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Research on 1-3 Orthogonal Anisotropic Piezoelectric Composite Material Sensors*

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Abstract: Piezoelectric composite material (PCM) is an important branch of modern sensor and actuator materials with wide applications in smart structures. In this paper, based on piezoelectric ceramic, composite and experimental mechanics theories, a kind of 1-3 orthogonal anisotropic PCM (OAPCM) sensor is developed, and the sensing principle is analyzed to describe sensor behaviors. In order to determine strain and stress on isotropic or orthogonal anisotropic component surface, the relationships between strain and stress are established. The experimental research on 1-3 OAPCM sensor is carried out in uniaxial and biaxial stress states. The results show that 1-3 OAPCM sensors offer orthotropic properties of piezoelectricity, and sensing equations can be used for strain or stress measurement with good accuracy.

Key words: 1-3 PCM, orthogonal anisotropic, sensor, strain-stress relationship

Smart materials and structures with integrated sensors, actuators, processing units and controllers offer completely new possibilities in the design of mechanical structures. The combination of piezoceramic with polymer matrix is one of the most promising approaches to reach multifunctionality or intelligence.

Piezoceramic elements have been widely used as sensors or actuators in smart structures in variety of aerospace applications including structural health monitoring, aeroelastic control of fixed or rotary wing aircraft, vibration and noise active control. Piezoceramics offer advantages of higher frequency response, broad frequency bandwidth, higher sensitivity and stability. However, their applications are limited because of the disadvantages, including low values for the piezoelectric voltage coefficients, brittle, non-flexible and smaller ultimate strain. To look for an entirely new class of piezoelectric materials without the above limitations, in the last two decades, researchers have successfully developed piezoelectric composite material (PCM), a new kind of functional material for sensors or actuators[1]. Combining two or more distinct constituents, PCM can take the advantages of each constituent and have superior electromechanical coupling characteristics in comparison with homogeneous piezoceramics. PCM has been developed in many forms including piezoelectric inclusions embedded in a polymer matrix and polymer filled piezoelectric inclusions. The piezoelectric inclusions in the matrix can be continuous fibers, short fibers, or dispersed quasispherical particles. PCM sensors are characterized by better flexibility compliance, toughness, high-sensitivity, wide-frequency response, and better linearity. The most outstanding advantage of PCM is marked by excellent designability, in which the properties of the materials can be tailored by changing the connectivity of the phases, volume fraction of the ceramic, and the spatial distribution of the ceramic phase. PCM can be satisfied for special applications by coupling piezoelectric materials with polymer in certain integrative mode. These advances in material technology open the door for sensor designers since they have more choices and are no longer restricted to single construction and simple geometric shape. This can explain why PCM constitutes an important branch of the recently emerging technologies of modern materials.

1 Construction of 1-3 OAPCM Sensor

Piezoelectric materials possess the piezoelectric effects that occur in a number of single crystals, ceramics and polymers. The direct piezoelectric effect relates a change in the polarization to an applied stress, whereas the converse effect relates a

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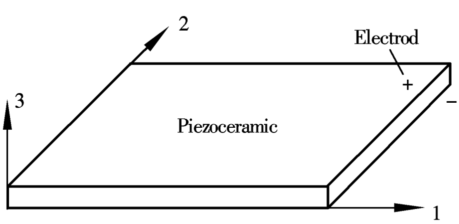
dimensional change to an applied electric field. Based on the direct piezoelectric effects, piezoelectric sensors, which convert mechanical energy to electrical energy, have found applications in various fields. Among all piezoelectric materials, lead zirconate titanate (PZT) has been most extensively used in sensors. PZT has high values for the piezoelectric charge coefficient, electromechanical coupling coefficient, dielectric coefficient, and low electrical losses. In common, the polarization direction of a piece of piezoceramic is generally defined as the direction 3. Therefore, the charge density is changed between two electrodes along the direction 3 when it is under plane strain state.

PCM is classified according to the connectivity. A particular sensor architecture is 1-3 PCM. 1-3 PCM consists of an array of parallel piezoceramic rods (which present a mechanical continuity following one dimension of the space) embedded in a polymer matrix (which presents a mechanical continuity following three dimensions of the space). Based on its directional sensitivity, 1-3 PCM can be made into orthogonal anisotropic PCM (OAPCM) sensors to meet the needs of strain or stress measurement in certain directions in smart structures or others. 1-3 PCM is fabricated by arranging small piezoceramic rods in parallel into the polymer matrix. In the 1-3 PCM, piezoceramic rods are poled in the axis x direction (shown in Fig.1), so this material offer the orthogonal anisotropic piezoelectricity because of the difference between the piezoelectric strain coefficient d_{33} and d_{31} or d_{32}($d_{31} = d_{32}$).



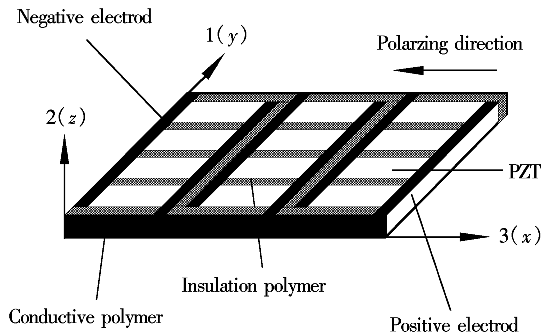


Fig. 1 A piece of piezoceramic and a 1-3 OAPCM sensor

When loaded, the matrix transmits strain to the piezoceramics rods. This strain is transformed into electrical polarization by the direct piezoelectric effect, producing a voltage difference between the electrodes. Therefore, strain distributions will be found out by the application of a voltage between the electrodes. Polymer matrix, piezoceramic volume fraction V_C and piezoceramic rod size are very important parameters to develop 1-3 OAPCM, and they affect the properties of OAPCM sensors. Fig.2 shows the relations between OAPCM piezoelectric strain coefficient d_{31} and d_{33}, voltage coefficient g_{31}, and stress coefficient e_{31} and V_C, respectively[2]. When V_C reaches 30% or above, g_{31} increases and is close to values of common piezoceramics. In addition, the coupling factor e and electric displacement output are directly proportional to the piezoelectric phase sizes along strain direction. Usually, V_C is between 30% – 60% and the ratio width to length of piezoceramic phase a/b is about 3. In this paper, the external dimensions of the 1-3 OAPCM sensor sample are 42.4 mm × 12.7 mm × 2 mm, the percentage of piezoceramic volume V_C is 50%.

2 Sensing Equations of 1-3 OAPCM Sensors

When a 1-3 OAPCM sensor (as shown in Fig.1) is adhered on a surface of isotropic material structure, without an external electric field, the electric displacement output D_x of the sensor is

$$D_x = e_{33}\varepsilon_x + e_{31}\varepsilon_y \tag{1}$$

where e_{33} and e_{31} mean stress coefficients of a 1-3 OAPCM sensor; ε_x and ε_y stand for the real strains along x and y direction, respectively. Similar to strain gauges, an OAPCM sensor is bounded on a calibration beam, and its sensitivity coefficient is K. Assuming $K_l = Ae_{33}$ to be the longitude sensitivity coefficient (the subscript "l" means longitude direction), and $K_t = Ae_{31}$ to be the transverse sensitivity coefficient (the subscript "t" means transverse direction), A is a coefficient related to a sensor form and amplifier properties. If in uniaxial stress condition, the relationship between D_x and ε_x is

$$AD_x = Ae_{33}\varepsilon_x + Ae_{31}\varepsilon_y = K_l\varepsilon_x + K_t\varepsilon_y = K_l(1 - \mu H)\varepsilon_x = K\varepsilon_x \tag{2}$$

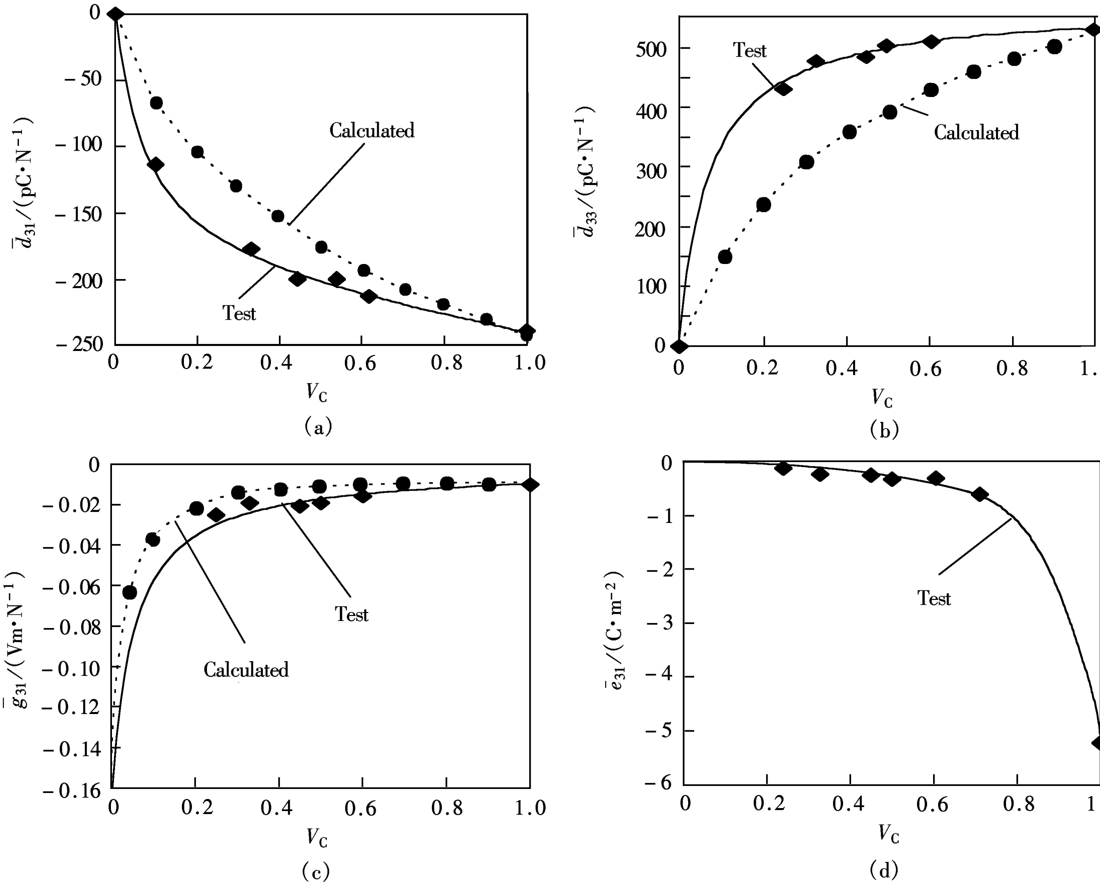


Fig.2 The relationship between 1-3 PCM parameters and V_C. (a) Piezoelectric strain coefficient $\bar{d}_{31}$ and V_C; (b) Piezoelectric strain coefficient $\bar{d}_{33}$ and V_C; (c) Voltage coefficient and V_C; (d) Stress coefficient and V_C

where μ is Poisson's ratio of the calibration beam; H is transverse effect coefficient of the sensor.

$$H = K_t / K_l = e_{31} / e_{33} \tag{3}$$

$$K = K_l(1 - \mu H) \tag{4}$$

For orthotropic component under unidirectional stress, the measured strain ε_x^m (superscript "m" means measurement value), is

$$\varepsilon_x^m = \frac{AD_x}{K} = \frac{K_l \varepsilon_x^{(x)} + K_t \varepsilon_y^{(x)}}{K} = \frac{(1 - \mu_{yx} H)}{(1 - \mu H)} \varepsilon_x^{(x)} \tag{5}$$

where the superscript "(x)" means that the component is under unidirectional stress along x direction. $\mu_{yx} = -\varepsilon_y^{(x)} / \varepsilon_x^{(x)}$ is the Poisson's ratio of the host material, and the two subscripts stand for the directions of deformation and a loading, respectively. From Eq. (5), the real strain $\varepsilon_x^{(x)}$ is deduced:

$$\varepsilon_x^{(x)} = \frac{(1 - \mu H)}{(1 - \mu_{yx} H)} \varepsilon_x^m \tag{6}$$

In plane stress state, OAPCM sensors are adhered as shown in Fig.3. Assuming $\varepsilon_{0°}^m$, $\varepsilon_{45°}^m$ and $\varepsilon_{90°}^m$ to be measured strains, ε_x, ε_y and γ_{xy} to be real strains and shearing strain, the questions can be obtained[3].

$$\left.\begin{aligned} \varepsilon_{0°}^m &= \frac{\varepsilon_x + H\varepsilon_y}{1 - \mu H} \\ \varepsilon_{90°}^m &= \frac{\varepsilon_y + H\varepsilon_x}{1 - \mu H} \\ \varepsilon_{45°}^m &= \frac{(1 + H)(\varepsilon_x + \varepsilon_y) + (1 - H)\gamma_{xy}}{2(1 - \mu H)} \end{aligned}\right\} \tag{7}$$

and

$$\left.\begin{aligned} \varepsilon_x &= \frac{(1 - \mu H)}{(1 - H^2)} \times (\varepsilon_{0°}^m - H\varepsilon_{90°}^m) \\ \varepsilon_y &= \frac{(1 - \mu H)}{(1 - H^2)} \times (\varepsilon_{90°}^m - H\varepsilon_{0°}^m) \\ \gamma_{xy} &= \frac{(1 - \mu H)}{(1 - H)} \times (2\varepsilon_{45°}^m - \varepsilon_{0°}^m - \varepsilon_{90°}^m) \end{aligned}\right\} \tag{8}$$

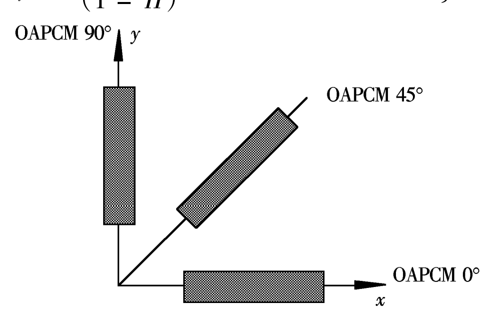


Fig.3 Arrangement of OAPCM

The relationships between stress and measured strain are described as follows:

$$\left.\begin{aligned}\sigma_x &= \frac{E_x(1-\mu_{xy}H)(1-\mu H)}{(1-\mu_{xy}\mu_{yx})(1-H^2)}\left(\varepsilon_{0^\circ}^{m}+\frac{\mu_{xy}-H}{1-\mu_{xy}H}\varepsilon_{90^\circ}^{m}\right)\\ \sigma_y &= \frac{E_y(1-\mu_{yx}H)(1-\mu H)}{(1-\mu_{xy}\mu_{yx})(1-H^2)}\left(\varepsilon_{90^\circ}^{m}+\frac{\mu_{yx}-H}{1-\mu_{yx}H}\varepsilon_{0^\circ}^{m}\right)\\ \tau_{xy} &= \frac{G_{xy}(1-\mu H)}{(1-H)}(2\varepsilon_{45^\circ}^{m}-\varepsilon_{0^\circ}^{m}-\varepsilon_{90^\circ}^{m})\end{aligned}\right\} \tag{9}$$

Eqs. (7), (8) and (9) can be used to determine strains and stresses in orthotropic material structures with OAPCM sensors.

If neglecting the traverse effect of OAPCM sensors, the equations for stress calculation can be written in

$$\left.\begin{aligned}\sigma_x^* &= \frac{E_x}{(1-\mu_{xy}\mu_{yx})}(\varepsilon_{0^\circ}^{m}+\mu_{xy}\varepsilon_{90^\circ}^{m})\\ \sigma_y^* &= \frac{E_y}{(1-\mu_{xy}\mu_{yx})}(\varepsilon_{90^\circ}^{m}+\mu_{yx}\varepsilon_{0^\circ}^{m})\\ \tau_{xy}^* &= G_{xy}(2\varepsilon_{45^\circ}^{m}-\varepsilon_{0^\circ}^{m}-\varepsilon_{90^\circ}^{m})\end{aligned}\right\} \tag{10}$$

Then, the errors are

$$\left.\begin{aligned}\delta\sigma_x &= \frac{(\sigma_x^*-\sigma_x)}{\sigma_x}\times 100\% \approx \\ &\frac{(\mu_{xy}+\mu)\varepsilon_{0^\circ}^{m}+(1+\mu\mu_{xy})\varepsilon_{90^\circ}^{m}}{(1-\mu H)(\varepsilon_{0^\circ}^{m}+\mu_{xy}\varepsilon_{90^\circ}^{m})-H(\mu_{xy}\varepsilon_{0^\circ}^{m}+\varepsilon_{90^\circ}^{m})}\times H\times 100\%\\ \delta\sigma_y &= \frac{(\sigma_y^*-\sigma_y)}{\sigma_y}\times 100\% \approx \\ &\frac{(\mu_{yx}+\mu)\varepsilon_{90^\circ}^{m}+(1+\mu\mu_{yx})\varepsilon_{0^\circ}^{m}}{(1-\mu H)(\mu_{yx}\varepsilon_{0^\circ}^{m}+\varepsilon_{90^\circ}^{m})-H(\varepsilon_{0^\circ}^{m}+\mu_{yx}\varepsilon_{90^\circ}^{m})}\times H\times 100\%\end{aligned}\right\} \tag{11}$$

To investigate the properties of OAPCM sensors, a testing device is built[4]. The sample is made of glass fiber reinforced plastic (GFRP) with thickness 2.6 mm. The loading ratio in two directions is 1 : 1.1, the material parameters are $E_x = 30.97$ GPa, $E_y = 27.12$ GPa, $\mu_{yx} = 0.194$ and $\mu_{xy} = 0.192$. In the central area, stresses σ_x^c and σ_y^c are calculated by

$$\sigma_x^c = \frac{F_x}{(A_x)_{equ}}, \quad \sigma_y^c = \frac{F_y}{(A_y)_{equ}} \tag{12}$$

where $(A_x)_{equ}$, $(A_y)_{equ}$ are the equivalent cross section area. In this experiment, the equivalent cross section areas are 110 mm × 2.6 mm.

The OAPCM sensor parameters are listed in Tab.1. The sensitivity is calibrated on a steel beam with $\mu = 0.285$. The testing results are shown in Tab.2 under the action of biaxial tension conditions.

Tab.1 Paramenters of a 1-3 OAPCM sensor

Size of piezoelectric phase		Piezoelectric coefficient		Polymer	Parameter of OAPCM	
a	b	d_{33}	d_{31}	τ_b	H	Calibration coefficient
5 mm	1.5 mm	530	247	6.83 MPa	1.14%	2.78 kV

Tab.2 Measurement results in plane stress state

Strain measured by gauges			Output of OAPCM sensor/mV			Loading/N	
$\Delta\varepsilon_{0^\circ}$	$\Delta\varepsilon_{45^\circ}$	$\Delta\varepsilon_{90^\circ}$	ΔU_{0°	ΔU_{45°	ΔU_{90°	ΔF_x	ΔF_y
37×10^{-6}	48×10^{-6}	50×10^{-6}	108	131	145	450	500

Substituting the experimental output of OAPCM sensor into Eq.(8), then

$\Delta\varepsilon_{0^\circ} = 38.13\times10^{-6}$, $\Delta\varepsilon_{90^\circ} = 51.55\times10^{-6}$

Comparing to strains by gauges listed in Tab.2, the errors show

$\delta(\Delta\varepsilon_{0^\circ}) = 3.05\%$, $\delta(\Delta\varepsilon_{90^\circ}) = 3.1\%$

Substituting the measured data and elasticity coefficients into Eq.(9), the measured stresses on the test sample surface are displayed as follows:

$\Delta\sigma_{0^\circ} = 1.52$ MPa, $\Delta\sigma_{90^\circ} = 1.66$ MPa

By Eq. (12), the stresses caused by loading are $\Delta(\sigma_x^c) = 1.57$ MPa and $\Delta(\sigma_y^c) = 1.75$ MPa, the errors between measured stress and loading stress are

$\delta(\Delta\sigma_{0^\circ}) = -3.18\%$, $\delta(\Delta\sigma_{90^\circ}) = -5.14\%$

3 Conclusion

Based on the piezoelectric theory, composite mechanics and experimental mechanics, the parameters of 1-3 OAPCM are calculated and measured, and the sensitivity coefficient and transverse effect coefficient are calibrated by the method similar to that of strain gauges. The sensing equations of 1-3 OAPCM strain sensors are derived for strain measurement on a surface of isotropic and orthotropic material structures under plane stress state. The results show that 1-3 OAPCM sensors offer orthotropic properties of piezoelectricity, and sensing equations can be used for strain or stress measurement without introducing much error. The research also shows the potential benefits to the strain or stress measurement for fiber-reinforced composite especially.

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1-3 型正交异性压电复合材料传感元件的研究

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摘 要 压电复合材料是一种重要的、具有广阔应用前景的传感和驱动材料.本文在压电材料基本理论、复合材料设计方法和实验力学的基础上,构造了一种 1-3 型正交异性压电复合材料传感元件,探讨了它的传感原理,推导了该种元件的传感方程和用于各向同性材料/正交各向异性材料构件表面测量的应力-应变关系,并在单向和双向应力状态下,进行了实验研究.结果表明:1-3 型正交异性压电复合材料传感元件可应用于构件表面上某一方向的应变测量,并具有较高的准确性.

关键词 1-3 型压电复合材料, 正交异性, 传感元件, 应变-应力关系

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