Review of In-situ Fabrication Methods of Piezoelectric Wafer Active Sensor for Sensing and Actuation Applications

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ABSTRACT

Structural health monitoring (SHM) is important for reducing maintenance costs while increasing safety and reliability. Piezoelectric wafer active sensors (PWAS) used in SHM applications are able to detect structural damage using Lamb waves. PWAS are small, lightweight, unobtrusive, and inexpensive. PWAS achieve direct transduction between electric and elastic wave energies. PWAS are essential elements in the Lamb-wave SHM with pitch-catch, pulse-echo, and electromechanical impedance methods. Traditionally, structural integrity tests required attachment of sensors to the material surface. This is often a burdensome and time-consuming task, especially considering the size and magnitude of the surfaces measured (such as aircraft, bridges, structural supports, etc.). In addition, there are critical applications where the rigid piezoceramic wafers cannot conform to curved surfaces. Existing ceramic PWAS, while fairly accurate when attached correctly to the substance, may not provide the long term durability required for SHM. The bonded interface between the PWAS and the structure is often the durability weak link. Better durability may be obtained from a built-in sensor that is incorporated into the material. An in-situ fabricated smart sensor may offer better durability. This paper gives a review of the state of the art on the in-situ fabrication of PWAS using different approaches, such as piezoelectric composite approach; polyvinylidene fluoride (PVDF) approach. It will present the principal fabrication methods and results existing to date. Flexible PVDF PWAS have been studied. They were mounted on a cantilever beam and subjected to free vibration testing. The experimental results of the composite PWAS and PVDF PWAS have been compared with the conventional piezoceramic PWAS. The theoretical and experimental results in this study gave the basic demonstration of the piezoelectricity of composite PWAS and PVDF PWAS.

Keywords: structural health monitoring, smart sensors, piezoelectric wafer active sensors, PVDF, piezoelectric composites, piezomagnetic composites, magneto electric composites

1. INTRODUCTION

1.1 Background

Structural health monitoring (SHM) addresses an urgent need of our aging infrastructure. In recent years, several investigators Chang^{1, 2}, Wang and Chang³, Lin and Yuan^{4, 5}, Ihn and Chang⁶, Giurgiutiu et al^{7, 8}, and others) have explored the generation and detection of structural waves with piezoelectric wafer active sensors (PWAS). Most of the methods used in conventional NDE, such as pitch-catch, pulse-echo, and phased arrays, have also been demonstrated experimentally with PWAS (Giurgiutiu et al.^{8, 9}). These successful experiments have positioned PWAS as an enabling technology for the development and implementation of active SHM systems. PWAS are inexpensive, non-intrusive, un-

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obtrusive, and minimally invasive. They can be surface-mounted on existing structures, inserted between the layers of lap joints, or placed inside composite materials. Figure 1 shows an array of 7 mm square PWAS mounted on an aircraft panel, adjacent to rivet heads and an electric discharge machined (EDM) simulated crack. The minimally invasive nature of the PWAS devices is apparent. A PWAS weighs 0.068 g, is 0.2 mm thick, and costs around \$7 each. In contrast, a conventional ultrasonic transducer weighs 50 g, is 20 mm thick, and costs around \$300. PWAS are used in SHM applications and are able to detect structural damage using Lamb waves. PWAS are small, lightweight, unobtrusive, and low cost. PWAS achieve direct transduction between electric and elastic wave energies. PWAS are essential elements in Lamb-wave SHM with pitch-catch, pulse-echo, and electromechanical impedance methods.

Figure 1 (a) Piezoelectric wafer active sensors (PWAS) mounted on an aircraft panel; (b) PWAS is attached to a substrate structure through the adhesive bond layer, which is susceptible to environmental attacks

However, there are some issues that need to be addressed:

- (1) Current PWAS are adhesively bonded to the substrate structure or incorporated between the layers of a laminated composite structure during fabrication. This adhesive bonding between the PWAS and the structural substrate is the weak link in the sensory system because it deteriorates in time under environmental attacks (humidity, temperature cycles, etc.). There is an acute need for a better approach that would seamlessly connect the PWAS with the structure.
- (2) Brittle piezoceramic PWAS can withstand very small bending. This brittleness imposes difficulties in handling and bonding of the PWAS into the structure being monitored.
- (3) In addition, piezoceramic PWAS have poor conformability to curved surfaces and local straightening of the structural surface is required for PWAS installation.^{10, 11, 12}

1.2 Motivation

The focus of this paper is to investigate alternate ways of creating PWAS that have better properties and durability than those currently employed. One way that is being explored is that of in-situ composite PWAS fabrication using different materials. We believe that in-situ fabricated sensor should be well suitable for structural health monitoring due to the ease with which their mechanical properties may be tailored, low cost, ease of implementation, conformability to curved surface and compatibility with polymeric materials.

2. STATE OF THE ART

Investigation of the state of the art in the fabrication methods of piezoelectric or piezomagnetic or magnetoelectric actuators and sensors reveals that considerable work has already been done in this direction.

2.1 Composites method

One common approach is to disperse particles of electroactive or magnetoactive particles (powders) in polymeric matrix materials. The resulting particulate composite displays effective piezoelectric or piezomagnetic properties that are somehow dependent on the volume ratio. However, the connectivity and the interfacial bond between the phases also

play a considerable role. Recent research interest has been shown in the combination of electroactive and magnetoactive effects into a more complex composite that displays both electroactive and magnetoactive responses. These composites, which have a three-way coupling between the electric, magnetic, and elastic fields, are known as magnetoelectric or multiferroic composites. Details on previous work on piezomagnetic, piezoelectric, and magnetoelectric composites are given next.

2.1.1 Piezomagnetic composites

Terfenol-D ($\text{Tb}_x\text{Dy}_{1-x}\text{Fe}_2$) is a magnetic anisotropy-compensated alloy which shows a strong magnetostrictive behavior. When subjected to mechanical strain, Terfenol-D produces magnetic field. White¹³ reviewed the magnetostrictive tagging methodology of composites for structural health monitoring and measured the response of magnetostrictive-tagged composites under axial loading. Neat resin beams tagged 2.24% by volume with magnetostrictive Terfenol-D powder were used. Trovillion *et al.*¹⁴ studied the magnetic characteristics of neat resin and glass-fiber-reinforced magnetostrictive composites subjected to axial load. The fiber reinforced polymer composite (FRP) beams consisted of 4 layers of continuous strand glass mat fibers embedded in a polyester resin. The top lamina of the composite was impregnated with Terfenol-D powder at a volume fraction of 2.24% for that lamina. The beams were subjected to uniaxial loading under load control at a rate of 0.02 kN/s. Rearrangement of the magnetic dipoles chains of the magnetostrictive molecules through application of strong magnetic field was performed by applying a magnetic field through the thickness of the beam using a pair of magnets to apply a field of 800 Gauss. Giurgiutiu *et al.*²⁹ studied the piezomagnetic response of composite beam tagged with Terfenol-D powders. The beam was 1000 mm long, and had a 100 mm by 6.5 mm cross section. It had 7 layers of woven glass roving 36oz./sq.yd with Atlac 580-05 urethane-modified vinyl ester resin. Terfenol-D tagging powder was used in the two outer laminate in the middle 500 mm of the span. Of the 1000 grams of resin used, 250 grams had the MS powder. The weight fraction of MS Terfenol-D tagging was 15 %. The magnetic flux density response of the beam was measured during bending cycles, and the piezomagnetic strain and stress coefficients were determined.

Armstrong¹⁵ presented a new model of non-linear magneto-elastic behavior of magnetostrictive particulate composite. The analysis assumed uniform external magnetic field that is operating on a large number of well-distributed ellipsoidal magnetostrictive particles encased in an elastic, nonmagnetic composite matrix. Nersessian and Carman¹⁶ studied five different volume-fraction of magnetostrictive particulate composites which were tested under two different conditions: (a) constant magnetic field and varying mechanical load; and (b) constant mechanical load and varying magnetic field. The results presented for the constant load indicated a strong dependence of strain output on applied pre-stress. Krishnamurthy *et al.*¹⁷ considered health-monitoring detection of delaminations in composite materials using an excitation coil and a sensing coil. The open-circuit voltage induced in the sensing coil is proportional to the stress generated in the magnetostrictive layer by the presence of the delamination.

2.1.2 Piezoelectric composites

The combination of polymer and piezoelectric ceramic to form composite PWAS offers the unique blending of the high electro-active properties of piezoelectric ceramics and the mechanical flexibility and formability of organic synthetic polymers. Recently, active composite PWAS have been developed, namely 1-3 composites by Smart Materials Corp, active fiber composite developed by MIT, and macrofiber composite (MFC) actuators at NASA Langley Center. These composite PWAS are capable of being repeatedly manufactured at low cost, are tolerant to damage, capable of conforming to complex or curved surfaces, and embeddable into structures. The uses of composite PWAS would provide the advantages of being robust, reliable, and easily adaptable for impedance-based health monitoring. Composites PWAS can be classified according to the connectivity of piezoelectric ceramics and matrix phases. The composite PWAS described in this paper has a 0-3 connectivity pattern. The “0-3” means that the ceramic particles are randomly dispersed in a polymer matrix. 0-3 composites can be more easily fabricated in complex shapes than other forms of composites. Various approaches have been tried for producing 0-3 composites.^{12, 18, 19}

2.1.3 Magnetoelectric composites

Composite aggregates that consist of an electroactive phase and a magnetoactive phase exhibit a magnetoelectric effect, which is not present in the constituents. The magnetoelectric effect consists in coupling the magnetic and electric responses through the elastic interaction between the magnetoactive and electroactive phases. For example, if an applied electric field activates the electroactive phase, the resulting geometric change will be felt by the magnetoactive phase

and, through the magnetoactive effect, will result in an output magnetic field. Conversely, an input magnetic field will result in an output electric field. Several magnetoelectric composite configurations have been considered. One configuration comes in the form of multilayer magnetoelectric composites consist of alternating layers of electroactive and magnetoactive materials. Another configuration is that of particulate composites with multi-phase aggregates of electroactive and magnetoactive phases. For example, a magnetoactive phase may appear as particulate inclusions into an electroactive phase. If the aspect ratio of the particulates is large, the particulate may appear as elongated inclusions that can be idealized as cylindrical microfibers. A third configuration is that of self-assembled nanofilms having magnetoactive nanopillars in an electroactive matrix that are grown vertically on a substrate.

The most common magnetoelectric composite is the combination of electroactive BaTiO₃ with the magnetoactive CoFe₂O₄. In the electroactive phase, the perovskite crystal structure of BaTiO₃ imparts ferroelectric properties that result in the piezoelectric effect. In the magnetoactive phase, the spinel structure of CoFe₂O₄ imparts magnetostrictive response that, upon biased linearization, results in the piezomagnetic effect. Nan²² developed a theoretic framework for the analysis of magnetoelectric composites using a modified Green's function approach. In their derivation, they started from the coupled magnetic-electric-elastic constitutive equations in the form

$$\begin{aligned}\boldsymbol{\sigma} &= \mathbf{C}\mathbf{s} - \mathbf{e}^T \mathbf{E} - \mathbf{q}^T \mathbf{H} \\ \mathbf{D} &= \mathbf{e}\mathbf{s} + \boldsymbol{\varepsilon} \mathbf{E} + \boldsymbol{\alpha} \mathbf{H} \\ \mathbf{B} &= \mathbf{q}\mathbf{s} + \boldsymbol{\alpha}^T \mathbf{E} + \boldsymbol{\mu} \mathbf{H}\end{aligned}\tag{1}$$

where the notation $(\dots)^T$ signifies the transpose operation and $\boldsymbol{\sigma}$, $\mathbf{s}$, $\mathbf{D}$, $\mathbf{E}$, $\mathbf{B}$, $\mathbf{H}$, $\mathbf{C}$, $\boldsymbol{\varepsilon}$, $\boldsymbol{\mu}$ are tensors representing stress, strain, electric displacement, electric field, magnetic induction, magnetic field, stiffness (at constant electric and magnetic fields), dielectric and magnetic permeabilities (at constant strain), respectively. The interaction between the electric, magnetic, and elastic fields is represented by the tensors $\mathbf{e}$, $\mathbf{q}$, $\boldsymbol{\alpha}$ which contain the piezoelectric, piezomagnetic, and magnetoelectric coefficients. The magnetoelectric property tensor $\boldsymbol{\alpha}$ is a new property that was not present in the individual piezoelectric and piezomagnetic phases. In compressed Voigt notations, the tensors $\mathbf{C}$, $\mathbf{e}$, $\mathbf{q}$, $\boldsymbol{\varepsilon}$, $\boldsymbol{\mu}$, $\boldsymbol{\alpha}$ are (6×6) , (6×6) , (3×6) , (3×6) , (3×3) , (3×3) , (3×3) matrices, such that Equation (1) can be rewritten as

$$\begin{pmatrix} \boldsymbol{\sigma} \\ \mathbf{D} \\ \mathbf{B} \end{pmatrix} = \begin{bmatrix} \mathbf{C} & -\mathbf{e}^T & -\mathbf{q}^T \\ \mathbf{e} & \boldsymbol{\varepsilon} & \boldsymbol{\alpha} \\ \mathbf{q} & \boldsymbol{\alpha}^T & \boldsymbol{\mu} \end{bmatrix} \begin{pmatrix} \mathbf{s} \\ \mathbf{E} \\ \mathbf{H} \end{pmatrix}\tag{2}$$

For the composite, the coefficients in Equation (2) take local values depending on the spatial position $\mathbf{x}$. However, one can consider effective constitutive coefficients in terms of the average fields, namely,

$$\begin{pmatrix} \langle \boldsymbol{\sigma} \rangle \\ \langle \mathbf{D} \rangle \\ \langle \mathbf{B} \rangle \end{pmatrix} = \begin{bmatrix} \mathbf{C}^* & -\mathbf{e}^{*T} & -\mathbf{q}^{*T} \\ \mathbf{e}^* & \boldsymbol{\varepsilon}^* & \boldsymbol{\alpha}^* \\ \mathbf{q}^* & \boldsymbol{\alpha}^{*T} & \boldsymbol{\mu}^* \end{bmatrix} \begin{pmatrix} \langle \mathbf{s} \rangle \\ \langle \mathbf{E} \rangle \\ \langle \mathbf{H} \rangle \end{pmatrix}\tag{3}$$

where the notation $\langle \dots \rangle$ signifies space average. Using numerical simulation performed on 0-3 and 1-3 composites of BaTiO₃-CoFe₂O₄, Nan²² showed that the effective magnetoelectric coefficients of the composite can be strongly influenced by the connectivity, the volume fraction, and the aspect ratio of the particles. For example, low volume fractions of the piezoelectric phase result in large values of the magnetoelectric voltage coefficient of the composite results

Pan²³ considered the exact solution of a multilayer sandwich plate made of piezoelectric BaTiO₃ and magnetostrictive CoFe₂O₄. Simply supported boundary conditions were considered. It was found that the response of the electric and magnetic variables depends strongly on the stacking sequence. Echigoya *et al.*²⁴ studied experimentally the directional solidification of the BaTiO₃-CoFe₂O₄ eutectic fabricated by the floating zone melting method. It was observed that the structure of the eutectic consists of grains having lamellar or fibrous morphology. Intercalated elongated grains of BaTiO₃ and CoFe₂O₄ were observed (Figure 2). Misfit dislocations due to the accommodation of the lattice mismatch between the BaTiO₃ and CoFe₂O₄ were observed at the grain interfaces. Zheng *et al.*²⁶ considered the nanoscale magnetoelectric composites consisting of multiferroic BaTiO₃-CoFe₂O₄ structures. Several configurations were considered, such as multilayer films and self-assembled nanostructured rods (Figure 3a). Self-assembled BaTiO₃-CoFe₂O₄ nanocomposites were formed from a 0.65BaTiO₃-0.35CoFe₂O₄ target by pulsed laser deposition. (SrRuO₃ was chosen as the lattice-matched bottom electrode to enable heteroepitaxy as well as to facilitate electric measurements.)

The resulting samples displayed nano-structured pillars of CoFe_2O_4 with ~ 20 nm diameter embedded in a BaTiO_3 matrix (Figure 3b). Cai *et al.*²⁷ considered 3-component magnetoelectric composites consisting of a piezoelectric ceramic (PZT), a magnetostrictive alloy (Terfenol-D) and a piezoelectric polymer (PVDF). In one experiment, three-phase particulate composites of PZT and Terfenol-D in a PVDF matrix were considered. In a different experiment, three-layer laminates of two-phase particulate composites were investigated. A Terfenol-D/PVDF particulate composite layer was sandwiched between two PZT/PVDF particulate composite layers. The fabrication was achieved through lamination and hot-pressing. Both methods gave good magnetoelectric response, but the latter approach achieved better values than the former.

Figure 2 Optical photograph of directionally solidified BaTiO_3 - CoFe_2O_4 eutectic grown in air at 10 mm/h showing lamellar structure of alternating BaTiO_3 and CoFe_2O_4 elongated grains (after Echigoya *et al.*²⁴)

Figure 3 Nanoscale magnetoelectric composites consisting of multiferroic BaTiO_3 - CoFe_2O_4 structures: (a) (A) Superlattice of a spinel structure (top) and a perovskite structure (middle) on a perovskite substrate (bottom). (B) Resulting multilayer configuration; (C) Epitaxial alignment of a spinel (top left) and a perovskite (top right) on a perovskite substrate (bottom). (D) resulting pillars structure; (b) TEM picture of an experimental sample showing self-assembled nanostructured CoFe_2O_4 pillars with ~ 20 nm diameter embedded in a BaTiO_3 matrix (after Zheng *et al.*²⁶)

2.2 Piezopolymers

Piezopolymers (e.g., polyvinylidene fluoride, a.k.a. PVDF) are a class of piezoelectric materials that display piezoelectric properties similar to those of quartz and piezoceramics. Piezoelectric polymers are supplied in the form of thin films that are flexible and show large compliance. Piezoelectric polymers are less expensive and easier to fabricate than piezoceramics. The flexibility of polyvinylidene fluoride overcomes some of the drawbacks associated with the brittleness of the piezoelectric ceramics.²⁸ In particular, piezopolymers are good candidates for sensing because of their

small stiffness, which adds minimum local stiffening to the host structure. Normally, PVDF is provided in large sheets that can be easily cut into the desired size. Being flexible, the PVDF PWAS can easily conform to curved surfaces.

3. PIEZOELECTRIC COMPOSITES PWAS

One approach considered in our research was that of piezoelectric composites. The piezoelectric composites have the advantage that electric signals can be collected directly, whereas in the case of piezomagnetic composites magnetic flux probes had to be used. Our purpose in pursuing the fabrication of piezoelectric composites was to eventually be able to achieve in-situ fabrication of PWAS of a quality comparable with that of ceramic PWAS. By fabricating the PWAS directly onto the structure, a seamless bond would be achieved between the PWAS and the structure that would be impervious to environmental attacks can be created. Thus, we will eliminate the “weak link” in the present use of bonded PWAS and achieve a long time durability of the embedded sensory system.

3.1 Preparation of piezoelectric composite PWAS Preparation

The epoxy resin used in the fabrication of the piezoelectric composite PWAS was EPO-TEK 301-2 from Epoxy Technology, Inc. This epoxy has a good handling property, high dielectric strength and a low viscosity. The mixture ratio for the epoxy part “A” and part “B” (hardener) is specified as 1:0.35 by the supplier and was followed in this study.

Figure 4 Composite PWAS experiments: materials used; (b) poling apparatus

The PZT particles in the composite PWAS were PZT-5B powders from Morgan Electro Ceramics. PZT-5B powders have a high sensitivity and high time stability (Figure 4). The silver paint used for creating the electrodes was acquired from SPI Supplies and Structure Probe, Inc. The poling workstation consists of an oven, a constant DC power supply, a high voltage power supply, a multimeter and a thermometer.

3.2 Piezoelectric Composite PWAS Fabrication

The procedure for the fabrication of piezoelectric composite PWAS is as follows. Clean the surface of host structure and put a mask. The mask has a 7mm diameter, 0.2mm thickness hole and its center is in the desired position. PZT powder was added to the epoxy matrix phase and was stirred thoroughly to achieve a weight fraction of 85%. The resulting paste was spread into the mask and let cure at 50 degree C until hard. The excess was removed and the composite PWAS was sanded down to final thickness. A small piece of copper foil was applied to one side of the cured composite PWAS to form an electrode. After curing and electroding had been completed, poling of the composite PWAS was subsequently carried out to activate its piezoelectric effect. A constant DC voltage of 1 kV was applied to the composite PWAS to pole the sample for four hours at 80 degree C.

Figure 5 Composite PWAS sample fabricated on a thin aluminum plate was used in measuring the impact waves

3.3 Characterization of Piezoelectric Composite PWAS

We measured the final size of the composite PWAS to be 7mm diameter and 0.2mm thickness, which is same as the conventional piezoceramic PWAS. The electrical properties of the composite PWAS were measured before and after poling. The resistance was greater than 40 M Ω before and after poling. The resistivity was higher than 40 M Ω . The capacitance of composite was only 0.02 nF which is lower than the piezoceramic PWAS value of 3 nF.

3.4 Impact Test on Piezoelectric Composite PWAS

The effectiveness of the composite PWAS for impact was investigated based on an impact test setup show in Figure 5. The impact point shown in Figure 5 is 20 mm away from the center of the composite PWAS. The output of the composite PWAS was measured as a voltage signal using a digital oscilloscope. We measured the voltage signal before and after poling. Before poling, the voltage signal damped out very soon (Figure 6a). After poling, we found that the voltage amplitude is much higher. It also displayed some vibration signals after the impact (Figure 6b). It can be seen that, upon receiving a hit, the plate vibrated for a while and then damped out. The composite PWAS showed a good repeatability in its output signal when subjected to similar impacts.

Figure 6 The electric voltage signal measured by the impact hammer, (a) before poling (b) after poling

4. PVDF PWAS

4.1 PZT and PVDF PWAS Comparison Experiment Setup

The comparison of the piezoceramic PWAS and PVDF PWAS for dynamic measurement was investigated based on a vibration test setup shown in Figure 7. Different thickness PVDF sheets were cut into the same size as piezoceramic PWAS. The beam was mounted as a cantilever in a calibrated cantilever fixture. Two PVDF PWAS were placed on the top of the beam and a conventional piezoceramic PWAS and a strain gauge were placed at the other side of the beam. The tip of the beam was displaced to a certain value (approx. 10 mm) and then suddenly released as the beam entered in free vibration.

Figure 7 PZT PWAS, PVDF PWAS, and strain gauge on a cantilever beam: (a) experimental setup; (b) close-up view of the bottom surface showing the 200µm piezoelectric ceramic PWAS and strain gauge; (c) close-up view of the top surface showing the 28µm and 110µm PVDF

Figure 8 Vibration signal recorded by strain gauge, PVDF PWAS and PZT PWAS.

4.2 Comparison of PVDF PWAS with PZT PWAS

A 4-channel Tektronix TDS5030B oscilloscope was used. Channel one was connected to the strain indicator to record the electric signal generated by the resistance change in the strain gauge due to strain elongation. The other three channels were directly connected to the PZT and PVDF PWAS to record the electric signals generated through the piezoelectric coupling between the mechanical vibration and the electric field. The recorded traces are shown in Figure 8. The Fourier transform was used to analyze the frequency contents of the signals, which should correspond to the natural free vibration frequencies of the cantilever beam. The resulting spectra are shown in Figure 9. The first three natural frequencies are shown to be $f_1 = 29.7\text{Hz}$, $f_2 = 181\text{Hz}$, and $f_3 = 501\text{Hz}$. The PZT PWAS was found to give the highest voltage but it was less responsive to the higher frequencies. The PVDF PWAS were found to be more responsive to the higher frequencies but gave a lower voltage (Table 1).

Figure 9 Vibration signal and spectrum of magnitude (Fourier transform) recorded by (CH 1) strain gauge; (CH 2) 28 μm thick PVDF PWAS; (CH 3) 110 μm thick PVDF PWAS, (CH 4) 200 μm thick PZT PWAS.

Table 1 Comparison of the results

Channel	Sensor	$V_{pp}(\text{V})$	f_1 (Hz)	A_1 (mV)	f_2 (Hz)	A_2 (mV)	A_2/A_1 (%)	f_3 (Hz)	A_3 (mV)	A_3/A_1 (%)
CH 1	Strain Gauge	1.320	29.69	327.4	182.8	12	3.66	509.4	20	6.1
CH 2	28 μm PVDF PWAS	0.332	29.69	55.64	181.3	28.75	51.67	501.6	6.16	11.07
CH 3	110 μm PVDF PWAS	0.508	29.69	82.5	181.3	45.65	55.33	501.6	11	13.33
CH 4	200 μm PZT PWAS	30.800	29.69	8568	181.3	800	9.337	502.5	100	0.44

4.3 Theoretical Prediction of PWAS Performance

PWAS performance in dynamic regime was analyzed by using one-dimensional assumptions. If a PWAS of length l , width b and thickness h that is undergoing longitudinal expansion (u_1) induced by the thickness polarization electric field (E_3) (Figure 10), the result voltage is harmonic with frequency ω when vibration is harmonic with natural frequency ω . For compactness, the notation used:

$$\frac{\partial}{\partial t}(\dot{}) = \ddot{} \quad (4)$$

Consider the dynamic regime under the one-dimensional assumptions; the general constitutive equations are reduced to the simpler expressions:

$$\dot{S}_1 = s_{11} \cdot \dot{T}_1 + d_{31} \cdot \dot{E}_3 \quad (5)$$

$$\dot{D}_3 = d_{31} \cdot \dot{T}_1 + \epsilon_{33} \cdot \dot{E}_3 \quad (6)$$

where S_1 is the strain, T_1 is the stress, D_3 is the electrical displacement(charge per unit area), E_3 is electric field which equals $\dot{E}_3 = -\frac{\dot{V}}{h}$, s_{11} is the mechanical compliance at zero field, ϵ_{33} is the dielectric constant at zero stress, and d_{31} is the induced strain coefficient. For harmonic voltage, $\dot{V} = i\omega V$.

Figure 10 Schematic of a PWAS connected with a measurement equipment which has a admittance Y_e

When PWAS is under harmonic strain and connected with external measurement equipment, it will generate an AC current in circuit (Figure 10). The AC current can be expressed by using:

$$I = \dot{D}_3 \cdot A \quad (7)$$

$$I = V \cdot Y_e \quad (8)$$

where Y_e is the external admittance, and A is the PWAS surface area $A = l \cdot b$.

Using Kirchhoff's current law for a closed circuit, we obtain the relation between voltage and stress:

$$V = \frac{A \cdot d_{31}}{Y_e + Y_0} \dot{T}_1 \quad (9)$$

where Y_0 is PWAS admittance $Y_0 = i\omega\epsilon_{33} \frac{A}{h}$.

From equation(5), we obtain

$$\dot{T}_1 = \frac{1}{s_{11}} \left(\dot{S}_1 + \frac{d_{31}}{h} \dot{V} \right) \quad (10)$$

Finally we obtain the resulted voltage from the strain:

$$V = \frac{1}{Y_e + (1 - k_{31}^2)Y_0} \cdot A \frac{d_{31}}{s_{11}} \dot{S}_1 \quad (11)$$

where k_{31} is the electromechanical coupling coefficient,

$$k_{31}^2 = \frac{d_{31}^2}{s_{11} \cdot \epsilon_{33}} \quad (12)$$

4.4 Comparison of the Experimental Results with the Theoretical Predictions

Vishay P3 strain indicator and recorder has an analog output from 0 to 2.5V which equals strain value from -320 $\mu\epsilon$ to +320 $\mu\epsilon$. The peak to peak analog output of strain indicator was 1.32 V, which means the peak to peak vibration strain equaled 338 $\mu\epsilon$. Assuming the oscilloscope's capacitance is 3 nF and using the Equation (11), the theoretical peak to peak voltage of PZT PWAS, 110 μm PVDF PWAS and 28 μm PVDF PWAS are 30V, 0.361V and 0.346V respectively. The experimental results can be read from Table 1, which were 30.8V, 0.508V and 0.332V respectively. The experimental results agreed with the theoretical prediction.

5. CONCLUSION

Investigation of The state of the art in the fabrication methods for piezoelectric, piezomagnetic, magnetoelectric sensors reveals has been reviewed.

A technique for fabricating piezoelectric composite PWAS has been studied. The effectiveness of composite PWAS has been preliminarily characterized through a series of tests, which include impact testing. Flexible PVDF PWAS have been also studied. They were mounted on a cantilever beam and subjected to free vibration testing. The experimental results of the composite PWAS and PVDF sensors have been compared with the conventional piezoceramic PWAS. The theoretical and experimental results in this study gave the basic demonstration of the piezoelectricity of composite PWAS and PVDF PWAS. The composite PWAS and PVDF PWAS are capable of use as an active sensor. Piezoceramic PZT gives a stronger response than piezopolymer PVDF and composite PWAS for same stress wave amplitude. Piezopolymer PVDF is conformable to curved surfaces and more responsive to higher frequencies

Our future work is focused on using the composite technology methods for the in-situ fabrication of composite PWAS. The composite fabrication methods considered for investigation are: (a) mask; (b) poling; (c) powders technology; (d) coatings. **The ultimate vision** is to create a methodology to create the in-situ PWAS directly onto the structural substrate through an easy technique.

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