Development of 6-axis Motion Sensors Using Piezoelectric Elements

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Abstract

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 angular velocity sensors, piezoelectric type 2-axis angular velocity sensors have been developed. By applying such piezoelectric type 2-axis angular velocity sensors, 3-axis angular velocity can be detected with the oscillator's velocity components in the directions of two axes, and the detection components of Coriolis force produced by angular velocity in the directions of two axes. By using this principle, we have succeeded in developing a 3-axis angular velocity sensor [(1)] that detects 3-axis angular velocity with one detecting element, which was announced at this symposium last year. By applying the 3-axis angular velocity sensor, acceleration and angular velocity can be discriminated with use of the difference in frequency between the force produced by acceleration and the Coriolis force produced in synchronization with the oscillator's drive frequency. With this, we have succeeded in developing a 6-axis motion sensor that detects 3-axis acceleration and 3-axis angular velocity 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 of the 6-axis motion sensor using a piezoelectric element, and furthermore the influence of acceleration on angular velocity characteristics.

Keywords: 6-axis, motion sensor, angular velocity, 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 velocity, and angular acceleration. Thus far, for detection of the six physical quantities of distance, velocity and acceleration, which represent parallel motion, and angle, angular velocity and angular acceleration, which represent rotational motion, only acceleration sensors and angular velocity sensors have been operational in use of micromachining technologies and ceramic technologies. As a matter of course, acceleration and angular velocity are important physical quantities in detecting the motion of objects in 3-dimensional space. In the field of acceleration sensors, 3-axis acceleration sensors [(2)-(4)] of the piezoresistance type, capacitance type, and piezoelectric type have already been developed, and marketed by many companies. However, in the field of angular velocity sensors, 1-axis angular velocity sensors are predominant, though only a few 2-axis angular velocity sensors have been marketed. The authors reported on 3-axis angular velocity sensors using piezoelectric elements at this symposium last year. Recently, demands for motion sensors that detect acceleration and angular velocity simultaneously have increased in the automobile market in particular. We have conducted research of 6-axis motion sensors [(5),(6)] to meet such demands. We wish to report on the 6-axis motion sensor using a piezoelectric element we have developed recently.

2 Detection principle of the 6-axis motion sensor

The 6-axis motion sensor detects 3-axis acceleration and 3-axis angular velocity with one detecting element. Here, the detection principles of 3-axis acceleration and 3-axis angular velocity are explained.

2-1 Detection principle of 3-axis acceleration

The construction of the 6-axis motion sensor is shown in Fig. 1. The piezoelectric element substrate is bonded to the top face of the diaphragm made of elinvar, and the oscillator is joined to the back. The node point of the diaphragm is supported, and fixed to the package. Nine split electrodes are formed on the top face of the piezoelectric ceramic substrate as shown in Fig. 2. When acceleration acts on the oscillator, force (F=ma) is exerted on the oscillator, and the diaphragm is deformed. When acceleration in the X-axis direction acts, the diaphragm is deformed as shown in Fig. 3-1, and also when acceleration in the Z-axis direction acts, it is deformed as shown in Fig. 3-2. With this deformation, charge is produced on the electrodes on the piezoelectric element shown in Fig. 2 as shown in Table 1. By considering the presence or absence and the sign of this charge, 3-axis acceleration can be detected.

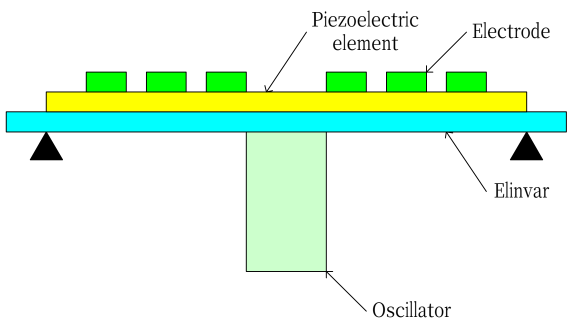


Fig. 1. Cross-section of the 6-axis motion sensor

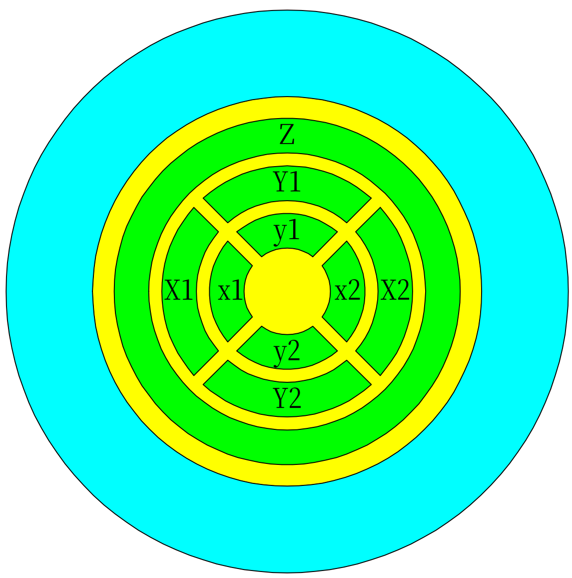


Fig. 2. Top face of the 6-axis motion sensor

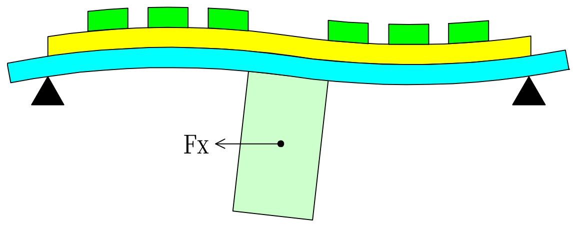


Fig. 3-1. Deformation by X-axis direction acts

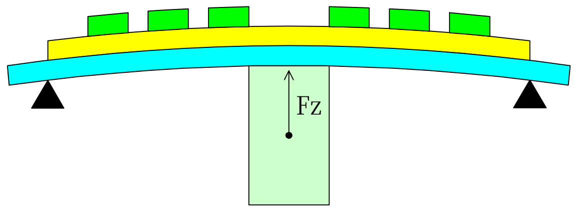


Fig. 3-2. Deformation by Z-axis direction acts

Table 1. The electric charge produced on the electrodes

	x1	x2	y1	y2	X1	X2	Y1	Y2	Z
Ax	-	+	0	0	-	+	0	0	0
Ay	0	0	-	+	0	0	-	+	0
Az	+	+	+	+	+	+	+	+	+

2-2 Detection principle of 3-axis angular velocity

When an object having a mass moves at a certain velocity, angular velocity acts on the object with the result that Coriolis force acts on it. The 3-axis angular velocity sensor also uses the Coriolis force. In the case of 3-axis angular velocity sensors, the object (oscillator) having a mass is brought into rotational motion on the X-Z plane as shown in Fig. 4. In this motion, the oscillator has motion component Vx in the X-axis direction, and has velocity component Vz in the Z-axis direction. As shown in Fig. 5, when the oscillator moves having velocity component Vx in the X-axis direction, if angular velocity ωz around the Z-axis acts, Coriolis force Fy in the Y-axis direction is produced. Also, when the oscillator moves having velocity component Vz in the Z-axis direction, if angular velocity ωy around the Y-axis acts, Coriolis force Fx in the Z-axis direction is produced. When angular velocity ωx in the X-axis direction acts, Coriolis force Fy in the Y-axis direction is produced. The relationship is shown by the following expression (1).

$$Fy = 2mVz \times \omega x$$
$$Fx = 2mVz \times \omega y \qquad (1)$$
$$Fy = 2mVx \times \omega z$$

This expression shows that the angular velocity components (ωx, ωy, ωz) of three axes can be detected by detecting Coriolis force (Fx, Fy) in the directions of two axes while giving velocity components (Vx, Vz) in the directions of two axes by bringing the oscillator into rotational motion on the X-Z plane. When Coriolis force Fx acts on the oscillator, the diaphragm is deformed as shown in Fig. 3-1 Coriolis force Fx in the X-axis direction is detected as in the case where acceleration acts in the X-axis direction. Coriolis force Fy in the Y-axis direction is also detected in a like manner. The 3-axis angular velocity sensor we have developed this time uses piezoelectric ceramic. The piezoelectric effect of the piezoelectric element is used for both circular motion within the X-Z plane, and detection of Coriolis force in the X-axis direction and Y-axis direction. Since drive and detection are essential to angular velocity sensors, it can be said that the piezoelectric element is one of the suitable materials for angular velocity sensors.

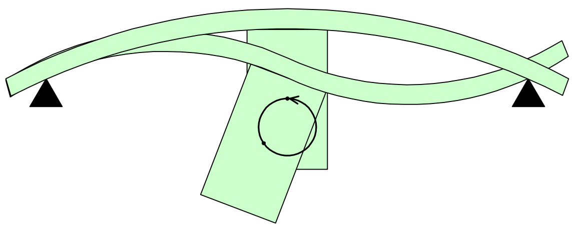


Fig. 4. Rotational motion of the oscillator on the X-Z plane

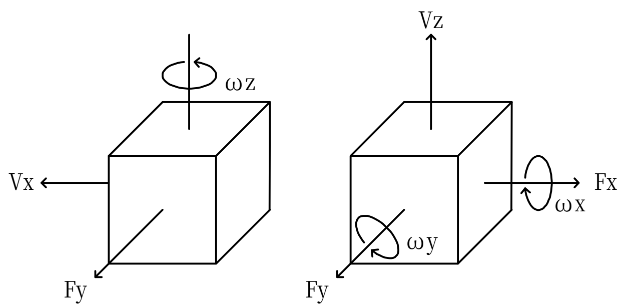


Fig. 5. Detection of ωx, ωy and ωz

3 Detection of force and driving method of the oscillator

When force in the X, Y and Z-axis directions acts on the piezoelectric type 6-axis angular velocity sensor shown in Fig. 1, charge is produced on each electrode as shown in Table 1. Force in the X-, Y- and Z-axis directions is detected by the four sector electrodes (x+, x-, y+, y-) placed at the center and the surrounding ring electrode. Force Fx 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 force Fy in the Y-axis direction is detected from the difference in charge produced between the two electrodes (y+, y-) placed on the Y-axis, and also force Fz in the Z-axis direction is detected by ring electrode Z. Two electrodes (X+, X-) out of the four electrodes (X+, X-, Y+, Y-) placed outside the detecting electrodes, and ring electrode Z placed outermost are used for bringing the oscillator into rotational motion. By applying AC signals with a phase difference, the oscillator can be brought into rotational motion on the X-Z plane. The placement of the nine electrodes shown here is determined by FEM analysis. Especially, the positions of the force detecting electrodes are important, which must be placed in the stress concentration area.

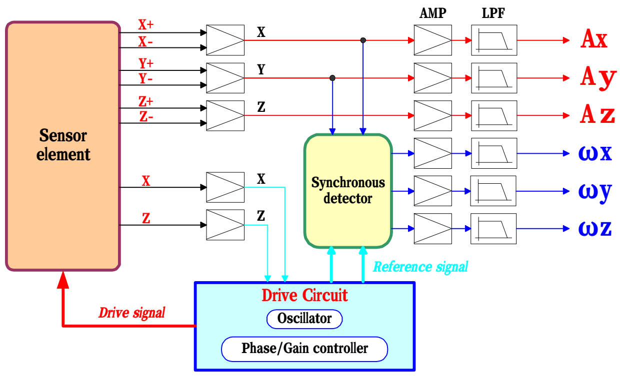


Fig. 6. Circuit block diagram of 6-axis motion sensor

4 Detection circuit of the 6-axis angular velocity sensor

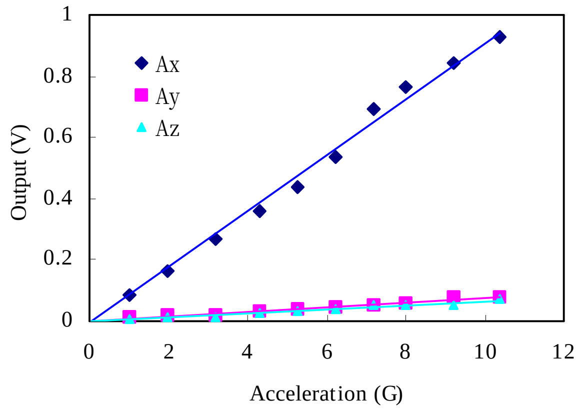
In this research, the oscillator was brought into rotational motion on the X-Z plane in consideration of the detection sensitivity and noise resistance. The charge produced on the piezoelectric ceramic by force in the directions of three axes (Fx, Fy, Fz) is converted to voltage proportional to force (Vx, Vy, Vz). By passing this voltage (Vx, Vy, Vz) through a low-pass filter, 3-axis acceleration components (Ax, Ay, Az) can be obtained. If force in the X-axis direction and in the Y-axis direction (Fx, Fy) is measured the instant when passing on the X-axis (velocity component Vz), angular velocity ωx and angular velocity ω y are detected. By synchronous detection of voltage (Vx, Vy) with the drive signal (Dx or Dz), angular velocity ωx and angular velocity ωy can be detected. Furthermore, if Coriolis force in the Y-axis direction is measured the instant when passing on the Z-axis (velocity component Vx), angular velocity ωz can be detected. By synchronous detection of voltage (Vy) with the drive signal (Dx, Dz), angular velocity ωz can be detected. The circuit block diagram of the 6-axis motion sensor is shown in Fig. 6. It can be seen that 3-axis acceleration can be detected by simply adding a low-pass filter to the 3-axis angular velocity sensor, which allows for the configuration of the 6-axis motion sensor.

5 Performance of the 6-axis motion sensor

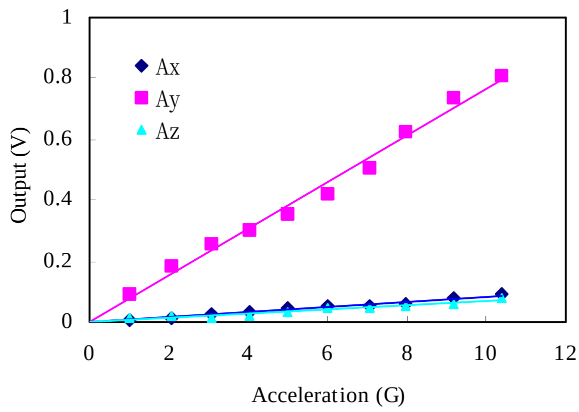
The principal axis sensitivity and cross-axis sensitivity of the 6-axis motion sensor we have developed this time are shown in Fig. 7 and Fig. 8. Performance is shown in Table 2. Linearity and cross-axis sensitivity of acceleration characteristics are inferior to angular velocity characteristics. This is because there is a problem with the method of supporting the diaphragm. By supporting the diaphragm with increased rigidity, the acceleration characteristics are improved. However, the angular velocity characteristics deteriorate thereby. The acceleration characteristics and angular velocity characteristics vary depending on the method of supporting the diaphragm, which are in a trade-off relationship. Next, the angular velocity output and acceleration characteristics of the time when acceleration ±4G acts are shown in Fig. 9. From this figure, it can be seen that the angular velocity characteristics are not affected by acceleration. Lastly, the angular velocity output and acceleration output of the time when impact acceleration acts on the 6-axis motion sensor are shown in Fig. 10. Since the angular velocity output and acceleration output are almost the same in waveform, it is suggested that signal disturbance of the angular velocity output by impact acceleration can be corrected by the acceleration output. From the above results, we have found that 3-axis acceleration components (Ax, Ay, Az) and 3-axis angular velocity components (ωx, ωy, ωz) can be detected simultaneously with one detecting element.

Table 2. Performance of 6-axis motion sensor

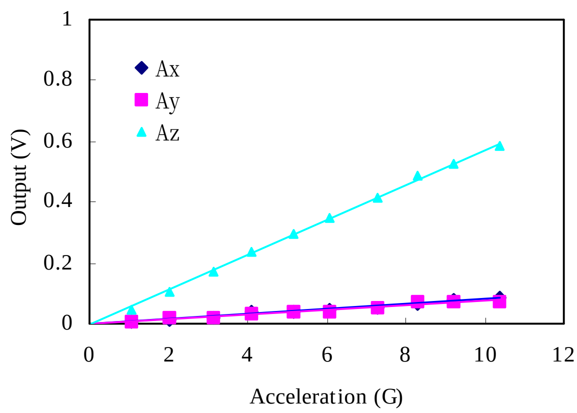
	Angular velocity	Acceleration
Sensitivity	2.5mV/deg/sec	300mV/G
Cross-axis sensitivity	5%	8% (20Hz)
Non-linearity	3%	5%
Response frequency	DC-50Hz	1-100Hz



(a) Acceleration output of X-axis

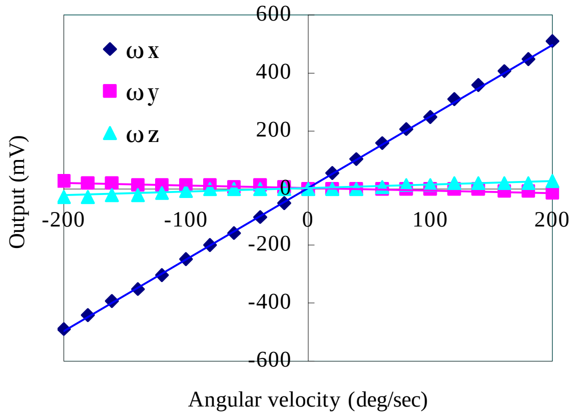


(b) Acceleration output of Y-axis

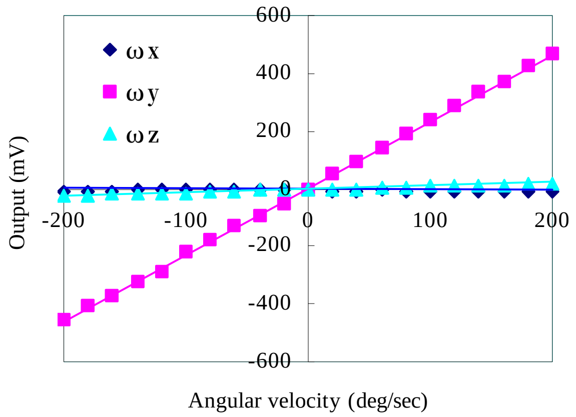


(c) Acceleration output of Z-axis

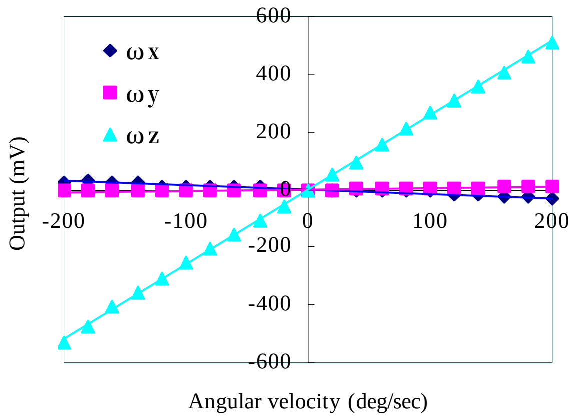
Fig. 7. Acceleration characteristics of 6-axis motion sensor



(a) Angular velocity around Z-axis (ωx)

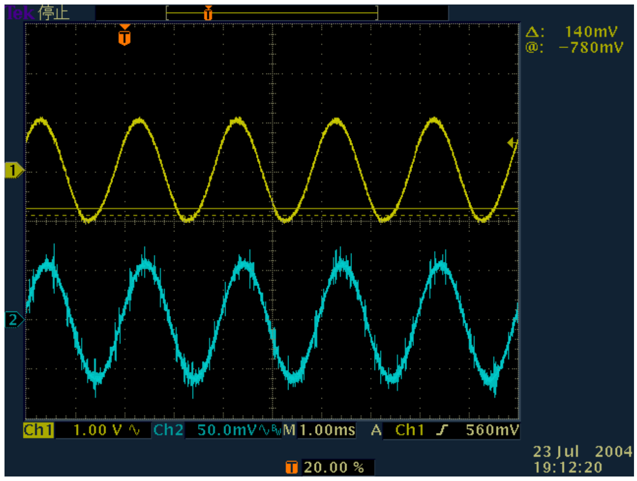


(b) Angular velocity around Y-axis (ωy)



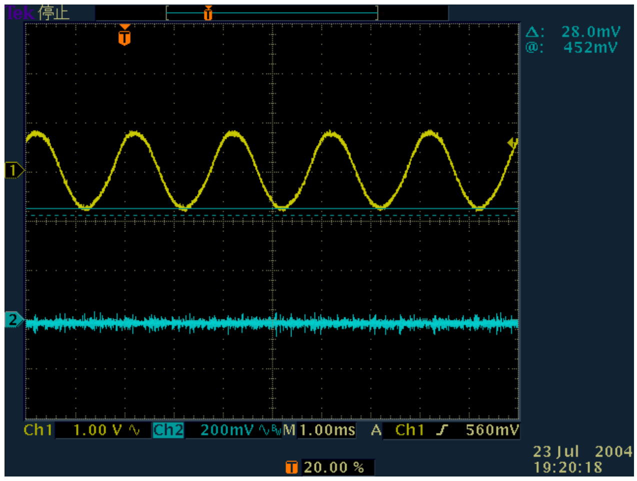
(c) Angular velocity around Z-axis (ωz)

Fig. 8. Angular velocity characteristics of 6-axis motion sensor



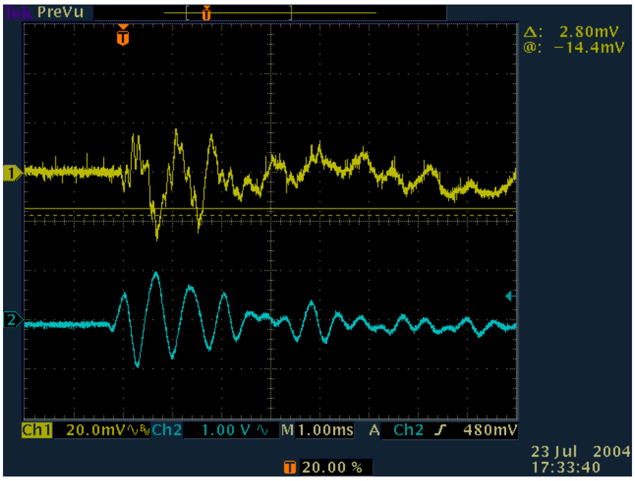
(1) Reference of acceleration (2) Acceleration output

Fig. 9-1. The acceleration output of the time when acceleration(±5G) acts



(1) Reference of acceleration (2) Angular velocity output

Fig. 9-2. The angular velocity output of the time when acceleration(±4G) acts



(1) Angular velocity output (2) Acceleration output

Fig. 10. The angular velocity output and acceleration output of the time when impact acceleration acts

6 Conclusion

This report has shown that 3-axis angular velocity components (ω x, ω y, ω z) and 3-axis acceleration components (Ax, Ay, Az) can be detected with one detecting element by bringing the oscillator into rotational motion within a 2-dimensional plane, and detecting the directions of three axes. Also, it has been shown that the angular velocity characteristics of the 6-axis motion sensor we have developed this time do not change with acceleration of about ±4G. Furthermore, with the conventional angular velocity sensors, their output waveforms would be disturbed by impact acceleration when it acts, where there would be no means of correction, but with this sensor, we have found the possibility of correcting the angular velocity signal disturbance caused by impact acceleration because acceleration and angular velocity are detected simultaneously. In this research, the oscillator 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 capacitance. In this case, it is considered that compact and highly reliable 6-axis motion sensors can be realized with use of micromachining technologies. We think that research in this field will advance in synchronicity with market trends in the future.

Acknowledgement

The authors wish to acknowledge Mr. Matsumoto of Toyama Industrial Technology Center for helpful suggestion in carrying out this research and cooperation in making rotary table measurements and FEM analysis.

References

[1] K. Okada et al "Development of 3-axis Gyro-Sensor Using Piezoelectric Element" Tech. Dig. of The 20th Sensor Symposium, pp123-126, 2003

[2] K. Okada "Tri-axial piezoresistive accelerometer" Tech. Dig. of The 11th Sensor Symposium, pp245-248, 1992

[3] Joost C. Lotters "A Highly Symmetrical Capacitive Traxial Accelerometer" ISBN 90-365-0982-3

[4] K. Okada et al "Development of Micro-machined Three-axis Sensors in Venture Business" Transducer '01 Munich 1280-1283, 2001

[5] N. Taniguchi, H. Itano, K. Okada "The 5-axis Motion Sensor" Tech. Dig. of The 16th Sensor Symposium, pp41-44, 1998

[6] Y. Watanabe et al "Five-axis motion sensor with electrostatic drive and capacitive detection fabricated silicon bulk micromachining", Sensors and Actuators A 97-98(2002), pp109-115