The Design and Test of the Single Chip Integration Accelerometer Gyroscope

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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:

<table>
<thead>
<tr>
<th>velocity</th>
<th>Random drift</th>
<th>100°/h</th>
</tr>
</thead>
<tbody>
<tr>
<td>measurement</td>
<td>Nonlinearity</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Stability</td>
<td>15°/h</td>
<td></td>
</tr>
</tbody>
</table>

Table1 The characteristics of the accelerometer gyroscope 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.

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:

\[
\begin{bmatrix}
    k_1 & 0 & 0 & 0 & 0 & 0 \\
    0 & k_2 & 0 & 0 & 0 & 0 \\
    0 & 0 & k_3 & 0 & 0 & 0 \\
    0 & 0 & 0 & k_4 & 0 & 0 \\
    0 & 0 & 0 & 0 & k_5 & 0 \\
    0 & 0 & 0 & 0 & 0 & k_6 \\
\end{bmatrix}
\]

Where

\[
\begin{aligned}
    k_1 &= \frac{Ebh}{l} \\
    k_2 &= \left( \frac{12l}{Gbh} + \frac{l^3}{Ebh} \right)^{-1} \\
    k_3 &= \left( \frac{12l}{Gbh} + \frac{l^3}{Ebh} \right)^{-1} \\
    k_4 &= \frac{Gbh^3}{3l} \\
    k_5 &= \frac{Ebh^3}{12l} \\
    k_6 &= \frac{Ebh^3}{12l}
\end{aligned}
\]

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:

\[
\begin{bmatrix}
    1.1238 \times 10^3 & 0 & 0 & 0 & 0 & 0 \\
    0 & 1.2098 \times 10^3 & 0 & 0 & 0 & 0 \\
    0 & 0 & 2.3469 \times 10^3 & 0 & 0 & 0 \\
    0 & 0 & 0 & 2.198 \times 10^{-5} & 0 & 0 \\
    0 & 0 & 0 & 0 & 8.142 \times 10^{-4} & 0 \\
    0 & 0 & 0 & 0 & 0 & 6.451 \times 10^{-5}
\end{bmatrix}
\]
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:

<table>
<thead>
<tr>
<th>Mode</th>
<th>1st mode (Hz)</th>
<th>2nd mode (Hz)</th>
<th>3rd mode (Hz)</th>
<th>4th mode (Hz)</th>
<th>5th mode (Hz)</th>
<th>6th mode (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>frequency</td>
<td>12906</td>
<td>13375</td>
<td>18338</td>
<td>25137</td>
<td>27505</td>
<td>35614</td>
</tr>
</tbody>
</table>

Table2 The resonant frequency of the former six modes

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 \( V_a \) generated by the voltage controlled oscillator is amplified by the AGC. After the phase adjustment of \( V_a \) and added with the DC voltage \( V_d \), 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 feedback 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.

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].

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.

![Graph](image1)

**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.

![Graph](image2)

**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 HP35760A 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.

![Graph](image3)

**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.
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

[6][7]:

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

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 following 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 multidimensional inertial force sensor is a key problem in the design of the accelerometer. It includes the inherent cross coupling of the microstructure and the fabrication error.

The vacuum package 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 microstructure together.

Reference:


