Development of 3-axis Gyro-Sensor Using Piezoelectric Element

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Abstract

Operation of objects in 3-dimensional space can be expressed by acceleration and angular rate. Sensors to detect them are made by using micromachining technology and ceramic technology. In the field of acceleration sensors, 3-axis acceleration sensors that detect acceleration in 3-dimensional space have already been commercialized, and also in the field of gyro-sensors, piezoelectric type 2-axis gyro-sensors have been developed. By applying such piezoelectric type 2-axis gyro-sensors, 3-axis angular rate can be detected with velocity components of an oscillator in the directions of two axes, and the detection components of Coriolis' force produced by angular rate in the directions of two axes. By using this principle, we have succeeded in developing a 3-axis gyro-sensor that detects 3-axis angular rate with one detecting element. This report details the construction, detection principle, and detection circuit, as well as the performance, such as sensitivity, cross-axis sensitivity, and linearity.

Keywords: 3-axis gyro-sensor, angular rate, piezoelectric, Coriolis' force.

1 INTRODUCTION

Operation of objects in 3-dimensional space can be expressed by parallel motion and rotational motion. Parallel motion can be expressed by physical quantities, such as distance, velocity, and acceleration, while rotational motion can be expressed by the physical quantities of an angle, angular rate, and angular acceleration. These physical quantities can be expressed by the mathematical relationship of differential or integration function. Thus far, for detection of the six physical quantities of distance, velocity and acceleration, which represent parallel motion, and angle, angular rate and angular acceleration, which represent rotational motion, only acceleration sensors and gyro-sensors have been operational in use of micromachining technology and ceramic technology. As a matter of course, acceleration and angular rate are important physical quantities in detecting the motion of objects in 3-dimensional space. In the field of acceleration sensors, 3-axis acceleration sensors[(1)-(3)] of the piezoresistance type, capacitance type, and piezoelectric type have already been developed, and marketed by many companies. However, in the field of gyro-sensors, 1-axis gyro-sensors are predominant, though only a few 2-axis gyro-sensors have been marketed.

Angular rate is also a vector quantity like force and acceleration, and 3-axis gyro-sensors are indispensable to detect the angular rate accurately. Recently, on the market, needs for multi-axis gyro-sensors are increasing gradually as is the case with acceleration sensors. We have conducted research of 3-axis gyro-sensors[(4),(5)] to meet such demands. We wish to report on the piezoelectric type 3-axis gyro-sensor we have developed recently, superior in sensitivity, cross-axis sensitivity, and linearity.

2 Detection principle of the 3-axis gyro-sensor

When an object having a mass moves at a certain velocity, angular rate operates on the object with the result that apparent force (Coriolis' force) acts on it. It is the so-called Coriolis' force. The 3-axis gyro-sensor also uses the Coriolis' force. In the case of 3-axis gyro-sensors, the oscillator having a mass is brought into rotational motion on the X-Y plane as shown in Fig. 1.

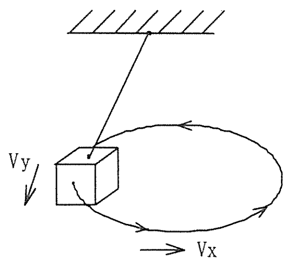


Figure 1. Detection principle of the 3-axis gyro-sensor

In this motion, the oscillator has velocity component Vx in the X-axis direction at a certain instant, and has velocity component Vy in the Y-axis direction at the next instant. As shown in Fig. 2, when the oscillator moves having velocity component Vy in the Y-axis direction, if angular rate ωz in the Z-axis direction acts, Coriolis' force Fx in the X-axis direction is produced, and if angular rate ωx in the X-axis direction acts, Coriolis' force Fz in the Z-axis direction is produced.

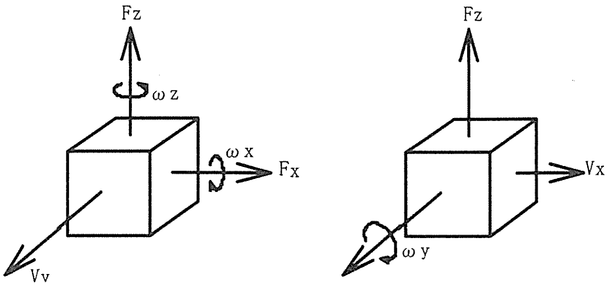


Figure2. Detection of ωx, ωy and ωz

Also, when the oscillator moves having velocity component Vx in the X-axis direction, if angular rate ωy in Y-axis direction acts, Coriolis' force Fz in the Z-axis direction is produced.
The relationship is shown by the following expression (1).

$$
\begin{aligned}
Fx &= 2mVy \times \omega z \\
Fz &= 2mVy \times \omega x \qquad (1) \\
Fz &= 2mVx \times \omega y
\end{aligned}
$$

This expression shows that the angular rate components (ωx, ωy, ωz) of three axes can be detected by detecting Coriolis' force (Fy, Fz) in the directions of two axes while giving velocity components (Vx, Vy) in the directions of two axes by bringing the oscillator into rotational motion on the X-Y plane. The 3-axis gyro-sensor we have developed this time uses the so-called piezoelectric effect of piezoelectric ceramic; "principle on which distortion occurs if voltage is applied, and charge occurs if distortion is given." The piezoelectric effect of the piezoelectric element is used for both circular motion within the X-Y plane, and detection of Coriolis' force in the Y-axis direction and Z-axis direction. Since drive and detection are essential to gyro-sensors, it can be said that the piezoelectric element is one of the suitable materials for gyro-sensors.

3. Construction of the 3-axis gyro-sensor

For the piezoelectric effect, the cross-sectional view of the 3-axis gyro-sensor is shown in Fig. 3. The piezoelectric element substrate is bonded to the top face of the diaphragm made of elinvar, and the oscillator is joined to the back.

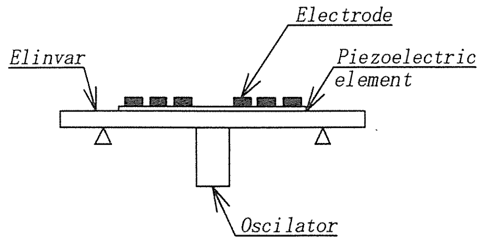


Figure3. Cross-sectionofthe 3-axis gyro-sensor

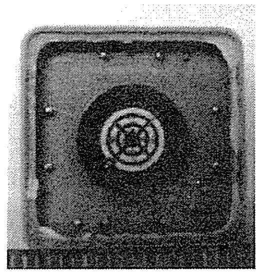


Figure4. Surface of the piezoelectric ceramic substrate

The node point of the diaphragm is supported, and fixed to the package. The surface of the piezoelectric ceramic substrate is shown in Fig. 4. Nine divided electrodes are formed on the surface. Coriolis' force is detected by the four sector electrodes (x+, x-, y+, y-) placed at the center. Coriolis' force in the X-axis direction is detected from the difference in charge produced between the two electrodes (x+, x-) placed on the X-axis, and Coriolis' force in the Y-axis direction is detected from the difference in charge produced between the two electrodes (y+, y-) placed on the Y-axis also. The four electrodes (X+, X-, Y+, Y-) placed outside the detecting electrodes are used for bringing the oscillator into rotational motion, and the oscillator makes rotational motion on the X-Y plane when AC signals with a 90° phase shift are applied. Ring electrode placed outermost is to monitor the motion in the Z-axis direction, which is used for synchronous detection. The placement of the nine electrodes shown here is determined by FEM analysis. Especially, positions of electrodes (x+, x-, y+, y-) detecting Coriolis' force are important, which must be placed in the stress concentration area. The results of FEM analysis of stress and displacement in this construction are shown in Fig. 5 and Fig. 6. From these results, it can be seen that stress concentrates around the oscillator joining part. If the Coriolis' force detecting electrodes (x+, x-, y+, y-) are placed in this area, Coriolis' force can efficiently be detected. It is efficient to bring the oscillator into rotational motion by the surrounding four electrodes (X+, X-, Y+, Y-).

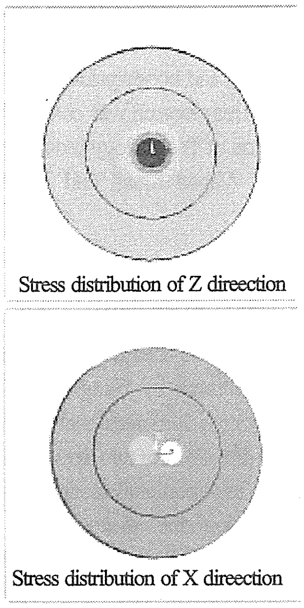


Figure5. FEM analysis of stress

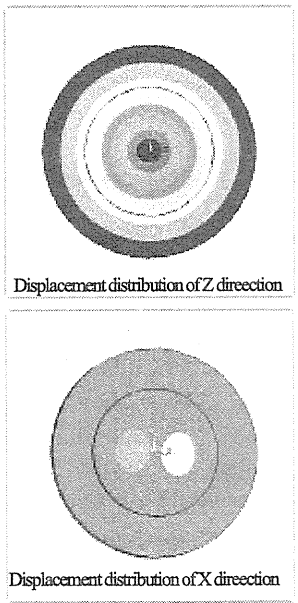


Figure6. FEM analysis of displacement

4. Detection circuit of the 3-axis gyro-sensor

Since the oscillator of the 3-axis gyro-sensor makes rotational motion as shown in Fig. 1, the velocity components are constant. In this research, the oscillator was brought into rotational motion on the X-Z plane in consideration of the detection sensitivity and noise resistance. When passing on the X-axis, it has a velocity component in the Z-axis direction, and when passing on the Z-axis, it has a velocity component in the X-axis direction. If Coriolis' force is measured in the X-axis direction and Y-axis direction the instant when it passes on the X-axis (velocity component Vz), angular rate ωx and angular rate ωy can be detected. Furthermore, if Coriolis' force is measured in the Y-axis direction the instant when it passes on the Z-axis (velocity component Vx), angular rate ωz can be detected. Rotational motion on the X-Z plane is made by applying signals with a phase difference of 0°,90°,180°,270° from the corresponding phase of the electrodes (X+ and X-) on the X-axis alternately, and Coriolis' force in the X-axis direction and Y-axis direction is detected from the charge produced between the central four detecting electrodes (x+, x-, y+, y-).
The circuit block diagram used for detecting 3-axis angular rate is shown in Fig.7. Synchronous detection of the signals from the detecting electrodes (x+, x-, y+, y-) with the drive signal of the oscillator can be seen.

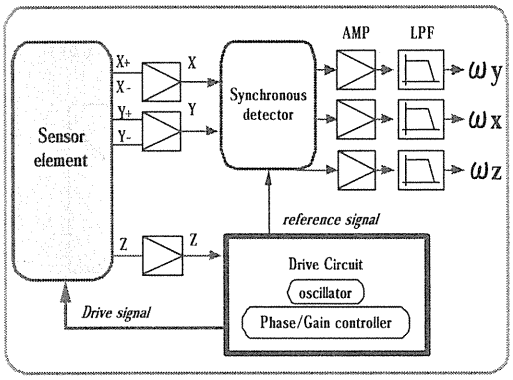
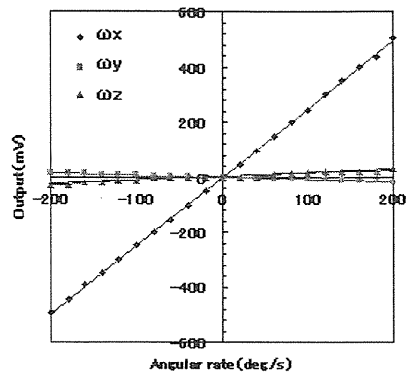


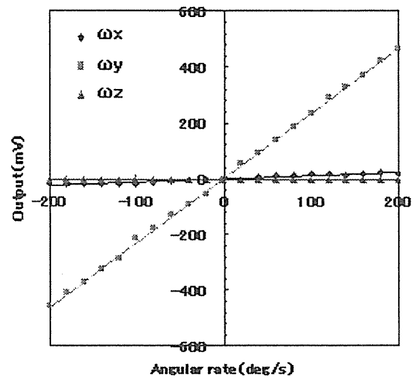
Figure7. Circuit block diagram of 3-axis gyro-sensor

5. Performance of the 3-axis gyro-sensor

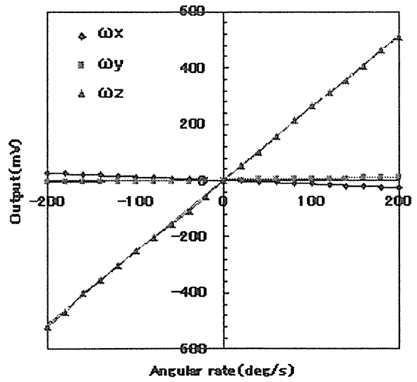
The principal axis sensitivity and cross-axis sensitivity of the 3-axis gyro-sensor we have developed this time are shown in Fig. 8. It can be seen that the cross-axis sensitivity is 5% or less on each axis. Performance is shown in Table 1. Compared with the piezoelectric ceramic type 1-axis gyro-sensor that is commercially available at present, we have found that the 3-axis gyro-sensor can achieve performance of the same level in the cross axis sensitivity, non-linearity et al, and the performance is equivalent to three 1-axis gyro-sensors.



(a) Angular rate around Z-axis (ωx)



(b) Angular rate around Y-axis (ωy)



(c) Angular rate around Z-axis (ωz)

Figure8. Detection sensitivity and cross-axis sensitivity

Items	Performance
Detection axis	3-axis(X,Y,Z)
Sensitivity	2.5mV/deg/sec
Cross-axis sensitivity	5%
Non-linearity	3%
Response frequency	DC-50Hz

Table1. Performance of 3-axis gyro-sensor

6. Acknowledgement

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Conclusion

This report has shown that 3-axis angular rate can be detected with one detecting element by bringing the oscillator into rotational motion within a 2-dimensional plane, and detecting Coriolis' force in the directions of two axes. In this research, the vibrator was brought into rotational motion and Coriolis' force was detected by using the piezoelectric effect of the piezoelectric element, but the oscillator may be brought into rotational motion by Coulomb force and Coriolis' force being detected by electrostatic capacitance. In this case, it is considered that compact and highly reliable 3-axis gyro-sensors can be realized with use of micromachining technology. We think that research in this field will advance in synchronicity with market trends in the future.

7 References

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