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Development of Tri-Axial Accelerometers Using Piezoresistance, Electrostatic Capacitance and Piezoelectric Elements

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ABSTRACT

We have developed tri-axial accelerometers which use piezoresistance, electrostatic capacitance and piezoelectric element. Piezoresistive accelerometers use piezoresistive effect, and electrostatic capacitive accelerometers use variations in electrostatic capacitance. Both sensors are made by combining semiconductor technology and micromachining technology. Piezoelectric accelerometers use piezoelectric ceramic. The tri-axial accelerometers which have been developed on this occasion have a number of unique features. This report discusses the construction and detection principles about three types tri-axial accelerometers as well as their performance.

INTRODUCTION

Recently, centered on the automotive industry, there is a growing demand for high performance accelerometers for vehicle safety and comfort controls, typified by air bag systems, anti-lock brake systems and chassis control. Also, since the Kobe earthquake, it is hoped that accelerometer with high sensitivity will be developed for earthquake detection. Accordingly, several accelerometers are already being developed using the piezo resistive effect and variations in electrostatic capacitance. Most of these sensors are so-called uni-axial sensors which detect acceleration in one axial direction. Acceleration is a vector quantity. Three uni-axial sensors are required for the vector detection of acceleration. When we consider vehicle collisions as mentioned in the examples above, the detection not only of head-on collisions but also of side collisions necessitates at the very least sensors which detect bi-axial acceleration. When we cosider a rolling collision, a tri-axial sensor is needed. With regard to earthquakes, tri-axial accelerometers which will detect vibration in the horizontal directions as well as the vertical direction are required for the detection of all kinds of earthquakes. There are recent reports of successive development of electrostatic capacitance type (1), (2) tri-axial accelerometers. We too have already been developing piezoresistive tri-axial accelerometers (3). In addition, most recently, we have been successful in developing tri-axial electrostatic capacitive accelerometers and piezoelectric accelerometers with excellent productivity. In this report, we shall make a comparative study of the construction and acceleration detection principles of piezoresistance type, electrostatic capacitance type and piezoelectric type as well as their relative performances.

PRINCIPLES

The piezoresistive, electrostatic capacitive and piezoelectric accelerometers which are discussed here are capable of detection by one detection element separating acceleration A in three dimensional space into its acceleration components (A_x, A_y, A_z) along the X, Y and Z axes. The detection principles of these sensors are different and each has characteristics features.

Piezoresistance type

The piezoresitive tri-axial accelerometers is made by using semiconductor technology and micromachining technology, as shown in Figure 1. Three sets of piezoresistance elements (12 in all) are

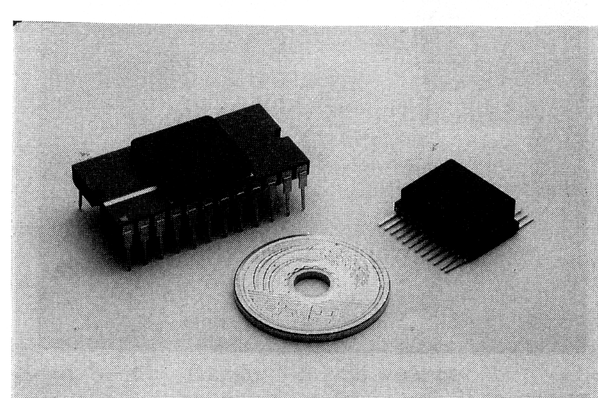

Fig. 1 Piezoresistive tri-axial accelerometer

formed on the surface of a silicon substrate for detecting the tri-axial acceleration components. On the back, a ring-shaped diaphragm is formed and, mass and pedestal are connected to the center and circumference respectively. Originally, the pedestal and mass are made from the one glass substrate. After the diaphragm surface of the silicon wafer has been connected to the glass substrate, mass and pedestal are separated by cutting them off the glass substrate with a dicing machine. This method of assembly facilitates batch processing and the manufacturing can be automated.

When an acceleration acts on the mass, the mass is displaced in the direction of the acceleration. Matching this displacement, the three sets of piezoresistance elements (12 in all) are formed on the diaphragm. By combining these piezoresistance elements effectively to make a bridge circuit, the axial acceleration components (A_X, A_Y, A_Z) can be detected without cross-axis sensitivity. See reference (3) for details.

Electrostatic capacitance type

Like the piezoresistive tri-axial accelerometer, the electrostatic capacitive accelerometer is made by semiconductor and micromachining technology. Structurally also, it is similar to the piezoresistive accelerometer and the manufacturing method is almost the same. The difference is that the fixed substrate (the glass plate) is joined to the silicon substrate so as to face the silicon substrate. A side view is shown in Figure 2. Five separate electrodes shown in Figure 3 are formed on the lower surface of the fixed substrate and a single electrode is formed on the upper surface of the silicon substrate. Five electrostatic capacitances are formed between the silicon substrate and the fixed substrate.

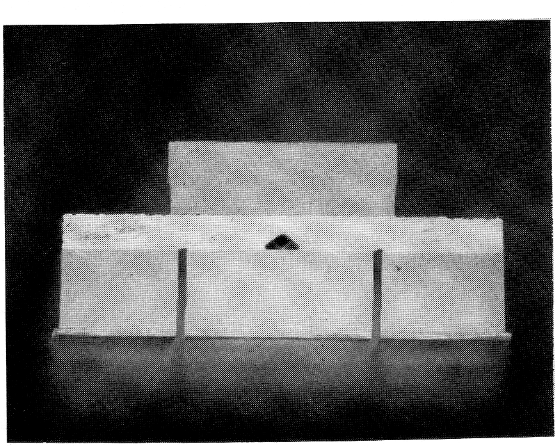

Fig. 2 Side view of electrostatic capacitive tri-axial accelerometer

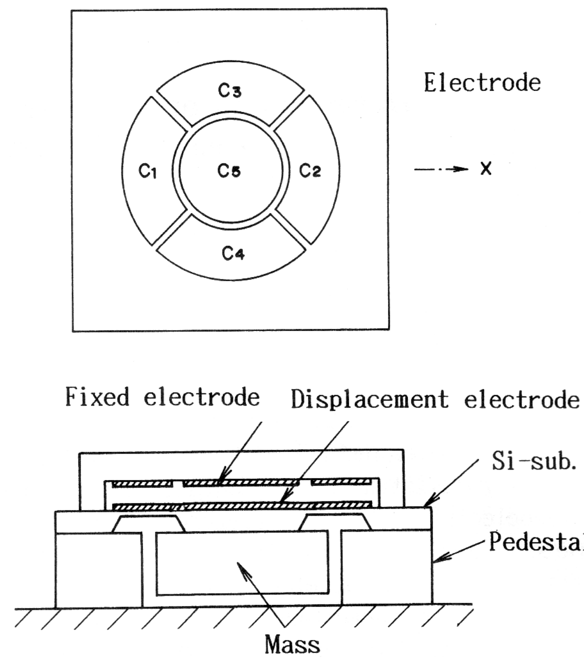

Fig. 3 Schematic structure of capacitive tri-axial accelerometer

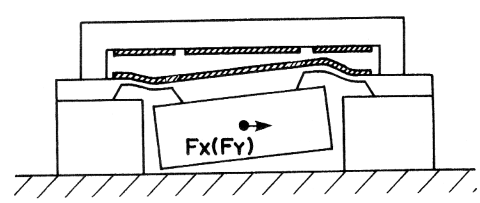

Fig 4(a) Displacement of diaphragm by X(Y)-axis acceleration

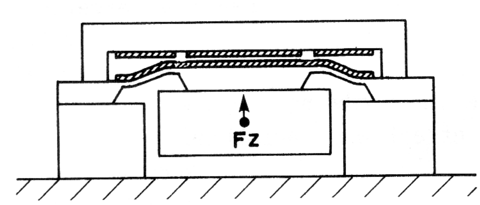

Fig 4(b) Displacement of diaphragm by Z-axis acceleration

When an acceleration acts on the mass, the mass is displaced in the direction of the acceleration. At the same time, this deforms the diaphragm. The diaphragm is deformed as shown in Figure 4(a) in the case of the X-axial acceleration and as shown in Figure 4(b) in the case of Z-axial acceleration. Diaphragm deformation is accompanied by changes in elecrostatic capacitance. Acceleration in the X, Y, and Z directions causes electrostatic

	X-axis detec.		Y-axis detec.		Z-axis
	C 1	C 2	C 3	C 4	C 5
A x	+	−	0	0	0
A y	0	0	+	−	0
A z	+	+	+	+	+

+ : +ΔC, − : −ΔC, 0 : No change

Table 1 Change of capacitance C1 to C5

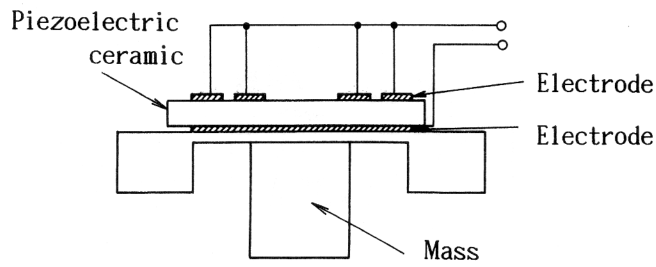

Fig. 5 Schematic structure of piezoelectric tri-axial accelerometer

capacitances C1 to C5 to change as shown in Table 1. In order to detect acceleration in the X-axial direction, the difference between electrostatic capacitance C1 and electrostatic capacitance C2 is obtained. In order to detect acceleration in the Y-axial direction, the difference between electrostatic capacitance C3 and electrostatic capacitance C4 is obtained. In order to detect acceleration in the Z-axial direction, the value of electrostatic capacitance C5 is obtained. In this way, acceleration can be detected without cross-axis sensitivity.

Piezoelectric type

The piezoelectric tri-axial accelerometer can detect tri-axial components of acceleration (A_x, A_y, A_z) using one sheet of piezoelectric ceramic. The basic construction is similar to that of the pizoresistive accelerometer. The difference is that, instead of piezoresistive effect, daiphragm strain is detected by the electric charge which it produces on the piezoelectric element.

The structure of the piezoelectric accelerometer is shown in Figure 5. The piezoelectric ceramic is connected to the upper surface of the diaphragm and the mass is connected to the lower surface. An electrode pattern on the surface of the piezoelectric ceramic is shown in Figure 6(a).

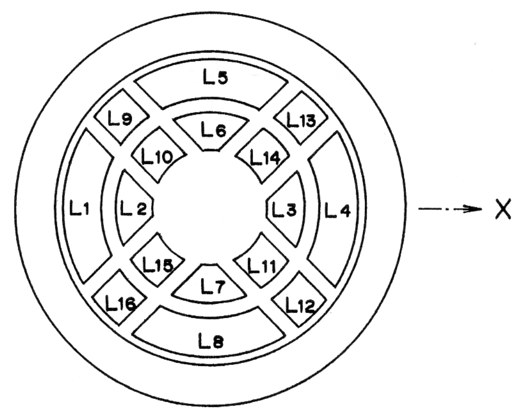

Fig. 6(a) Electrode pattern on ceramic

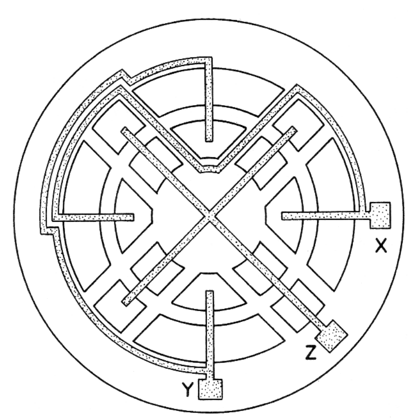

Fig. 6(b) Interconnecting pattern of electrode

	X-axis detec.				Y-axis detec.				Z-axis detection							
	L1	L2	L3	L4	L5	L6	L7	L8	L9	L10	L11	L12	L13	L14	L15	L16
A x	+	+	+	+	0	0	0	0	+	−	+	−	+	−	+	−
A y	0	0	0	0	+	+	+	+	+	−	+	−	+	−	+	−
A z	−	+	−	+	−	+	−	+	+	+	+	+	+	+	+	+

+ : + charge, − : − charge, 0 : no charge

Table 2 Generation charge on electrodes L1 to L16

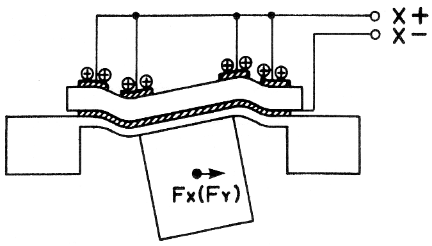

Fig 7(a) Displacement of diaphragm by X(Y) axis acceleration

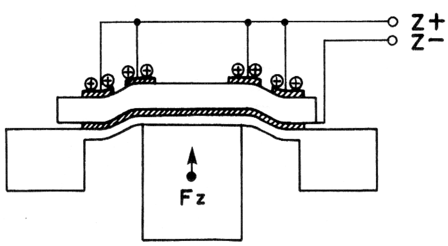

Fig 7(a) Displacement of diaphragm by Z axis acceleration

When an acceleration acts on the mass, the mass is displaced in the direction of the acceleration. This is accompanied by a deformation of the diaphragm and the piezoelectric ceramic. The deformation is as shown in Figure 7(a) in the case of X-axial acceleration and as shown in Figure 7(b) in the case of Z-axial acceleration. Based on this deformation, the electric charges shown in Table 2 are produced in the various electrodes with respect to X, Y and Z axial acceleration. However, double polarization is necessary in order to obtain the electric charges shown in Table 2. Electrodes L1 to L4 are connected together to detect X-axial acceleration, electrodes L5 to L8 are connected together to detect Y-axial acceleration, electrodes L9 to L16 are connected together to detect Z-axial acceleration as shown Figure 6(b). In this way, tri-axial acceleration components (A_X, A_Y, A_Z) can be detected without cross-axis sensitivity. As mentioned above, by double polarization and electrode connections as shown in Figure 6(b), the various axial accelerations are detected by differences, the influence of the pyro-effect is difficult to receive and it is stable with respect to temperature drift.

PERFORMANCE

The main capabilities of tri-axial accelerometers which we have developed at this time are shown in Table 3. These capabilities change with even slight changes in form. For example, in the case of the piezoresistive sensor, altering the diaphragm thickness from 15 micron to 30 micron changes the sensitivity to 0.25mV/G/V and the response frequency to 1.0KHz. The performance of the electrostatic capacitive sensor is similar to that of the piezoresistive sensor. If the dimensions of the electrostatic capacitive sensor and piezoresistive sensor were the same, the response frequencies would be the same. The piezoelectric accelerometer behaves differently from the previous two types of sensors. In the case of the piezoelectric type, in principle, static acceleration can not be detected. Since the electric charges is produced directly by the acceleration, the signal processing circuit simply needs to be a charge amplifier. The frequency response on the low frequency side is determined by the input impedance of the charge amplifier which is connected.

	Piezoresis.	Capacitance	Piezoelectric
Sensitivity	$1mV/V_{DD}/G$	0.05pF/G	30mV/G
Linearity	1%FS	1%FS	2%FS
Response fre.	0 - 200Hz	0 - 200Hz	0.5 - 1200Hz
Cross-axis sen.	5%	5%	10%

Table 3 Performance of three type accelerometers

CONCLUSION

We have developed tri-axial piezoelectric, electrostatic capacitive, piezoresistive accelerometers. Since the detection principles of these tri-axial sensors are different, they each have different characteristics. Hopefully there will be methods of utilizing these characteristics advantageously. As future developement issues, we can expect the development of tri-axial accelerometers having the same high performance as servo types (resolution of 10^{-6}G, for example).

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