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The 5-Axis Motion Sensor

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Summary

We developed a 5-axis motion sensor, which is made by the silicon micromachining technology. The 5-axis motion is composed of 2-axis angular velocity and 3-axis acceleration. We succeeded to sense these 5-axis motions at the same time by one sensor. The principal is to measure the force act on a mass attached under a diaphragm. By acceleration, Newton's force F ($F = mA$, m : weight of the mass, A : acceleration) act on the mass. And when the mass is vibrating, the Coriolis force F_c ($F_c = 2m\Omega V$, Ω : angular velocity, V : velocity of the mass) act on the mass by angular velocity. For example, when the rotation around X- or Y-axis is occurred on the mass, which is vibrating along the Z-axis, the Coriolis force will be generated along the Y- or X-axis. Therefore 3-axis acceleration and 2-axis angular velocity can be measured. To vibrate the mass, we used the electromagnetic force, and to measure the force we used a change of electrostatic capacitance. In this report we describe the construction, the principle of detection and the performance about the 5-axis motion sensor.

Keywords: angular rate, acceleration, silicon micromachining, 2-axis, 3-axis, 5-axis

Introduction

The method measuring acceleration and angular velocity is generally used to detect movement of the object. Actually, numerous accelerometers and angular velocity sensors are used to detect movement. Recently, the sensors are used not only to detect, but to control the movement itself. In the automobile, for example, such kinds of sensor are used in navigation system, air bag system and chassis control system. And uses of the motion detect sensor are going to spread to the field of amusement machine, helicopter, head mount display, digital camera and so on. Although the movement is originally vector quantity, most of sensors are so-called uni-axial sensors, which detect only one axial direction. To detect movement, we have to use a few accelerometers and a few angular velocity sensors. Consequently, size of the sensing system and difficulty of fabrication will be increased. We succeeded to develop the 5-axis motion sensor, which can be measured 2-axis angular velocity and 3-axis acceleration. Using this sensor, these 5-axis motion data can be obtained at the same time.

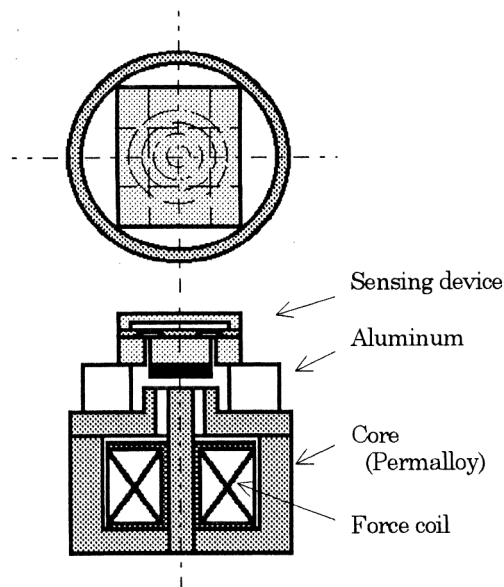


Fig.1: Schematic illustration
of 5-axis motion sensor

Structure and Principle

Structure

As shown in fig.1, the structure of this sensor is that a silicon electrostatic capacitive sensing device is attached upon a core, through an aluminum block.

The sensing device is made by silicon micromachining, and the structure is shown in fig.2. On the upper surface of the silicon substrate, single electrode is formed. And fixed substrate (the glass plate) is bonded to the silicon substrate so as to face the silicon substrate. Five separate electrodes are formed on the lower surface of the fixed substrate, as shown in fig.2. On the lower surface of the silicon substrate, a ring-shaped diaphragm is formed and a mass and pedestals are connected to the center and circumference respectively. On the bottom of the mass, magnetic substance (iron plate) is attached (fig.3). The core, in which the force coil is contained, is made from high permeance material (permalloy), and designed electromagnetic force, which generated by the force coil, work effectively to the magnetic material attached on the mass.

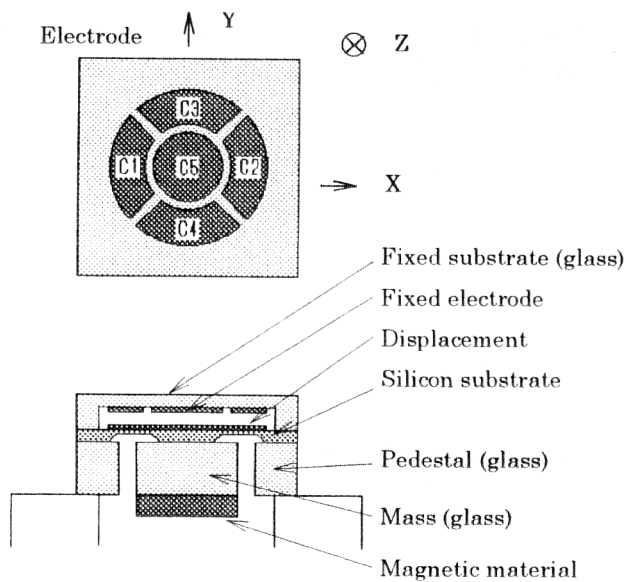
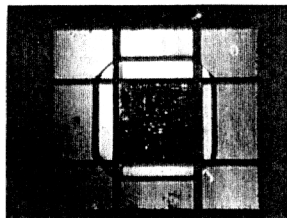


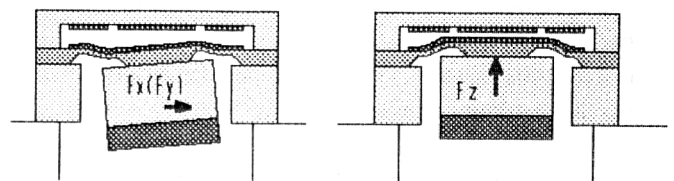
Fig. 2: Schematic structure of sensing device



(a) Force coil (b) Sensing device
Fig. 3: Main unit of the 5-axis motion sensor

Principle

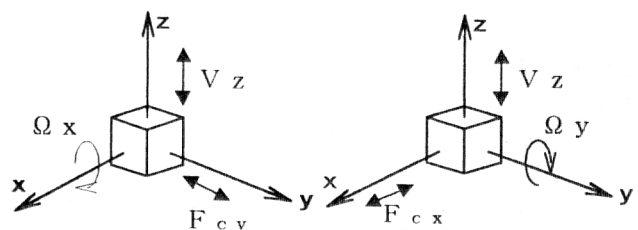
When a force acts on the mass, the mass is displaced along the direction of the force. At the same time, this causes transformation of the diaphragm. The force of X or Y-axis direction transforms diaphragm as shown in fig.3(a), and the force of Z-axis direction transforms diaphragm, as shown in fig.3(b). This transformation of diaphragm is accompanied with changes of electro-static capacitance. Therefore the force works on the mass can be measured. For example, the X-axis direction's force can be detected from the difference of capacitance between C1 and C2, shown in fig.2. At the same principle, the Y-axis direction's force can be detected from the difference of C3 and C4, and the Z-axis direction's force can be detected from the C5.



(a) X(Y)-axis force (b) Z-axis force
Fig. 4: Transformation of diaphragm

2-axis Angular velocity

By the supplement of the pulse current, the force coil generates pulse shaped electromagnetic field. It works to the magnetic material attached on the bottom of the mass, and the mass vibrates along the Z-axis.



(a) X-axis rotation (b) Y-axis rotation
Fig.5 Principal of 2-axis angular velocity sensor

When the mass is rotated around the X-axis, the Coriolis force is generated along the Y-axis direction, as fig.5(a). And when the mass is rotated around the Y-axis, the Coriolis force is generated along the X-axis direction. X and Y-axis Coriolis force are described in equations (1) and (2) where F_{cx} and F_{cy} are Coriolis force, M is

weight of the mass, Ω_y and Ω_x are input angular velocity to be measured, and V_z is velocity of Z-axis vibration.

$$F_{cx} = 2 \cdot M \cdot \Omega_y \cdot V_z \quad (1)$$

$$F_{cy} = 2 \cdot M \cdot \Omega_x \cdot V_z \quad (2)$$

The Coriolis force is measured by changes in electrostatic capacitance. But it is necessary to measure the Coriolis force synchronously to the velocity of Z-axis for detection of the angular velocity

As shown in fig.6, the signal of X and Y-axis direction, and reference signal, which is synchronized V_z , are input to the synchronous detector. And though amplifier and filter, the angular velocity can be measured.

3-axis acceleration

When acceleration acts on the mass, the mass is displaced in the direction of the acceleration. By change in electrostatic capacitance, the acceleration can be measured. [1,2,3,4] But the mass is vibrating along the Z-axis. Therefore the vibration signal is overlapped in the Z-axis direction's acceleration signal. And in the X- and Y-axis direction's acceleration signal, the signal of Coriolis force is overlapped. The acceleration to be measured is ranged from DC to 30Hz. On the other hand, the frequency of these unexpected signals is almost as same as vibration. Therefore using the low pass filter, acceleration can be measured.

On this way, 2-axis angular velocity and 3-axis acceleration can be measured at same time with one sensor unit.

Result

Performance of this sensor is as shown in table 1 and table 2. The output performance of the angular velocity is given in Fig.7. And the acceleration is given in Fig.8.

Future work

The output of angular velocity is influenced by acceleration. The reason is that the sensitivity of the force, which act on the mass, is depend on the distance between displacement electrode on silicon substrate and fixed electrode on glass substrate.

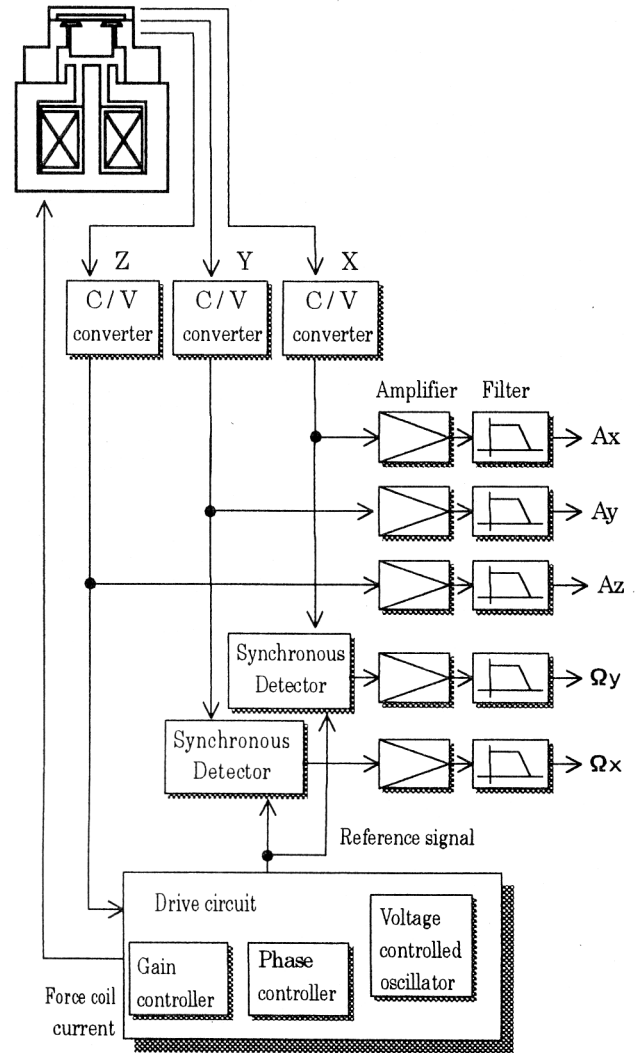


Fig.6: Block diagram

Table 1: Angular velocity

	Ω_x	Ω_y
Sensitivity	12 mV/(deg/sec)	10 mV/(deg/sec)
Cross axial sensitivity	8 %	8 %
Linearity	5 %	5 %

Table 2: Acceleration

	Ax	Ay	Az
Sensitivity	1.01 V/g	1.01 V/g	1.04 V/g
Cross axial sensitivity	5 %	4 %	4 %
Linearity	2 %	2 %	2 %

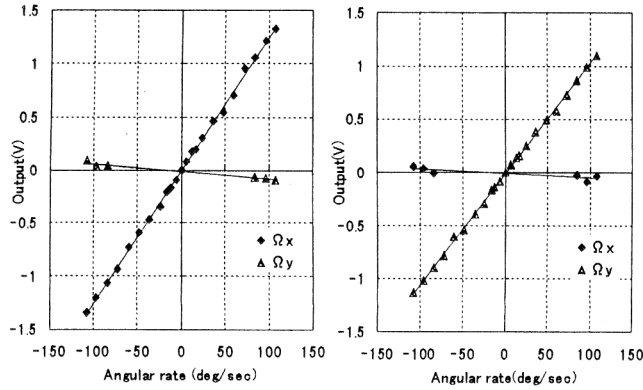


Fig.7: Angular velocity

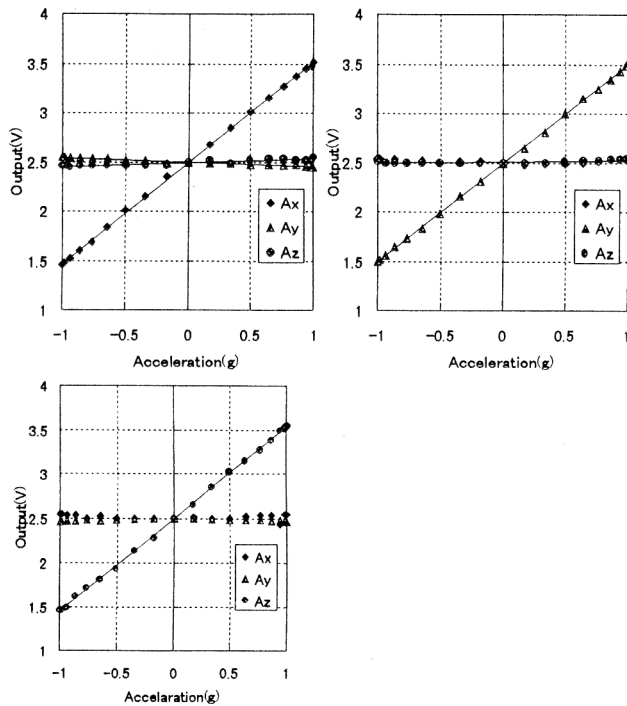


Fig.8: Acceleration

For example, when acceleration is applied from bottom of the sensor, diaphragm transforms to upper direction and distance between tow electrode become close. At this position, change of electrostatic capacitance is bigger than change at the normal position, if same Coriolis force is act on the mass. So sensitivity against the angular velocity is changed by acceleration. Generally it is difficult to eliminate this error. But the 5-axis motion sensor measure the 3-axis acceleration at the same time. Consequently, using the acceleration output, the influence of acceleration against the angular velocity can be eliminated. Next, we want to develop the circuit or

software to eliminate this error.

In addition, we want to improve the performance, for example, temperature characteristic, S/N ratio and so on.

Conclusion

In this sensor, we adapted the electromagnetic force instead of electrostatic force to vibrate the mass. Now we don't want to give up the capability of utilize of electrostatic force. But the power of the electro-magnetic force is attractive. Actually it generate enough power to make the mass vibrate at a certain frequency which is slightly different from Z-axis resonant frequency. And to minimize the core is possible to use the miniature size coil, which is used in printer. From the fact described above that to utilize the electromagnetic force is one of the best way to realize the 5-axis motion sensor.

In this paper, we reported a prototype of the 5-axis motion sensor. In conclusion, this shows the possibility to realize the motion sensor with small size, lightweight and low cost.

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