MEMS Pressure Sensor With Two Thin Film Piezoelectric Read-Out

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ABSTRACT

MEMS accelerometers using piezoelectric lead zirconate titanate (PZT) thin films as read-out have been attracting a great deal of attention due to their simple structures and high sensitivity. This paper proposes a model of micro pressure sensor with two suspended flexural PZT-on-silicon beams. The geometry and elastic properties of the thin films have been taken into account when formulating the acceleration equations. To verify which vibration mode is the dominant one on the press, mode analysis has been carried out by using MEMS software: CoventorWare. The analytical equation between charge and press has been derived, which provides an opportunity to design the sensor. The research shows that the proposed pressure sensor is simple to manufacturing, and reliable for large g conditions and wide frequency response.

Keywords: Piezoelectric pressure sensor; MEMS; Sensitivity; Lead zirconate titanate (PZT) thin film

1 INTRODUCTION

The piezoelectric lead zirconate titanate (PZT) can produce a charge when it is loaded, and it will deform when it is charged. The charge produced by direct piezoelectric response is proportional to the rate of performance or acceleration. This character is the basis for measuring acceleration using electrical signal. Once an electrical signal is produced, the acceleration can be decided through collection and analysis of the signal. Because of the simple theory used, the circuit is relatively simple, has a small volume, can be easily integrated and has wide frequency range. All of these characteristics cause the PZT to be used more and more[1]-[4].

There are researches that focus on PZT thin film accelerometer design [5], manufacture [6], measurements [7], as well as framework analysis. For example, reference [8] analyzed vibration and electromechanical sensitivity of micro-sensor with four PZT thin films; reference [9] analyzed various arrangements of deformable sensors using the finite element theory; reference [10] introduced the design of accelerometer; reference [11] made the mechanical analysis of four PZT thin films sensor by determining the effects of the dimensions and the elastic characteristics of the thin films.

We propose the structure to have only two pares of PZT thin films on the basis of [11]. This causes the structure to become simpler and easier to fabricate. And except its first vibration mode that is also the base mode, the other modes have no effect on the acceleration measurement. So it can be a better choice for the measurement of acceleration and it can have a huge potential as a micro-sensor.

2 STRUCTURE OF TWO PZT THIN FILMS PRESSURE SENSOR

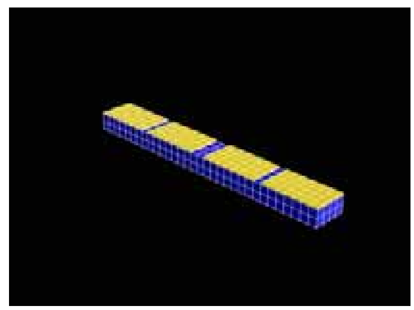

Fig.1 Pressure sensor with two thin film 3-D model

To avoid noise in the structure, PZT thin film is built up with two transducer parts and the whole structure will be

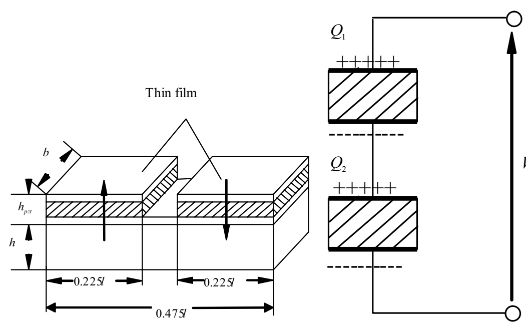

Fig.2 The structure and equivalent circuit of series configuration

measured with four PZT transducers (two for each part), Fig.1. At the same side of beam, the two PZT thin films have opposite polarization. Because the beam will vibrate and deform with the load effect, the PZT thin film will create a charge. The two PZT thin films on the same side of beam are connected in series.

In the series configuration, two PZT thin film transducers connect through lower electrodes and the output terminals are made through the upper electrodes, as shown in Fig.2(a). When the two opposite direction stresses caused by the bending of the beam act on each of the two thin films, the two PZT thin films become two power supplies, which connect in series. This is shown in Fig.2(b).

3 MODE ANALYSIS

There can be two types of load on the beam: changeless and changeable load. When there is only changeless load, the noise will not appear. The mode is shown as Fig.4. The mode analysis was done to determine the mode that affects the pressure, and this will be the base mode. Then the output charge created through the base mode can reflect the pressure along the direction of the base mode. In this paper, all the analyses were done using CoventorWare 2004, and the first six modes are shown Fig.3.

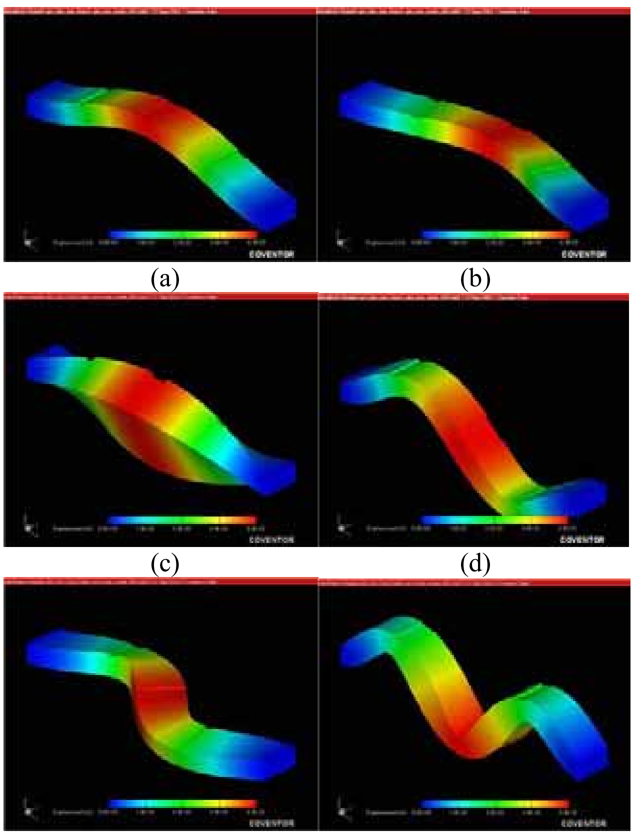

Fig.3 The mode caused by changeable pressure

As the figures show, in the second mode (Fig.3(b)) and the sixth mode (Fig.3(f)), the two beams did not bend, so there is no charge. In the fourth (Fig.3(d)) and the fifth (Fig.3(e)) mode, the two transducers of each beam exhibit symmetric bending. So the charge produced in the two transducers located on the two parts have equal value and opposite polarity, so the whole structure has no charge. In the third mode (Fig.3(c)), the two beams (transducer parts) have symmetric deformation. So the two beams output the same value, with opposite polarity charges. For the whole structure, the charge output cannot be detected. In the first mode (Fig.3(a)), which is the base vibration mode, the charge output can be detected and the vibration direction is consistent with the pressure which needs to be measured.

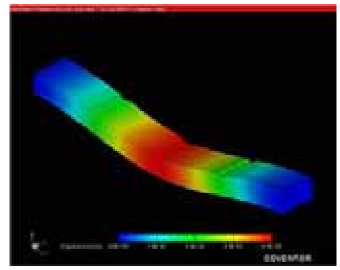

Fig.4 The deformation caused by changeless pressure

From Fig.4, the deformation is only and is same to the base mode of vibration.

So this structure can be used to measure the acceleration quiet accurately in one direction.

4 PRESSURE SENSOR EQUATIONS

The structure is a simple beam fixed on two ends, and the performance is shown in Fig.5.

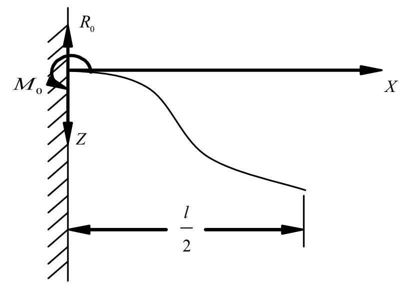

Fig. 5 The deformation of the beam

4.1 Assumption

The following assumptions are made in the model of this paper:

1) Compared with the mass of the beam, the mass of PZT thin films are too small they can be ignored;
2) The central seismic mass and rim of the whole structure are rigid;
3) PZT thin films and beams are elastic and they obey Hooke's law;
4) The material of PZT transducer is orthotropic;
5) With the central seismic mass only subjected to vertical acceleration and pure bending deformation originated in the beams, the strains in 2-direction and the stress in the 3-direction can

be ignored compared with the other strains and stresses. The directions are defined as Fig.6.

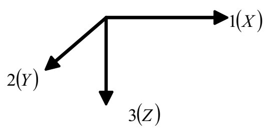

Fig. 6 Direction of the coordination

4.2 Formulation of pressure equations

According to assumption 5:

$$\sigma_3 = \sigma_5 = \sigma_6 = 0 \tag{1}$$

and

$$\varepsilon_2 = \varepsilon_4 = \varepsilon_6 = 0 \tag{2}$$

Commonly the strains in each direction are always expressed with the following symbols:

$$(\sigma_1 \quad \sigma_2 \quad \sigma_3 \quad \sigma_4 \quad \sigma_5 \quad \sigma_6)^T = (\sigma_{xx} \quad \sigma_{yy} \quad \sigma_{zz} \quad \sigma_{yx} \quad \sigma_{xz} \quad \sigma_{xy})^T$$

When the pressure is induced on the beam, it follows that the force equilibrium along three directions should be given by the following reaction force:

$$R_0 = \frac{1}{2} m\ddot{z} \tag{3}$$

where m is beam mass.

From the boundary conditions, we have the moment:

$$M(x) = \frac{1}{2} P\left(\frac{l}{4} - x\right) \tag{4}$$

where l is the length of the beam.

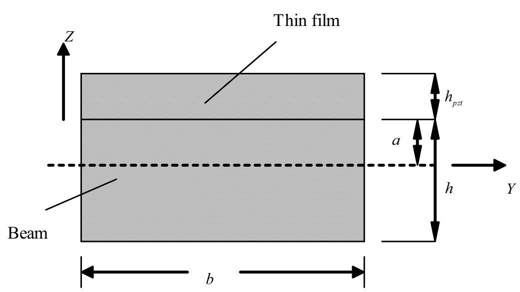

Fig. 7 Corss-section of the beam

Fig.7 is a cross-section of the beam. Assuming there is a perfect bond between the PZT thin films and the beam, the strain can be given by:

$$\varepsilon_1 = \frac{z}{\rho} \tag{5}$$

where ρ is the radius of bending.

From constitutive equations and based on assumption 4, the stress of the PZT thin film is defined as follow:

$$\sigma_3 = C_{31}\varepsilon_1 + C_{32}\varepsilon_2 + C_{33}\varepsilon_3 \tag{6}$$

Substituting Eqs.(1) and (2) into Eq.(6), we have:

$$\varepsilon_3 = -(C_{31}/C_{33})\varepsilon_1 \tag{7}$$

The stress of the PZT thin film σ_1 can be written as:

$$\sigma_1 = (C_{11} - C_{31}C_{13}/C_{33})\varepsilon_1 = E_p\varepsilon_1 \tag{8}$$

We consider the material of the beam to be anisotropic, then the stress on beam $\bar{\sigma}_1$ can be written as:

$$\bar{\sigma}_1 = \left[E_2/(1-\mu^2)\right]\bar{\varepsilon}_1 = E_B\bar{\varepsilon}_1 \tag{9}$$

where $\bar{\varepsilon}_1$ is the strain on the beam, E_2 and μ are Young's Modulus and Poisson's ratio of the beam, respectively.

For the cross-section shown in Fig.11, we have the following result from force equilibrium in one-direction:

$$\int_{-(h-a)}^{a} bE_B(z/\rho)dz + \int_{a}^{h_{pzt}+a} bE_P(z/\rho)dz = 0 \tag{10}$$

$$\int_{-(h-a)}^{a} bE_B(z/\rho)zdz + \int_{a}^{h_{pzt}+a} bE_P(z/\rho)zdz = M(x) \tag{11}$$

where a is the distance to the neutral axis of the beam measured from the interface, b is the width of the beam, h is the thickness of the beam, h_{pzt} is the thickness of the PZT thin film, and $M(x)$ is the moment on the cross-section.

From Eq.(10):

$$a = \left[(h^2E_B - h_{pzt}^2E_P)/(2hE_B + 2h_{pzt}E_P)\right] \tag{12}$$

From Eq.(11):

$$\begin{aligned}\rho M(x) &= 1/3\left[bE_B(h^3 - 3h^2a + 3ha^2)\right] \\ &+ 1/3\left[bE_P(h_{pzt}^3 + 3h_{pzt}^2a + 3h_{pzt}a^2)\right] \\ &= EI_{eq}\end{aligned} \tag{13}$$

Substituting Eqs.(5),(12),(13) into Eq.(8), the average stress in the PZT thin film can be found:

$$\sigma_1 = E_P\varepsilon_1 = (E_PM(x)/EI_{eq})(h_{pzt}/2 + a) \tag{14}$$

Assuming all the stresses are caused by bending, the contribution from any infinitesimal portion to the total charge is shown as follow:

$$D_3 = d_{31}\sigma_1 \tag{15}$$

where d_{31} is the piezoelectric coefficient.

Substituting Eq.(14) into the integration of Eq.(15), we can find the total charge output of PZT thin film over one suspending beam:

$$Q_S = 2\left(\int_0^{0.225l} D_{31} b dx - \int_{0.25l}^{0.475l} D_{31} b dx \right) \\ = 0.05625 d_{31} b \left(E_P / EI_{eq} \right) \left(h_{pzt} / 2 + a \right) l^2 P \tag{16}$$

From Eqs.(16), we can see that there is a linear relationship between the pressure P and the total charge Q, and the equations include piezoelectric coefficient d_{31}, elastic coefficient E_P, width b, thickness h for the thin film, and length l and elastic coefficient E_B for the beam. So we can adjust any of these parameters to increase the charge output.

4.3 Sensitivity analysis

The sensitivity can be obtained:

$$S_V^S = Q_S / PC_S \\ = 0.05625 d_{31} b \left(E_P / EI_{eq} \right) \left(h_{pzt} / 2 + a \right) l^2 / C_S \tag{17}$$

From the equation, sensitivity is the voltage produced by one unit of voltage reflected on the PZT thin film. The sensitivity is a direct ratio with the total charge output and inverse ratio with the capacitance of PZT thin film. Similar to the pressure equations, the sensitivity equations include piezoelectric coefficient d_{31}, width b, thickness h, elastic coefficient E_P of PZT thin film, and length l and elastic coefficient E_B of the suspending beam. So, we can adjust some of these to increase the sensitivity.

5 RESULTS

In this paper, we can get the following results through numerical and analytical analysis:

1) For all the structures that are identical or similar to the structure used in this paper, can use to measure the unidirectional pressure.
2) For all the structures that are identical or similar to the structure used in this paper, all modes, except the first one, do not affect the measurement of the unidirectional changeable pressure.
3) Following the sensor equation and sensitivity equation, we can adjust the demission and material characters to obtain the best result of measurement

The PZT thin film pressure sensor has a lot of applications, such as used as microphone of cell phone.

REFERENCES

[1] K. Kunz, P. Enoksson, G. Stemme, Highly sensitive triaxial silicon accelerometer with integrated PZT thin film detectors, Sens. Actuators A 92 (2001) 156–160.

[2] S.P. Beeby, N.J. Grabham, N.M. White, Microprocessor implemented self-validation of thick-film PZT/silicon accelerometer, Sens. Actuators A 92 (2001) 168–174.

[3] V.K. Varadan, V.V. Varadan, H. Subramanian, Fabrication, Sens. Actuators A 90 (2001) 7–19.

[4] D. Crescini, D. Marioli, E. Sardini, A. Taroni, Large bandwidth and thermal compensated piezoelectric thick-film acceleration transducer, Sens. Actuators A 87 (2001) 131–138.

[5] Y. Nemirovsky, A. Nemirovsky, P. Muralt, N. Setter, Design of a novel thin-film piezoelectric accelerometer, Sens. Actuators A 56 (1996) 239–249.

[6] H.G. Yu, L. Zou, K. Deng, R. Wolf, S. Tadigadapa, S. Trolier- McKinstry, Lead zirconate titanate MEMS accelerometer using interdigitated electrodes, Sens. Actuators A 107 (2003) 26–35.

[7] A. Spineanu, P. Bénabès, R. Kielbasa, A digital piezoelectric accelerometer with sigma–delta servo technique, Sens. Actuators A 60 (1997) 127–133.

[8] D. Eicher, M. Giousouf, W. von Munch, Measurement on micromachined silicon accelerometers with piezoelectric sensor action, Sens. Actuators A 75 (1999) 247–252.

[9] L. Ries, W. Smith, Finite element analysis of a deformable array transducer, IEEE Trans. Ultrason. Ferroelectr. Freq. Contr. 46 (1999) 1352–1363.

[10] J. Yu, C. Lan, System modeling of microaccelerometer using piezoelectric thin films, Sens. Actuators A 88 (2001) 178–186.

[11] Qing-Ming Wang, Zhaochun Yang, Fang Li, Patrick Smolinski, Analysis of thin film piezoelectric microaccelerometer using analytical and finite element modeling, Sens. Actuators A 113 (2004)1-11.