Design and Simulation of Capacitive, Piezoresistive and Piezoelectric Triaxial Accelerometers Using a Highly Symmetrical Quad-Beam Structure

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SUMMARY

This paper presents the design and simulation of the capacitive, piezoresistive and piezoelectric triaxial accelerometers, which all are based on the same highly symmetrical quad-beam structure [1]. Static and modal simulations with FEM (Finite Element Method) simulator are done to analyze the mechanical response at accelerations in different directions. All devices are predicted to have near zero cross-axis sensitivity, good linearity and high sensitivity theoretically and numerically.

Keywords: Triaxial, Accelerometer, Capacitive, Piezoresistive, Piezoelectric.

INTRODUCTION

Micromachined accelerometer is very attractive for space navigation and automobile applications, such as airbag and automatic guidance, because of its size, weight, cost and power advantages. In some applications, such as guidance and sophisticated motion control systems, triaxial accelerometers are needed to sense acceleration in three directions. In this paper, the monolithic capacitive, piezoresistive, and piezoelectric triaxial accelerometers, which has only one seismic mass, are designed and simulated. They are predicted to have near zero cross-axis sensitivity, good linearity and high sensitivity. Our capacitive triaxial accelerometer differs from that of group Puers [2] in the distribution of the capacitors. Three pairs of differential capacitors are used here to reduce the complexity of the measurement circuit. Besides, our device has uniform axial sensitivities. Our piezoresistive triaxial accelerometer differs from that of group Takao [3] who use the piezoresistivity of MOSFET. Moreover, the geometry and the placement of the piezoresistors are also different. Our piezoelectric triaxial accelerometer differs from that of group Scheeper [4], which has three seismic masses.

THEORY AND SENSOR DESIGN

The triaxial accelerometer requires very low cross-axis sensitivity and good linearity. Besides, close sensitivities in three directions are also expected. To meet these needs, a highly symmetric quad-beam is chosen. First, the mechanical behavior of the device is discussed. The schematic diagram of the structure is shown in Figure 1. The structure consists of a seismic mass and four beams suspending the seismic mass. When the seismic mass is accelerated vertically (Figure 1*(b)*), it translates down along *z*-axis and the suspending beams are bent symmetrically, causing symmetrical stress distribution on the beams. When the seismic mass is accelerated laterally (*x*-axis), it rotates along *y*-axis (Figure 1*(c)*). Consequently, it produces anti-symmetrical stress distribution on lateral beams.

For capacitive triaxial accelerometer, the position change of the seismic mass caused by acceleration is detected by capacitors. Three pairs of capacitors (Figure 2) are used to sense three axis accelerations separately.

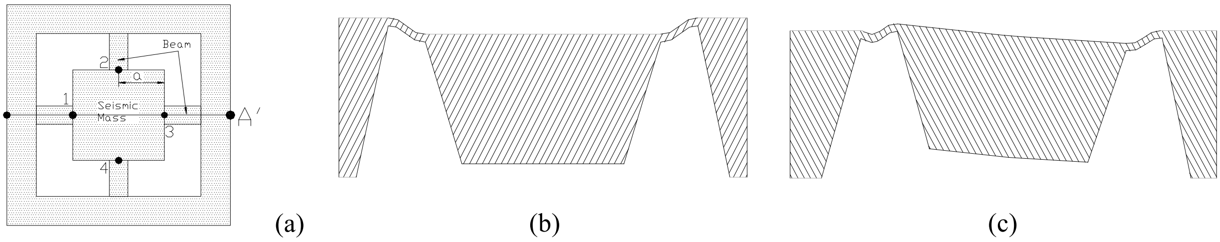

Fig. 1: *The schematic drawing of the structure: (a) Top view; (b) Vertical and (c) Lateral acceleration applied.*

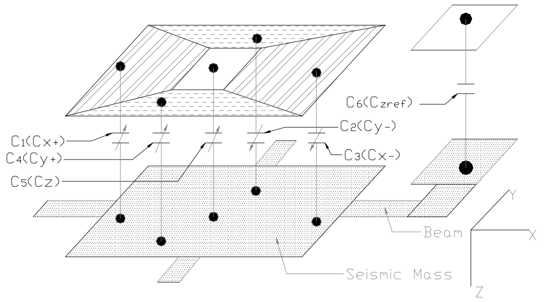

Fig. 2: *The distribution of capacitors.*

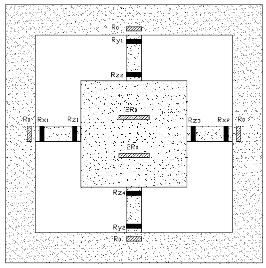

Fig.3: *Distribution and location of piezoresistors.*

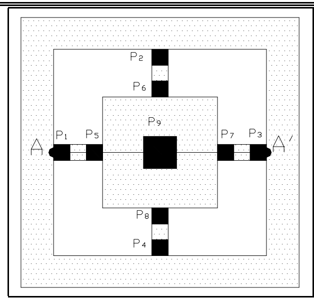

Fig. 5: *Distribution and location of piezoelectric cells.*

Six capacitors have one common plate on the top surface of seismic mass. Capacitors C_1~C_5 are variable with an acceleration, while C_6 is a reference one and has a constant value, which is half the value of C_1~C_4 but has the same value as C_5. Capacitors C_1 and C_3, C_2 and C_4, C_5 and C_6 are used to sense *x*-, *y*- and *z*-axis acceleration, respectively. The capacitance changes at different accelerations are summarized in Table 1.

For piezoresistive triaxial accelerometer, the stress changes of the beams, caused by acceleration, are detected by piezoresistors. Fourteen piezoresistors (Figure 3) form three Wheatstone bridges to sense three-axis acceleration respectively. Piezoresistors R_{x1} and R_{x2}, R_{y1} and R_{y2}, R_{z1}~R_{z4} are used to detect *x*-, *y*- and *z*-axis acceleration, respectively. Several resistors, such as R_0 and $2R_0$, have constant values, used to form Wheatstone bridge with other piezoresistors. The change of every piezoresistor at different accelerations is illustrated in Figure 4.

In similar way, the stress changes of the beams can also be detected by the piezoelectric cells. In piezoelectric triaxial accelerometer, nine piezoelectric cells (Figure 5) are used to sense three axis accelerations separately. A piezoelectric cell is taken as a piezoelectric capacitor equivalently. The bottom surfaces of all piezoelectric cells are connected together, as shown in Figure 6. C_1~C_9 are corresponded to the capacitance of piezoelectric cells P_1~P_9, respectively. C_1~C_8 have the same capacitance value C_0, while $C_9=4C_0$. C_9 is an unstrained compensatory capacitor, used to cancel the pyroelectric common mode signal. P_1 and P_3, P_2 and P_4, P_5~P_9 are used to sense *x*-, *y*- and *z*-axis acceleration respectively. The behavior of electric charge change at different accelerations is summarized in Table 2.

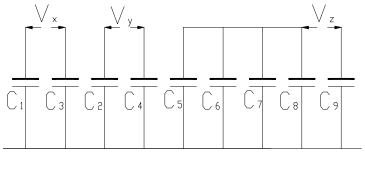

Fig.6*: Equivalent circuit for piezo -electric triaxial accelerometer.*

Table 1: *Capacitance change at different direction accelerations.*

	C_1	C_2	C_3	C_4	C_5	ΔC_{13}	ΔC_{24}	ΔC_{56}
x-axis	–	0	+	0	0	$2\Delta C_1$	0	0
y-axis	0	+	0	–	0	0	$2\Delta C_4$	0
z-axis	–	–	–	–	–	0	0	ΔC_5

Table 2: Electric charge change at different direction accelerations.

	Q_1	Q_2	Q_3	Q_4	Q_5	Q_6	Q_7	Q_8	Q_9	V_x	V_y	V_z
x-axis	–	0	+	0	+	0	–	0	0	$2Q_1/C_0$	0	0
y-axis	0	+	0	–	0	–	0	+	0	0	$2Q_2/C_0$	0
z-axis	–	–	–	–	+	+	+	+	0	0	0	Q_5/C_0

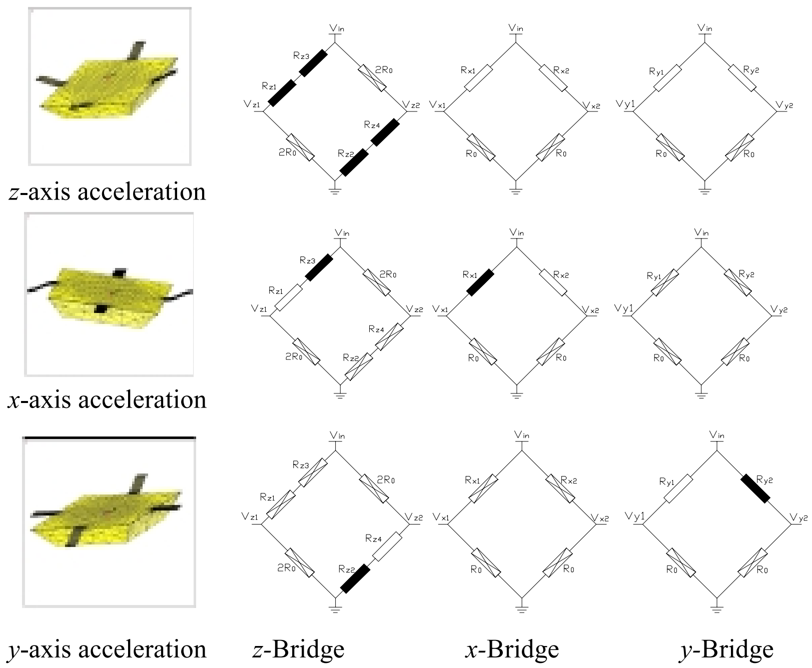

Fig. 4: *Displacement plots for the three perpendicular accelerations and their effects on the z-, x- and y- Wheatstone bridges. Black resistors increase, white ones decrease and crossed ones change little or don't change.*

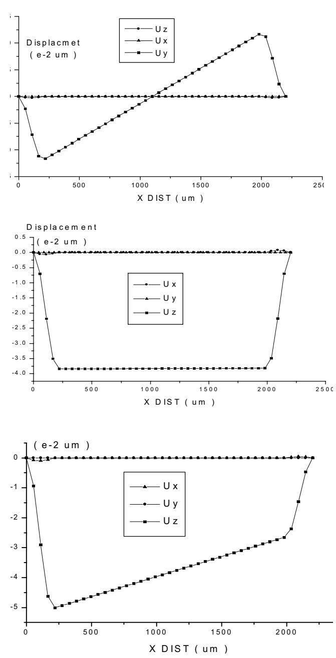

Fig. 7: *Displacement of each point on path AA'* (Figure 1 (a)) *in 1g (a) x-axis, (b) z-axis, and (c) x- and z-axis acceleration.*

FEM SIMULATION

The devices are simulated using finite element method (FEM) simulation program ANSYS 5.4. The modal and static analyses are very essential for device design. The calculated and simulated resonance frequencies are listed in Table 3. Where w, l, h and $a\times a$ are beam width, length, thickness and top surface area of the seismic mass, whose unit is μm. The thickness of all seismic mass is all 400 μm.

Table 3: Comparisons of the theoretical and ANSYS simulation resonance frequencies.

Resonance frequency (Hz)	Capacitive w, l, h, a=200, 50, 5, 1800		Piezoresistive w, l, h, a=500, 200, 10, 2000		Piezoelectric w, l, h, a=300, 100, 5, 1500	
	Theory	ANSYS	Theory	ANSYS	Theory	ANSYS
1st mode	2492	2519	3155	3166	2384	2444
2nd mode	3555	3594	5113	5162	3635	3744
3rd mode	3555	3595	5113	5168	3635	3745

Table 4: *The voltage of each Wheatstone bridge in the different accelerations (Voltage unit is mV).*

	V_x	V_y	V_z
$a_z=1g$	-1.12e-04	9.72e-05	2.60
$a_x=1g$	-3.07e-01	9.66e-06	1.53e-04
$a_z=a_x=1g$	-3.07e-01	1.07e-04	2.60

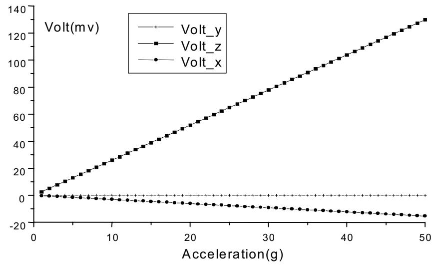

Fig.8: *The linearity of the device, applied on z- and x-axis accelerations from 1g to 50g.*

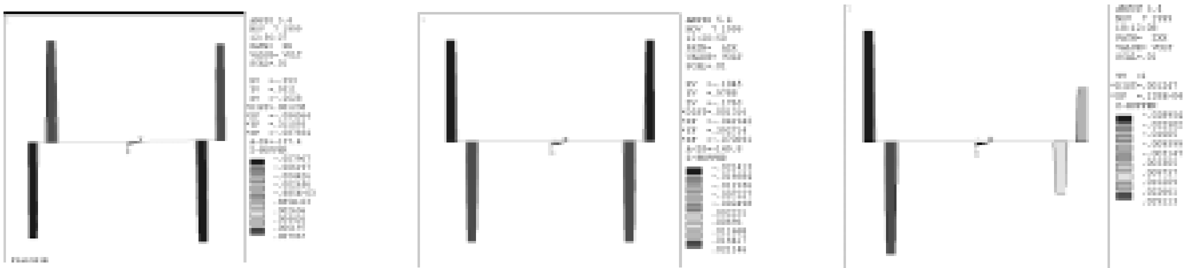

Fig. 9: *Voltage distribution on path AA'* (Figure 5) *in 1g (a) x-axis, (b) z-axis, (c) both x- and z-axis acceleration.*

For capacitive triaxial accelerometer, Figure 7 shows the simulated displacements of the points on the path *AA'* (Figure 1 (a)), when a vector acceleration is applied on the seismic mass. From Figure 7, it is obtained that the results of the static simulation of the device accord our thought well and the device has sensitivities about 7.66 *fF/g*, 6.08 *fF/g* in *z-* and *x*-axis. Near zero cross-axis sensitivity can also be gained.

For piezoresistive triaxial accelerometer, the stress calculated by ANSYS is used to compute the piezoresistive sensitivities of the device. The output voltage of each Wheatstone bridge in different direction accelerations is summarized in Table 4. From Table 4, we know the device has sensitivities about *2.60mv/g*, *0.31mv/g*, *0.31mv/g* in *z-*, *x-* and *y*-axis, respectively. Besides, the device has near zero cross-axis sensitivity.

For piezoelectric triaxial accelerometer, using multi-physics coupling analysis, the simulated results of the voltage distribution on the path *AA'* (Figure 5) are obtained in Figure 9, when a vector acceleration is applied on the seismic mass. From Figure 9, it is obvious that the device has sensitivities about 21 *mV/g*, 15 *mV/g* in *z-* and *x*-axis respectively. Near zero cross-axis sensitivity can also be gained.

CONCLUSION

In this paper, the capacitive, piezoresistive and piezoelectric triaxial accelerometers, which all are based on the same highly symmetrical quad-beam structure are designed and simulated using FEM program ANSYS. All devices are predicted to have near zero cross-axis sensitivity, good linearity and high sensitivity theoretically and numerically.

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