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Design and System Modeling of a Tri-Axial Microaccelerometer Using Piezoelectric Thin Films

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This study presents the system modeling of a tri-axial microaccelerometer that consists of a quadri-beam suspension, a seismic mass, and displacement transducers using piezoelectric thin films. Both ends of the seismic mass are supported by two suspension beams. Therefore, the out-of-plane acceleration will result in a symmetric bend, and in-plane accelerations will produce asymmetric bend and torsion. The electrodes are configured and interconnected to measure one out-of-plane acceleration and two in-plane accelerations selectively. Resonant frequency and sensor sensitivities to triaxial acceleration are investigated using FEM analysis. Sensitivity study of major dimensional parameters are presented for sensor design.

Keywords*:* Microsensor, Piezoelectric Accelerometer, Tri-axial, Thin film

Introduction

Microaccelerometers have been successfully applied in automotive industry such as control of airbags and suspension systems and interactive entertainment electronics. Potential markets also exist in the areas of biomechanics and aerospace technology. Piezoelectric accelerometers have the advantages of easy integration with existing measuring systems. Due to the excellent dynamic performance and linearity, they have been widely used in condition monitoring systems to measure machinery vibration.

Two types of piezoelectric micro-accelerometers are reported based on fabrication approaches. Surface micromachining based piezoelectric accelerometers are more cost effective due to its relatively simple fabrication [1]. On the other hand, bulk micromachining based piezoelectric accelerometers have a lower detection level that is suitable for precision measurement [2].

Van Kampen and Woffenbuttel analyzed multiple-supported beam structures and modeled the mechanical behavior of bulk-micromachined silicon accelerometers using a static mechanics analytical technique [3]. Yu and Lan used a simplified spring-mass system to represent a z-axial micro-accelerometer with piezoelectric thin film sensing [4]. Some takes into account both the substrate and PZT thin film in elastic properties of suspension beams by use of laminated plate theory [5][7]. Several design of tri-axial

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piezoelectric microaccelerometer have been reported [6][7]. Theoretical models agree well with FEM analysis. However, all the literatures neglect mass and elastic effects of patterned electrodes because of complexity. FEM analysis seems an effective tool for sensor design.

Design of Microaccelerometer

The proposed microaccelerometer consists of a quadri-beam suspension, a seismic mass, and eight piezoelectric displacement transducers arranged as shown in Figure 1. The device is fabricated from wet etching of <100> SOI silicon and dry etching of suspension beams. Both ends of the seismic mass are supported by two suspension beams. Two transducers are designed on each suspension as arranged in Figure 1 such that the discontinuous regions at both ends and low stress region at the middle of the beam are neglected.

The out-of-plane (z axial) acceleration will result in a symmetric vibration, and in-plane (x and y axial) accelerations will produce asymmetric and torsional vibrations. The inertia force will introduce bending and torsional stress on the beams that will produce electrical charge by the piezoelectric transducers. The electrodes are configured and interconnected as in Table 1 so the out-of-plane acceleration and in-plane accelerations can be selectively measured. For instance, the out-of-plane acceleration will bend the beams as shown in Figure 2(a) where the inward transducers (close to seismic mass) and the outward transducers are subject to stresses of different directions. The charge collected from transducers 1, 4, 5 and 8 minus the charge collected from transducers 2, 3, 6 and 7 will be in proportional to the out-of-plane acceleration while the effects due to in-plan accelerations will be cancelled out. This design not only increases transducer sensitivities, but also reduces noise effects.

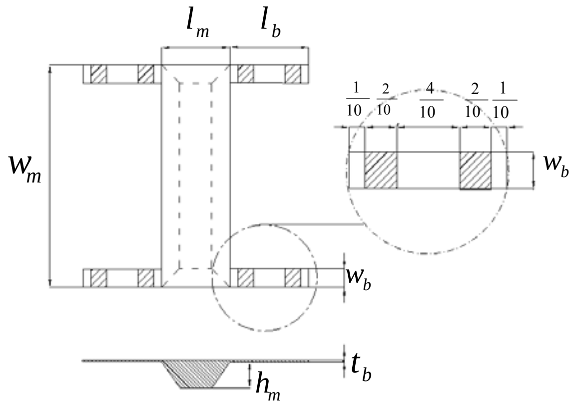
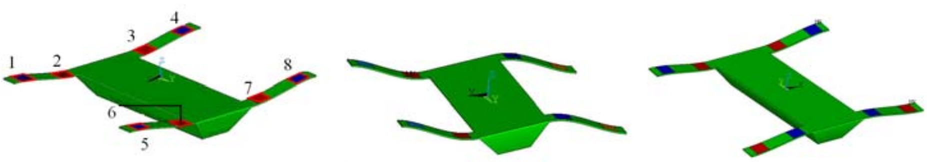


Figure 1. Schematic view of the piezoelectric micro-accelerometer



(a) Symmetric bend (z-axial) (b) Asymmetric bend (x-axial) (c) Torsional (y-axial)

Figure 2. Three basic vibration modes of the accelerometer due to tri-axial acceleration

Table 1. Arrangement of electrodes for tri-axial acceleration sensing

Symmetric	PZT(1+4+5+8) - PZT(2+3+6+7)
Asymmetric	PZT(2+4+6+8) - PZT (1+3+5+7)
Torsional	PZT(1+6+4+7) - PZT (2+5+3+8)

Structure Modeling

The complete system of the sensor can be divided into a mechanical subsystem and an electric subsystem. The performance of the mechanical subsystem is determined by the equivalent stiffness of the suspension and the seismic mass, while the electric subsystem is determined by the piezoelectric transducers [4]. The bandwidth of the accelerometer is constrained by the resonance frequency.

Resonance frequency $$\omega_n = \sqrt{\frac{K}{M}} \quad (1)$$

Mechanical sensitivity $$S_m \equiv \frac{M}{K} \quad (2)$$

where K is the structure stiffness and M is the seismic mass.

This study applies energy method - Castigliano's second theorem to derive structure stiffness. Differential of structure strain energy to a given load provides the displacement at the direction of the given load. For the instance of symmetric motion, the derived stiffness is

$$K_{symmetric} = \frac{48EI_z}{l_b^3} \quad (3)$$

where I_z is the moment of inertia of suspension beam $I_Z = \frac{w_b t_b^3}{12}$

Neglecting the imperfection of convex corner compensation, a simple integration of the structure will give the mass:

$$M = \rho \cdot \left[l_m w_m h_m - h_m{}^2 (l_m + w_m) \cot\theta + \frac{4}{3} h_m{}^3 \cot^2\theta \right] + \rho \cdot l_m w_m t_b \quad (4)$$

where ρ is the density of Silicon and $\theta = 54.7°$ for <100> silicon.

The mechanical sensitivity is as follows:

$$S_{symmetric} = \frac{M}{K_{\text{symmetric}}} = \frac{l_b^3 M}{12EI_z} \quad (5)$$

For a sample dimensional design as in Table 2, the derived resonance frequency of symmetric motion is 3295 Hz that is close to a FEM result of 3202 Hz.

Table 2. Initial dimensions of the micro-accelerometer (unit: μm)

l_b	w_b	t_b	l_m	w_m	h_m
1500	350	30	1300	4200	490

Finite Element Simulation

The maximum loading of the sensor without structure failure is 15*g*. To verify the configuration of the electrodes, four different loads are applied including unit acceleration at three principal directions and a tri-axial acceleration. The FEM results are shown as Table 3. The material properties can be found in previous literature [4]. The result shows that even a triaxial acceleration is applied to the sensor; the sensor can detect and provide the same results as uniaxial acceleration using the interconnection layout of Table 1.

Table 3. Sensitivity comparisons of uni-axial acceleration and tri-axial acceleration (unit: mV)

	$1\ddot{\vec{x}}$	$1\ddot{\vec{y}}$	$1\ddot{\vec{z}}$	$1\ddot{\vec{x}}+1\ddot{\vec{y}}+1\ddot{\vec{z}}$
Symmetric	0	0	7.54	7.54
Torsional	0	0.72	0	0.72
Asymmetric	0.99	0	0	0.99

The frequency response of the device is shown in Figure 3. The upper limit of bandwidth is about $\omega_n/5$. Since the resonance frequency of the symmetric motion is the lowest among three motions, the bandwidth of the microaccelerometer will be constrained by the bandwidth of symmetric motion. Also, Figure 3 shows that the sensitivity ratio between symmetric and torsional motions is about 10:1. Parameter designs should be introduced to close up the gap.

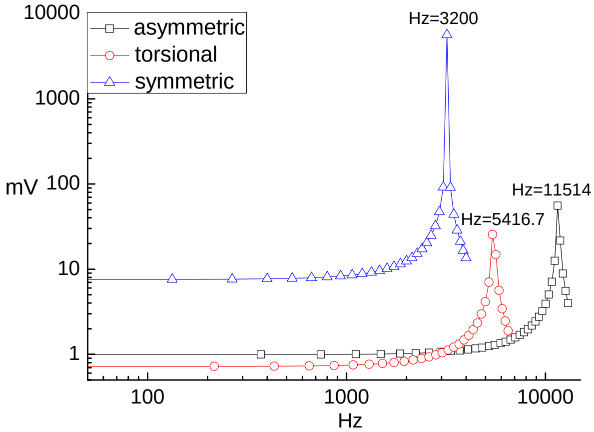
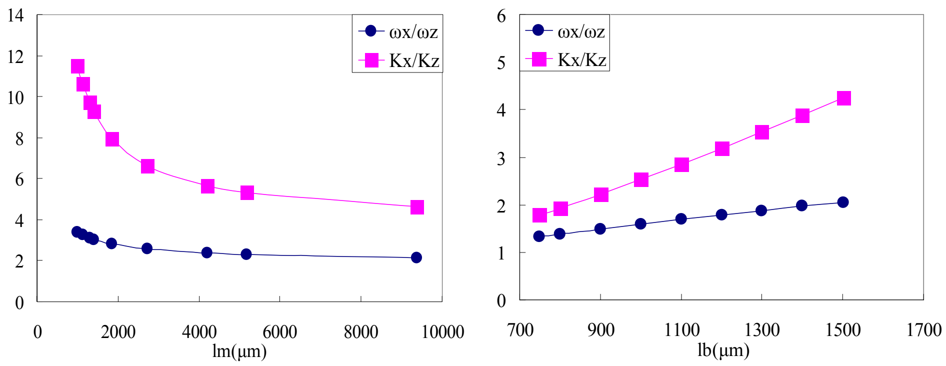


Figure 3. Frequency response of the accelerometer in triaxial acceleration

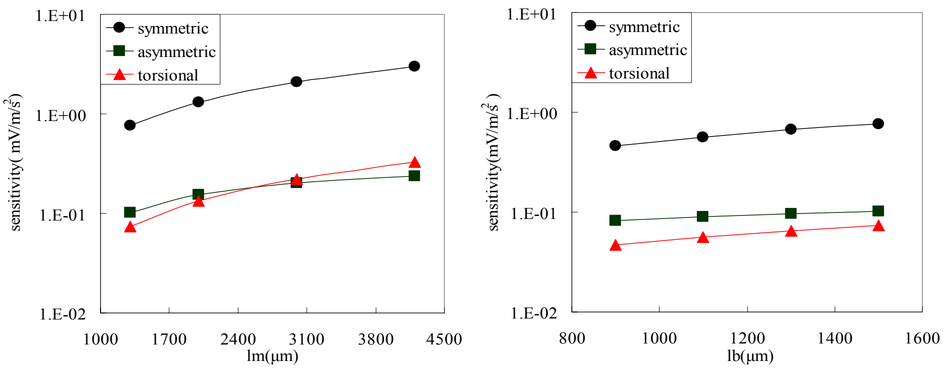
The study derives the sensitivities of ω_x/ω_z and K_x/K_z versus the length of seismic mass (l_m) and the length of suspension beams (l_b) as shown in Figure 4 using analytical model. The sensitivity of symmetric motion is higher than asymmetric motion. A shorter beam and a larger mass will reduce the mechanical sensitivity difference. However, a shorter beam will reduce the size of piezoelectric transducer and thus the electric sensitivity.

The effects of the length of suspension beam and mass on the overall sensor sensitivities are simulated using ANSYS. As shown in Figure 5, the sensor sensitivity ratio between torsional and symmetric motions are insensitive to the change of the length of seismic mass and suspension beams, while the relative torsional sensitivity increases with the increasing of the length of seismic mass. Given a bandwidth requirement, dimension optimization can be performed to increase sensitivities and reduce the sensitivity difference among three axes.



(a) (b)

Figure 4. Resonance frequency ratio ω_x/ω_z and stiffness ratio K_x/K_z versus the length of seismic mass (l_m) and the length of suspension beams (l_b)



(a) (b)

Figure 5. Sensor sensitivities versus the length of seismic mass (l_m) and the length of suspension beams (l_b)

Conclusion

A tri-axial piezoelectric microaccelerometer is investigated and the interconnection layout of transducers is presented. The proposed design can selectively measure triaxial acceleration. The performances in three axes are analyzed using FEM analysis. Differences of triaxial sensitivities are noted. Discussions of sensor performance tradeoff versus sensor parameters are presented. The result demonstrates the feasibility of sensor design, and future direction for design optimization is prompted.

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