Development of a single-structured MEMS gyro-accelerometer

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Abstract: This paper presents a study on the development of a multi-sensing inertial sensor with a single mechanical structure, which can be used both as a gyroscope and an accelerometer. The proposed MEMS gyro-accelerometer is designed to detect the angular rate and the acceleration at the same time using two separate detection circuits for one proof mass. In this study, the detection and signal processing circuit for an effective signal processing of different inertial measurements is designed, fabricated, and tested. The experimental results show that the performances of the gyro-accelerometer have resolutions of 1mg and 0.025deg/sec and nonlinearities of less than 0.5% for the accelerometer and the gyroscope, respectively, which are similar results with those of sensors with different structures and different detection circuits. The size of the sensor is reduced almost by 50% comparing with the sensors of separated proof mass.

Keywords: gyroscope, accelerometer, MEMS, inertial sensor, multi-sensor

1. INTRODUCTION

With the substantial advances in Micro-Electro-Mechanical System (MEMS) technologies, researches on inertial sensors such as gyroscopes and accelerometers have been widely accomplished in decades. They find various applications not only in the traditional Inertial Navigation System (INS) but in the automotive applications and consumer devices as well. The main reasons that attract peoples are small size and low cost [1-3]. The size of the sensor is crucial in practical applications. The smaller it is, the more applications it has.

The fundamental methods of reducing the size of the MEMS sensors are classified into two – reducing the proof mass (mechanical element) and reducing the circuit (electrical element). If the ratio of spatial occupation of one element is larger that the other, then it is effective to reduce the size of the larger one. In general MEMS sensors, the signal processing circuit needs more space than the mechanical part and it is desirable to design a simple circuit for fabrication. Moreover, we had better not reduce the mechanical element since the larger is the proof mass, the higher is the sensitivity of the sensor. Therefore, it is more reasonable to focus on the reduction of the circuit elements for smaller MEMS sensors.

The single-structure multi-axis sense is one of the solutions. Various papers have been published in terms of multi-axis sensing scheme for accelerometers [4-6] and gyroscopes [7-9]. Most of those studies concern the multi-axis sensing of a single inertial measurement, i.e. it is used only as a gyroscope or an accelerometer. In this paper, we suggest a single-structured sensor that can be used simultaneously as a gyroscope and an accelerometer.

The conventional MEMS gyroscopes or accelerometers use one proof mass for the measurement of the inertial force. These one-measurement-on-one-mass systems usually handle the measured signal in a certain frequency range. The operation of the proposed singled-structured gyro-accelerometer, however, is based on the different signal processing at different frequencies. The accelerometer part deals with the signal in a low frequency region, whereas the gyro part is on the high frequency region of several kHz since its output is modulated by the driving resonant frequency. The movement of the mass is influenced by those mixed input of the accelerometer and the gyroscope. This mixed movement in same direction can be separately detected since its operating frequencies are different. Therefore, those two signals are easily separated by the appropriate filtering circuits. In this study, the signal detection of the gyroscope and the accelerometer is achieved in same directions. The structural scheme and the operational principle are illustrated in the following chapters.

2. PRINCIPLE OF OPERATION

2.1 Structural illustration

Fig. 1 shows the device structure and the operation axis of gyro-accelerometer. The operational principle of a gyroscope is the same as a conventional z-axis vibratory gyroscope. When the proof mass is oscillating along a driving x-axis, the external angular rate along z-axis invokes another oscillation motion along the y-axis due to the induced Coriolis acceleration. If we detect the Coriolis acceleration through detection of the gap between the mass and sensing electrodes, the external angular rate input can be measured. Since the oscillating motion due to the Coriolis acceleration is modulated by the driving signal, the demodulation process is essentially needed to extract the original signal.

A linear acceleration along y-axis is directly measured by detecting capacitance change that is almost linear relation to a gap variation assuming that the variation is small. Since the motion along the sensing axis is influenced by these two accelerations, the overall motion along y-axis is mixed motion, which is depicted in Fig. 2.

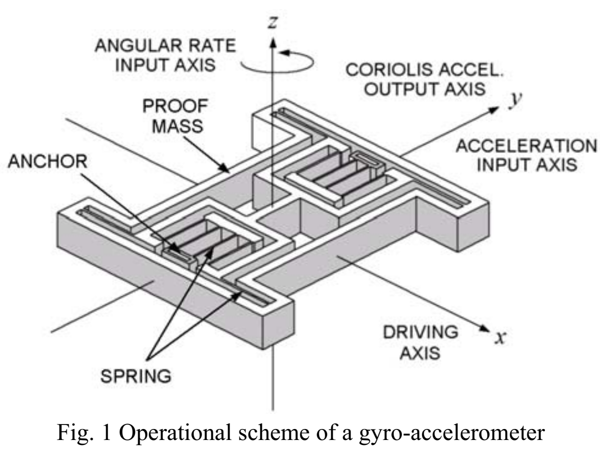
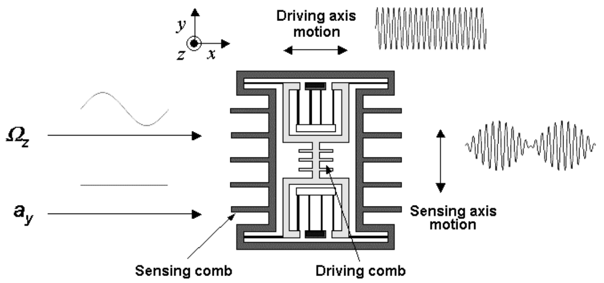
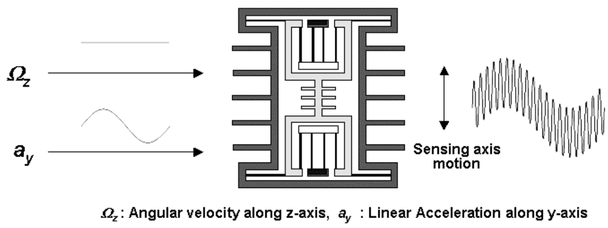


Fig. 1 Operational scheme of a gyro-accelerometer

In Fig. 2 the driving motion along x-axis is a sinusoidal oscillation with constant magnitude at the driving frequency. In this case, the oscillating body is both of two gimbals which are illustrated as dark and bright color respectively in the figure. If the angular velocity along z-axis is Ω_z and the linear acceleration along y-axis is a_y, then the total acceleration along y-axis is $2\Omega_z v_x + a_y$, where v_x is a velocity of the oscillating mass. Therefore the motion along sensing axis is determined by these two inputs. The shape of the actual motion is shown, for example, in the right side of the figure. (a) is the case when a sinusoidal angular velocity input and a constant linear acceleration input are applied simultaneously and (b) is the case of constant rate input and sinusoidal acceleration input. In both cases, the sensing motion is only applied to the outer gimbal (the dark one) since the frame is separately suspended by two orthogonal spring beams. Compared with the motion of usual vibratory gyroscope, these motions can be regarded as a superposition of a normal gyroscope motion with an acceleration input bias. Because these two motions take different regions in frequency domain, the signals are easily separated by filtering and demodulation process.



(a) Sinusoidal angular velocity and constant acceleration



(b) Constant angular velocity and sinusoidal acceleration

Fig. 2 Oscillation motion of the gyro-accelerometer when an angular velocity along z-axis and a linear acceleration along y-axis are applied simultaneously

2.2 Frequency domain operation

Fig. 3 shows the frequency response plot of the sensing axis dynamics that can be modeled as a low-damping second order spring-mass-damper system. At the resonant frequency of the system, the plot shows a high peak, which is an operating region of the gyroscope. The quality factor of the sensing axis or Q_y, determines the sensitivity of the gyroscope. In fact, in order to achieve high sensitivity in a MEMS gyroscope, the resonant modes of two axes should be matched. On the other hand, the resonant characteristics of the structure is not important for the accelerometer since it operates in a static response region that is shown in Fig. 3.

Signal distribution in frequency domain is briefly illustrated

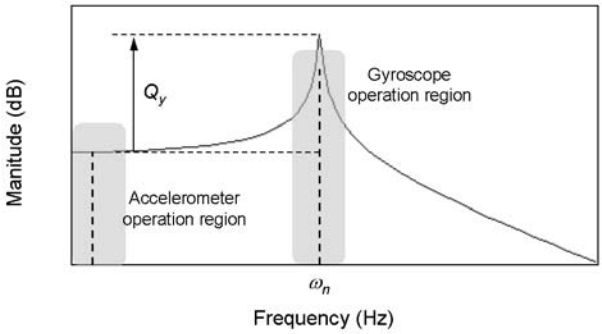


Fig. 3 Frequency response plot of the gyro-accelerometer and operation region of each sensor

in Fig. 4. If an angular rate and an acceleration input of low frequency are shown as above two graphs in the figure, the resultant signal is like the graph below. The resonant frequency, ω_n, of the sensing axis in this study is 3.1 kHz. We can separately obtain two signals by filtering and demodulation.

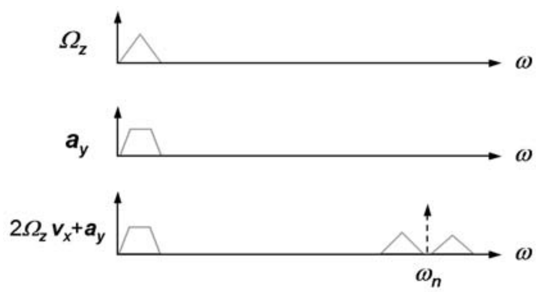


Fig. 4 Signal in frequency domain

3. CIRCUIT DESIGN

To verify the performance of the gyro-accelerometer, a capacitive detection and signal processing circuit is designed and fabricated. Fig. 4 shows a block diagram of the circuit. Two anti-phase 56kHz carriers are applied to the sensing electrodes to detect the capacitance change between the proof mass and electrodes [1-2]. The carrier enables us to remove a stray signal from the driving electrodes to the sensing electrodes and the carrier also enables to tune the resonant frequency of the sensing mode to that of the driving mode. Two anti-phase signals of the driving resonant frequency with DC offset voltages are applied into driving electrodes as a driving signal to make an in-plane oscillation for the operation

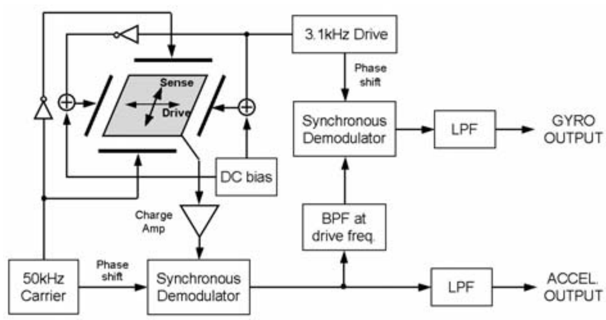


Fig. 5 Block diagram of detection circuit

of the gyroscope. Coriolis acceleration due to the z-axis angular rate input and a linear acceleration along the sensing axis make the proof mass move between sensing electrodes. A charge amplifier is used for effective detection of the capacitance variation between the proof mass and the sensing electrodes. The output of the charge amplifier is a mixed signal of a linear acceleration and Coriolis acceleration modulated by the carrier frequency. Fig. 6 depicts the signals at each signal processing stages in a frequency domain. First stage is a pickoff output at the charge amplifier. The acceleration input can be obtained by first demodulation of the output signal and low pass filtering. The angular rate input can be obtained by two steps of demodulations that are by the carrier signal and by the driving signal. This signal processing is realized using circuit components of active amplifiers, multiplies, phase shifters, and active filters. Since the circuit shares the proof mass and many elements, the area is reduced almost up to 50% comparing with those of the two separated sensors. This is also valid when we manufacture the sensor by an ASIC (Application Specific Integrated Circuit) [10]. The reduced size is a great benefit for MEMS sensors.

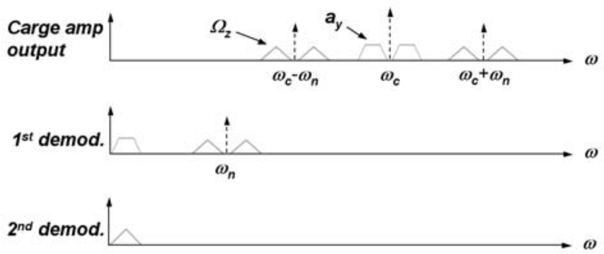


Fig. 6 Output signals in detection circuit

4. EXPERIMENTS

The designed and implemented detection circuit is applied to a SNU-Bosch MEMS gyro chip [1] to demonstrate the performance of the sensor. Experiments are accomplished through frequency analysis and dynamic tests using the fabricated detection circuit. Angular rate input and acceleration input are generated using a two-axis rate table. The experimental setup is shown in Fig. 7. The test board is mounted on the center of turn-table and test equipments are connected through the slip ring cable. The angular velocity is generated by turn-table and the acceleration input is applied using the gravity acceleration.

Fig. 8 shows a sample output signal to a constant angular rate and an acceleration input at the charge amplifier stage

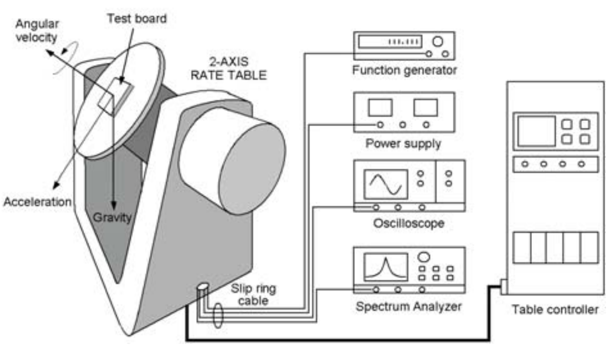


Fig. 7 Experimental setup

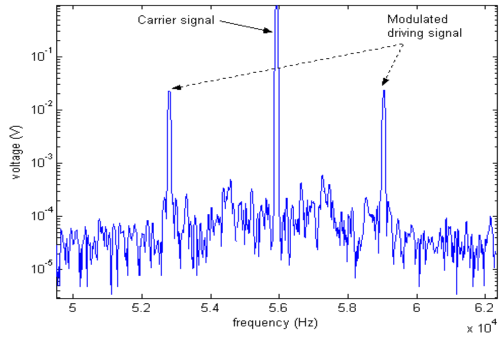
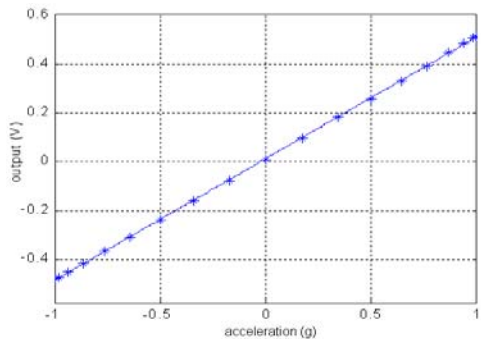
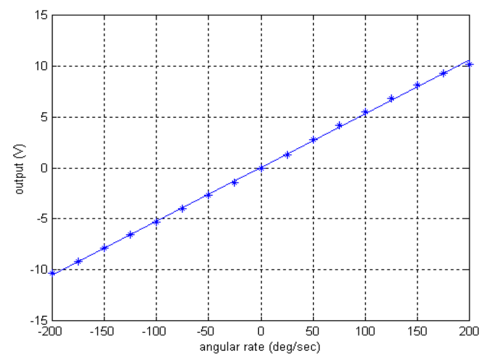


Fig. 8 Voltage output at the charge amp stage

measured by the spectrum analyzer. The middle peak is the carrier signal and the side band signal is a driving signal modulated by the carrier, which is previously illustrated in Fig. 6. The results of the performance test are given in following figures. Fig. 9 shows the response plot to acceleration and angular velocity inputs, respectively. The sensitivities or scale factors of the outputs are 500 mV/g and 50 mV/deg/sec for the accelerometer and the gyroscope, respectively. Since the noise levels of each sensors measured by spectrum analyzer (RMS values) are 0.5 mV and 1.25 mV, the resolution of the sensors are calculated as 1 mg and 0.025 deg/sec, respectively. The nonlinearities of the input-output responses are less than 0.5% for both of linear and angular inputs as can be seen at Fig. 9.



(a) Accelerometer



(b) Gyroscope

Fig. 9 Input-output response of the sensor

Finally, the effect of coupling phenomenon, in this case g-sensitive rate output and angular velocity sensitive acceleration output are measured. The acceleration output due

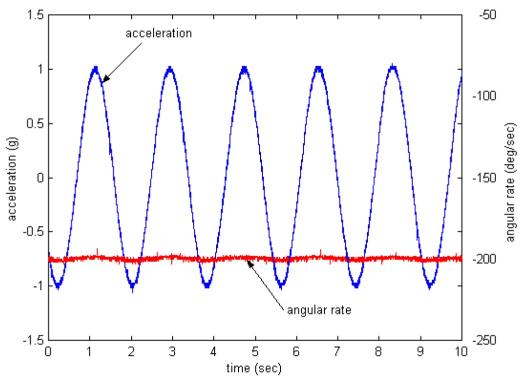


Fig. 10 G-sensitive rate output

to the angular velocity is very small and hardly measured. The g-sensitive angular rate output, on the other hand, is observed. Fig. 10 shows the gyroscope output is fluctuated when a sinusoidal acceleration input is applied. The sinusoidal acceleration is generated by rotating the turn-table along the horizontal axis, which means that the input z-axis of the gyroscope is positioned perpendicular to the gravity axis. Then the sinusoidal acceleration with the magnitude of 1g and the constant rate input can be generated simultaneously. The magnitude of the fluctuation ratio is somewhat dependent on the input angular rate. Fig. 10 shows the output of gyroscope of 200 deg/sec rate input with 1 g acceleration input. The maximum fluctuation is 1.5 deg/sec/g that occurs when maximum rate input is applied. Since we detect the acceleration at the same time, these errors can be compensated.

5. CONCLUSIONS

In this study, a multi-sensing inertial sensor with a single mechanical structure, which can be used simultaneously as a gyroscope and an accelerometer is developed and tested. The proposed MEMS gyro-accelerometer is designed to detect the angular rate and the acceleration at the same time using the signal processing at two different frequency regions and two-stage demodulation circuit.

The experimental results show that the performances of the gyro-accelerometer are same as those of the two separate sensors, which are the resolutions of 1 mg and 0.025 deg/sec for accelerometer and gyroscope, respectively, and nonlinearities of less than 0.5% for both sensors. The size of the sensor is reduced almost by 50% comparing with the sensors of separated proof mass. The g-sensitive angular rate output is observed, but that can be compensated by measuring the acceleration at the same time.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the great support of MicroInfinity Co., Ltd.

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