5][6], the stiffness matrix in the overall coordinate is:

$$C_{\{o\}} = \begin{bmatrix} 1.1238 \times 10^3 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1.2098 \times 10^3 & 0 & 0 & 0 & 0 \\ 0 & 0 & 2.3469 \times 10^3 & 0 & 0 & 0 \\ 0 & 0 & 0 & 2.198 \times 10^{-5} & 0 & 0 \\ 0 & 0 & 0 & 0 & 8.142 \times 10^{-4} & 0 \\ 0 & 0 & 0 & 0 & 0 & 6.451 \times 10^{-5} \end{bmatrix}$$

The mass of the accelerometer gyroscope structure is: $m = \rho \times V = 0.17347 \times 10^{-6}$ kg, so the resonant frequency of the former three modes of the accelerometer gyroscope can be calculated:

The first mode, in the x direction, the driving mode of the gyroscope:

$$f_1 = \frac{1}{2\pi}\sqrt{\frac{k_1}{m}} = 12816.6$$

The second mode, in the y direction, the sensing mode of the gyroscope:

$$f_2 = \frac{1}{2\pi}\sqrt{\frac{k_2}{m}} = 13297.9$$

The third mode, in the z direction, the sensing mode of the accelerometer:

$$f_3 = \frac{1}{2\pi}\sqrt{\frac{k_3}{m}} = 18521.5$$

By means of ANSYS, we can get the vibration modes of the accelerometer gyroscope:

Mode	1stmode(Hz)	2ndmode(Hz)	3rdmode(Hz)	4thmode(Hz)	5thmode(Hz)	6thmode(Hz)
frequency	12906	13375	18338	25137	27505	35614

Table2 The resonant frequency of the former six modes

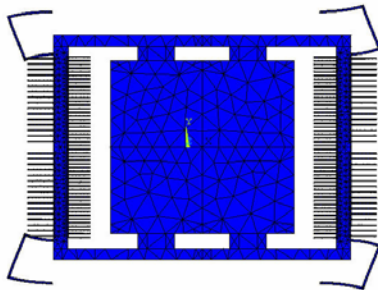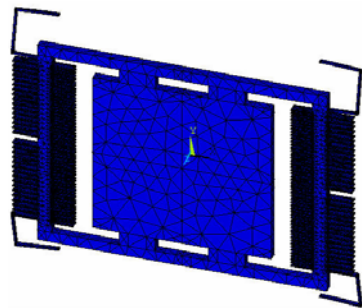Fig3 1st mode   driving mode x direction

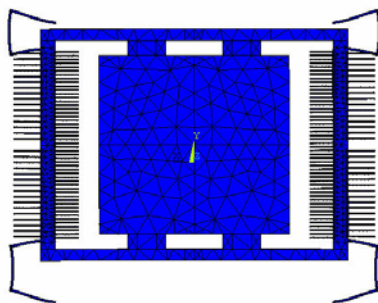Fig4 2nd mode   Gyro's measurement mode Z direction

Fig5 3rd mode accelerometer measurement mode Y direction

In the mode simulation, we can get the followed conclusion: the former two modes are the driving mode and measurement mode of the gyroscope respectively, the dispersion between them is 469Hz, which is 3.63% of the resonance frequency. The third mode is the measurement mode of the acceleration. The resonant frequency is far different to the former and later mode (4.96KHz and 6.799KHz respectively). By means of further structural optimization design, the resonance frequency of the high modes can be much bigger, and the multi dimensional coupling error can be reduced.

4 Measurement circuits design

There are two key parts in the measurement circuits: the driving circuit of the gyroscope and the high signal noise ratio (SNR) micro capacitance measurement circuit.

The schematic diagram of the driving circuit is shown in fig6. The driving signal Va generated by the voltage controlled oscillator is amplified by the AGC. After the phase adjustment of Va and added with the DC voltage Vd, two driving signals $V_d + V_a$ and $V_d - V_a$ are applied on the gyroscope. At the same time, the vibration signal of the gyroscope is divided into two feedback signals. One is feed back to the PLL, which is used to make the gyroscope vibrate on the invariable frequency. The other is feedback to the

rectifier and integrator, and the amplitude of the vibration is controlled after the AGC.
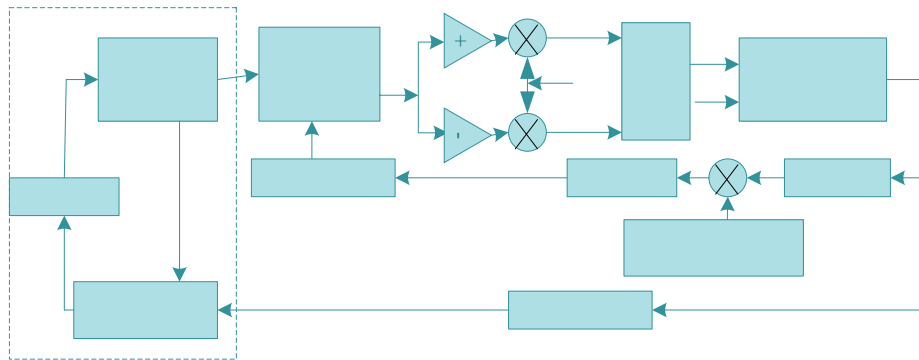

Fig 6 The closed loop driving circuit of the gyroscope

In order to improve the SNR and the zero drift of the micro capacitance measurement, a high SNR capacitance signal demodulation circuit is adopted, see in Fig 7. The circuit adopts differential modulation arithmetic, which can greatly restrain the interference capacitance if the followed phase relation is satisfied [6][7][8]:

$$\Psi_1 = -\Psi_2 = \frac{\pi}{4}$$

The detailed principle and demodulation arithmetic can be seen in reference paper [6].

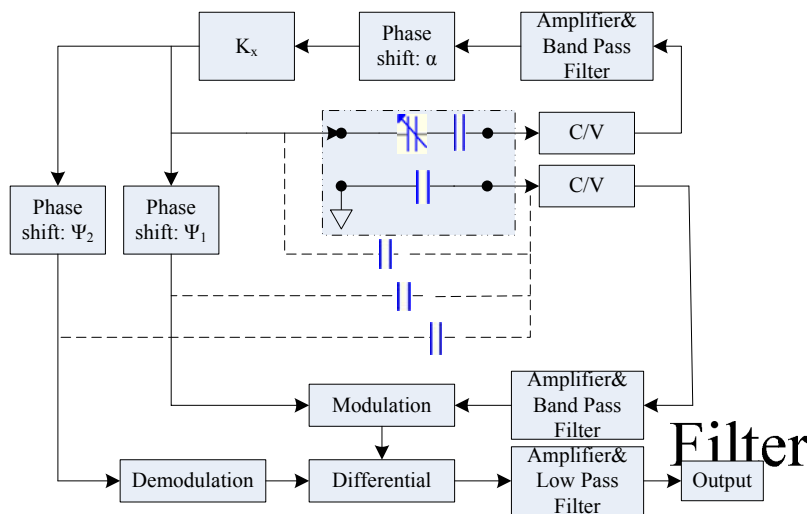Fig 7 The high signal noise ratio micro capacitance measurement circuit

5 Test

By means of the former discussed measurement circuit and some test instrument in the North University of China, the characteristics of this accelerometer gyroscope are tested.

1 Acceleration test

This test is mainly finished by the vibration test system TIRA TV5220. To test the acceleration response of this accelerometer gyroscope, two experiments were done. Fix the accelerometer gyroscope and its measurement circuit on TV5220 and power on. First, keep the accelerometer gyroscope vibrated in the invariable frequency (100Hz) and in different acceleration. By means of the multimeter, the voltage output of some disperse acceleration input is observed, and it is shown in figure. Second, keep the accelerometer gyroscope vibrated in the invariable acceleration (1g) and in

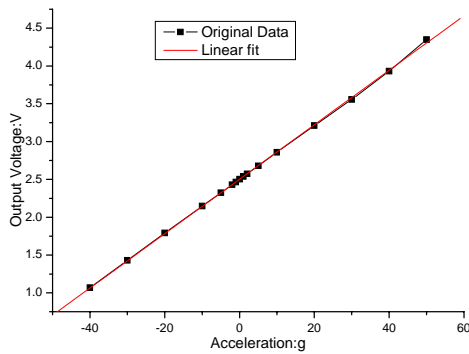different frequency. By means of the multimeter, the voltage output of some disperse frequency input is observed.

Fig 8 Acceleration linearity characteristic

From the experiment results of Fig8, we can know that in the range of ±50g, the output of the accelerometer measurement can be calculated by: $y = 0.0361x + 2.5034$, where x is the input acceleration(unit: g), y is the output voltage(unit: V). It can get a nonlinearity of 0.036207 when it is used to detection the acceleration.
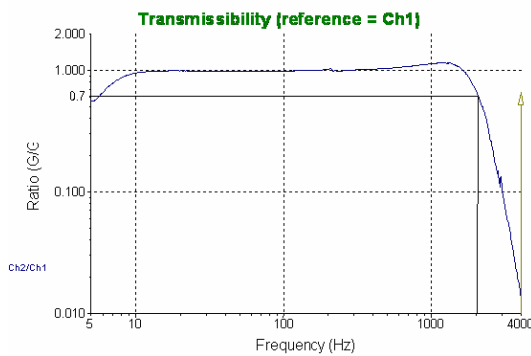

Fig 9 Frequency response

Fig9 shows the ratio of the output voltage of the accelerometer gyroscope to the standard accelerometer when they are all fixed on TV5220. From this result we can know that the bandwidth of the acceleration measurement is about 2000Hz.

2 Angle velocity test

The test of the accelerometer gyroscope's characteristics to the angle velocity is a little different. This experiment was mainly finished by the precision angle velocity motion table and

the HP35670A dynamic signal analysis equipment.

Fix the accelerometer gyroscope on the angle velocity motion table, and the output of it in different angle velocity is observed by the multimeter, and the result is shown in fig10.
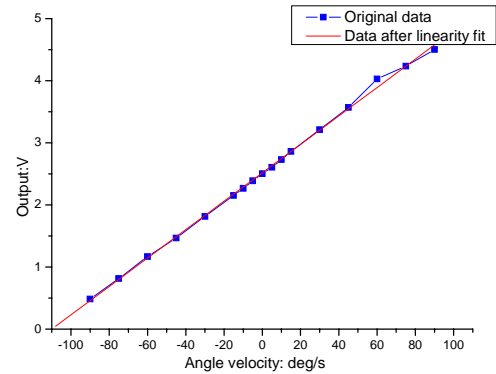

Fig 10 The acceleration response

From this result, we can know that in the range of ±100deg/s, the relation between the input angle velocity and the output voltage is: $y = 0.2288x + 2.51828$, where x is the input angle velocity(unit: deg/sec), y is the output voltage(unit: V), and it can get a nonlinearity of 0.05417 .

In order to test the bandwidth of the angle velocity measurement, we fixed the accelerometer gyroscope on the angle velocity motion table, and the rotation of the motion table is controlled by the control signal of HP35670A from one CH1. At the same time the output of the accelerometer is also observed by HP35670A in another channel CH2. We chose the function of CH2/CH1 in HP25670, and the magnitude-frequency characteristic and the phase-frequency characteristic is shown in Fig11 and Fig12.
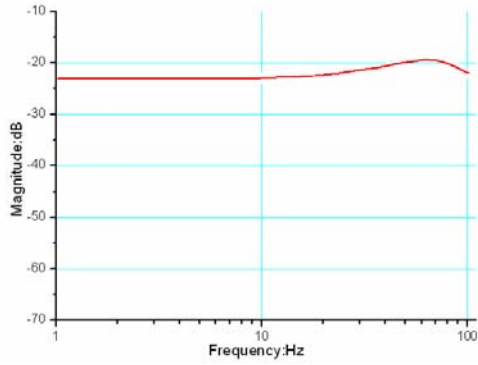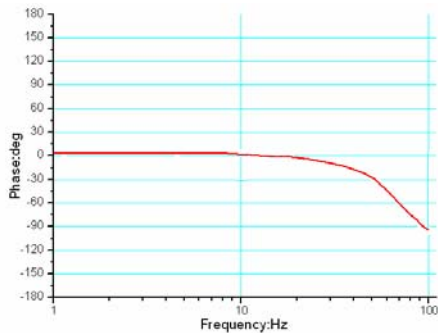
Fig 11 Phase-frequency characteristcs

Fig 12 Magnitude-frequency characteristics

It is usually considered that the bandwidth of a gyroscope is the frequency when the phase is decreased to 90° [6]. So according to the test result, the bandwidth of this accelerometer gyroscope is about 90Hz.

Another experiment to test the resolution of the angle velocity measurement is similar to the bandwidth test. The difference is the input control signal, which is stabilized at 10Hz and 10deg/sec
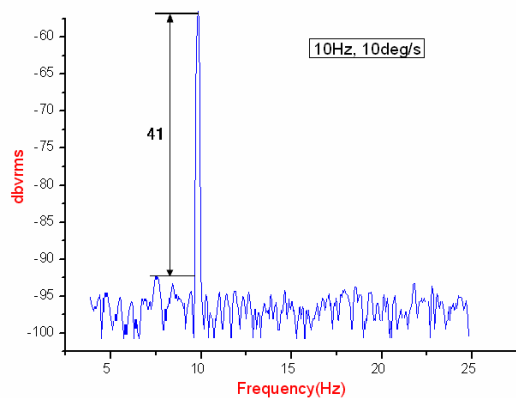

Fig 13 The resolution test of the gyroscope

The dB value of the noise and signal is about 41dB. So the resolution (FM) can be calculated

[6][7]:

$$FM = \frac{1}{10^{\frac{41}{20}}} \times \omega = 0.0089 \times 10\deg/s = 0.089\deg/s$$

6 Conclusion and future work

A single chip integration accelerometer gyroscope and its measurement were introduced in the paper. By means of a single mass, the measurement of the two kinds of the inertial parameter is integrated on a single chip. Compared with the traditional accelerometer gyroscope, it has the followed characteristic:

The measurement of the two kinds of the inertial parameter on a single chip, which has a high alignment precision.

It can sense the acceleration and angle velocity in the same direction and is very useful.

The structure is quite simple, the fabrication is easy.

The two signals are measured separately, which makes the design of the followed measurement circuit much easier.

As a new research project, the research of the accelerometer gyroscope still needs lots of work:

The cross coupling of this multi dimensional inertial force sensor is a key problem in the design of the accelerometer. It includes the inherent cross coupling of the micro structure and the fabrication error.

The vacuum package of is very necessary.

The design and debugging of the micro capacitance measurement is a hard work, so we need to do some further research and integrate the circuit with the micro structur together.

Reference:

[1]   Liu Jun, Shi Yunbo, Zhang Wendong *Study on a single chip integration accelerometer gyroscope* Journal of test and measurement technology, pp.156-160

[2] Hou Zhengjun, Lu Zhiqing, Peng Zhigao, *Vibrating Gyro with Accelerometers*, Piezo electrics & acoustooptics, Vol 20, NO.1, Feb 1998, pp.18-24

[3] Ruan Aiwu, Feng Depei, Guo Xiuzhong, *New development and analysis of silicon micromachined gyroscopes*, J. Chin. Inertial Technol.2(1998), pp.67-72

[4] Li Renfeng, *Research on the design technology of the MEMS high g accelerometers.* Master thesis of China Academy of Engineering Physics, 2003

[5] Adam Kovacs, Zsolt Vizvary, *Structural parameter sensitivity analysis of cantilever and bridge type accelerometers.* Sensors and Actuators A 89 2001 pp.197–205

[6] Li Jinming, *Research on High Signal-Noise Ratio of Capacitive Micromechanical gyroscope.* Doctor thesis of North University of China, 2005

[7] Kourepenis A, Borenstein J, Connelly J. *Performance of MEMS inertial sensors.* IEEE PLANS'98. New York, Aerospace & Electronics System Society, 1998, pp.1-18

[8] Michael Kranz. *Design, Simulation, and Iplementation of Two Novel Micromechanical Vibratory Rate gyroscopes.* [Ph.D. Dissertation]. 1998

[9] H.Matsumoto, H.Shimizu, K.Watanabe, *A switched-capacitor charge-balancing analog-to-digital converter and its application to capacitance measurement,* IEEE Trans. On Instrumentation and Measurement, Vol.IM-36, Dec.1995, pp.873-878

[10] Mark E. Spencer, Mesa Ariz, *Oscillator circuit and method for measuring capacitance and small charges in capacitance,* US Patent:5136262, Aug.4,1992

[11] R.F.Wolffenbuttle, P.P.L.Regtien, *Capacitance-to-phase angle conversion for the detection of extremely small capacities,* IEEE Trans. On Instrumentation and Measurement, Vol.IM-36, Dec.1987, pp.868-872

[12] V. Josselin, P. Touboul, R. Kielbasa ,*Capacitive detection scheme for space accelerometers applications,* Sensors and Actuators 78 1999 ,pp.92–98

[13] Alper Said Emre, Akin Tayfun, *A symmetric surface micromachining gyroscope with decoupled oscillation modes,* Sensor and actuators, A97 2002 ,pp.347-358

[14] K. Y. Park, C. W. Lee, Y. S. Oh, et al. *Laterally oscillated and force balanced micro vibratory rate gyroscope supported by fish hook shape springs.* Sensor and actuators, A64 1998, pp. 69-76