Technology Review

Nano Piezo Sensors for Structural Health Monitoring, Damage Detection and Failure Prevention

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Background: Structural health monitoring (SHM) addresses an urgent need of our aging infrastructure. The United States spends more than $200 billion each year on the maintenance of plant equipment and facilities. Maintenance and repairs represent about a quarter of commercial aircraft operating costs. Out of approximately 576,600 bridges in our national inventory, 32% are either "structurally deficient" and in need of repairs, or "functionally obsolete" and in need of replacement. Much of the civilian and military aircraft fleets have exceeded their design life. Some of NASA's space shuttles are more than 20 years old. The mounting costs of maintaining our aging infrastructure can be addressed through SHM systems that will reduce unscheduled repairs while increasing safety and reliability. The Aloha Airlines Boeing 737 experienced catastrophic "un-zipping" of large portions of the fuselage in 1988 due to multi-site cracks in the skin joints (Figure 1). More recently, Flight 587 accident in Queens, NY on Nov. 12, 2001, experienced the loss of its entire tail resulting in the **second deadliest** aviation accident in US history (Figure 2). It is conceivable that, if SHM systems were installed in these aircraft, then such accidents could have been prevented or at least alleviated. Boeing's new 7E7 aircraft will have a full-time built-in SHM system[1] comprising sensors embedded in the structure to assess the state of structural health. SHM systems consist of networks of embedded sensors that are permanently inserted into the structure and monitored over time. Piezoelectric wafer active sensors (PWAS) are used in SHM applications are able to detect structural damage using Lamb waves. PWAS are small, lightweight, unobtrusive, and low cost (Figure 3a). PWAS achieve direct transduction between electric and elastic wave energies. PWAS are essential elements in the Lamb-wave SHM

Figure 1 – Aloha Airlines Boeing 737 experienced catastrophic "un-zipping" of large portions of the fuselage in 1988 due to multi-site cracks in the skin joints

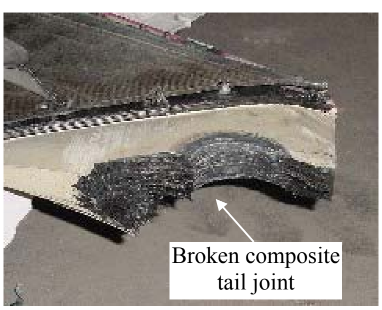
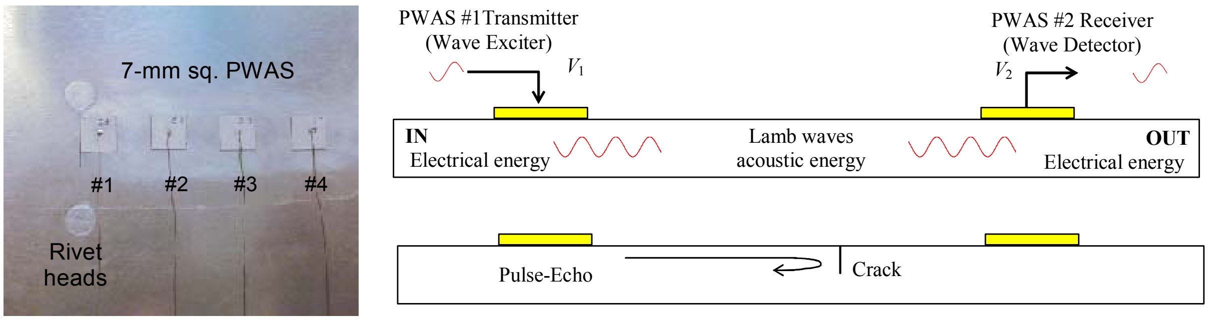


Figure 2 Broken tail of AA flight 587 that could have benefited from structural health monitoring

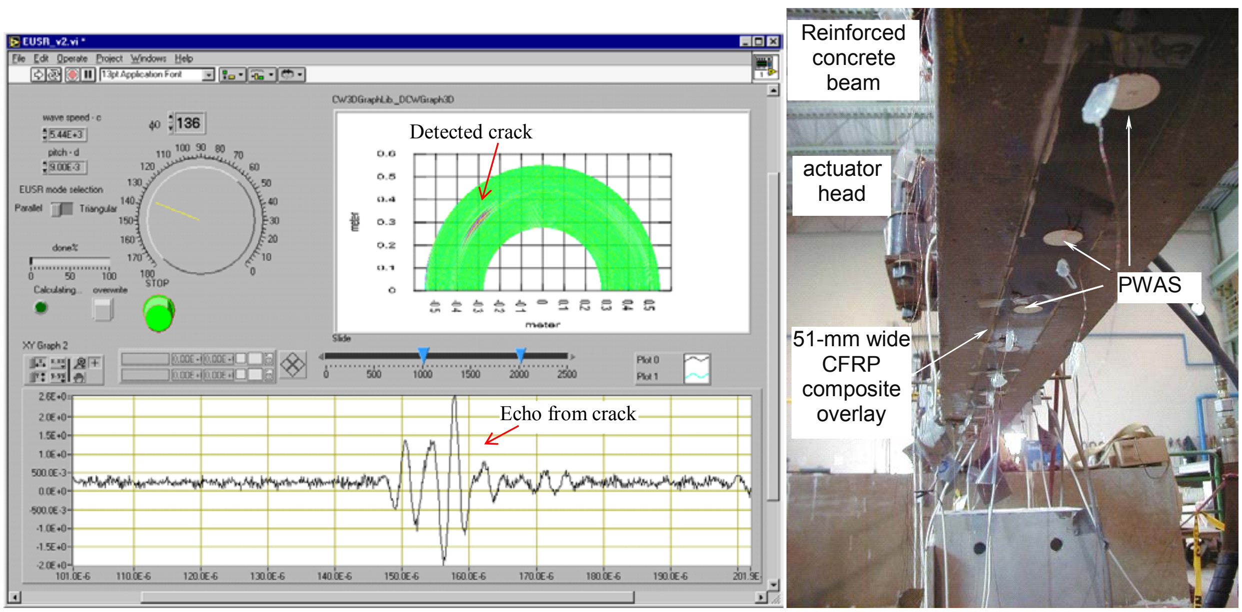
[1] *Aerospace America*, Nov. 2003, pp. 5

with pitch-catch, pulse-echo, and electromechanical impedance methods(Figure 3b). We developed the *embedded ultrasonics structural radar* (EUSR) concept that utilizes a PWAS phased array to create steered ultrasonic beams that interrogate large areas from a single location.



(a) (b)

Figure 3 (a) Four PWAS installed on an aircraft panel near with a crack emanating from a rivet row; (b) principles of active structural health monitoring with PWAS transducers near a crack

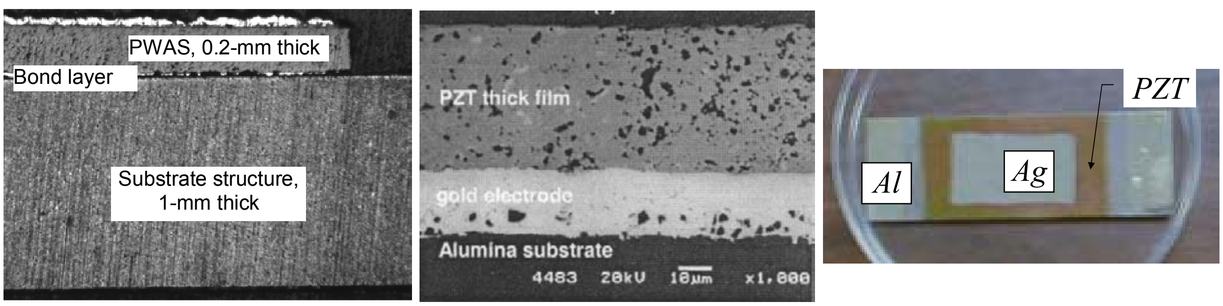


(a) (b)

Figure 4 Application of PWAS to damage detection: (a) Embedded ultrasonics structural radar uses Lamb waves and PWAS arrays to image cracks in a large plate; (b) PWAS impedance sensors are used to detect disbond cracks during fatigue testing of a reinforced-concrete beam strengthened with an adhesively-bonded carbon-fiber composite overlay

This concept can be applied to aircraft, storage tanks, large pipes, etc. By sequentially firing the individual elements of an array transducer at slightly different times, the ultrasonic wave front can be focused or steered in a specific direction. Thus, steering and/or refocusing of the beam is achieved electronically without physical manipulating the transducers. To reduce instrumentation needs, we created a virtual steering beam that uses only one PWAS as transmitter, but collects signals on all the PWAS, in a round-robin fashion. The steered beam allows the detection of crack with the pulse-echo method (Figure 4a). Another important application of the PWAS technology is in the detection of disbonds in adhesive joints. Figure 4b shows PWAS impedance sensors used to detect disbond cracks during fatigue testing of a reinforced concrete beam strengthened with an adhesively bonded carbon-fiber composite overlay.

Needs to be addressed: (1) Current PWAS are adhesively bonded to the substrate structure (Figure 5a) or incorporated between the layers of a laminated structure during fabrication. This adhesive bonding between the piezoelectric active sensor 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) Currently available piezoelectric wafers and PZT thick films have a porous ceramic structure with multi-orientation piezoelectric domains, which results in a poor piezoelectric performance (Figure 5a,b). **There is an urgent need for piezoelectric materials with coherent crystalline structure and well oriented domains with an enhanced piezoelectric response.** (3) Current PWAS require a large voltage (~ 150 V) for full activation because the electric field is the ration between applied voltage and wafer thickness which is still relatively large (Figure 5a). **There is a need for thinner wafers that will work with low voltages (< 10 V)**



(a) (b) (c)

Figure 5 Progress in PWAS technology: (a) PWAS attached to a substrate structure through the adhesive bond layer, which is susceptible to environmental attacks; (b) PZT thick film on gold-coated alumina has an intrinsic bond, but shows porosity and inhomogeneity in the its structure (Levassort et al., 2001); (c) PZT thin film nano fabricated at USC on Al substrate and with Ag top electrode

Purpose: The focus of our research is to create in-situ piezoelectric active sensors using nano technology fabrication techniques.

Specific Research Problems: We want to remove the critical element of current embedded piezoelectric sensors, specifically the adhesive bonding between the piezoelectric active sensor and the structural substrate, which is the weak link in the sensory system because it deteriorates under environmental attacks (humidity, temperature cycles, etc.). By fabricating the sensors directly onto the structure we will create a seamless atomic bond to the structure that will be impervious to environmental attacks. we will eliminate this weak link and ensure a long time durability of the embedded sensory system. In addition, the nano technology fabrication techniques will offer other advantages. The nano fabricated piezoelectric materials will have a well ordered crystalline structure with quasi single domain orientation that gives properties close to the single crystal properties, i.e. much better than existing piezoelectric ceramics which are porous and polycrystalline. Thus, an order of magnitude improvement in the piezoelectric properties over conventional piezoceramics is to be expected. Second, because the in-situ nano fabricated sensors can be made very thin, the required electric fields can be obtained with relatively low activation voltages. The current piezoelectric wafers cannot be made thinner than 0.2 mm due to handling issues, hence their activation voltage can be as high as 150 V. The in-situ nano fabricated piezo sensors will be one to orders of magnitude thinner, hence their activation voltages will be much smaller. Third, the in-situ nano fabricated piezo sensors will be much better coupled with the substrate structure, reducing the losses in exciting and detecting the elastic waves in the structure.

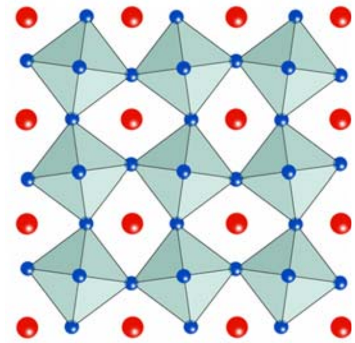


Figure 6 – Octohedral zone boundary rotation in perovskites

Research Activities: Research in PWAS structural health monitoring has been supported for several years by the National Science Foundation, the Air Force Research Laboratory, and the Sandia National Labs. Recently, we have started research into the nano piezo sensors under USC Nano Center internal funding. Our research activities are targeted in two directions: modeling and experiments. **Modeling** is aimed at first principle calculations to study the stress-induced phase transition in $Pb(Z_{1/2}Ti_{1/2})O_3$. The calculations will be performed with the density functional theory in the local density approximation. The study will try to predict, from first principles, the uniaxial stress-induced transition. The tetragonal-like and the rhombohedral-like phases of the (111)-$Pb(Z_{1/2}Ti_{1/2})O_3$ crystal under (100) uniaxial stress will be examined. Characterization of the two metastable structural phases emphasized the importance of strain coupling to polarization, since the simplest Landau theory of polarization, in which strain is neglected, does not permit more than one metastable structure. Other investigations have found a polarization response in the rhombohedral-like phase, which is inconsistent with currently held assumptions that, in the perovskites materials, the major contribution to the piezoelectricity is from *rotation* of a constant-magnitude polarization vector. Understanding the properties of ferroelectric materials at the atomic level will allow us to identify avenues for improving existing materials and finding new compositions. Since ferroelectricity is intimately connected with lattice instabilities and the interplay of competing structural distortions, accurate methodologies and realistic models of the perovskite ferroelectric alloys must be used. The interplay between lattice distortions associated with rotation of the perovskite octahedral and ferroelectric distortions is very strongly volume dependent. Predicting this interplay requires methodologies that can predict the volume to within one percent or better. Recent successes at Naval Research Laboratory have unraveled the lattice instabilities in the Navy SONAR transducer material $Pb(Zr,Ti)O_3$ near the morphotropic phase boundary, leading to an understanding of the importance of octahedral rotational modes -- a finding recently confirmed by experiments. Also confirmed was the prediction that alloying Cd for Pb in $PbTiO_3$ would favor increases in the c/a ratio, implying potential for large displacement actuation. The competitions between ferroelectric and rotational instabilities in rhombohedral $PbZr_xTi_{1-x}O_3$ near x = 0.5 could be investigated using first-principles density-functional supercell calculations leading to the identification of strong ferroelectric instabilities that could lead to large piezoelectric effects near the morphotropic phase boundary. **The experiments** are directed towards fabrication of piezoelectric thin films on aluminum and other substrates.

Recent Significant Achievements: To date, we have obtained preliminary results by sputtering amorphous PZT films on aluminum substrates initially deposited on glass slides. Silver electrodes were deposited on top. Full characterization of the chemical and physical properties was performed. Current efforts are directed towards crystallizing the films to obtain piezoelectric properties.

Current Intellectual Property: two patent applications on the use of piezoelectric wafer active sensors for structural health monitoring, damage detection, and failure prevention are being examined by the US patent office. A patent disclosure on nano piezo sensors has been recently filed with the University intellectual property office.

Industrial Relashionship: A visit to the AVX Corporation was made in Summer 2003, and further collaborations are expected.

Future Research Goals: Our future work is focused on perfecting the nano technology methods for the in-situ fabrication of nano piezo sensors. The nano fabrication methods considered for investigation are: (a) sputtering; (b) epitaxial growth through chemical vapor deposition; (c) sol-gel; (d) epitaxial growth through laser deposition; (e) nano-composites through mixture of nano-size piezoelectric powders with a polymeric matrix; (f) powders technology; (g) functionally graded materials; (h)coatings and spraying. **The ultimate vision** is to create a methodology to create the nano piezo sensors directly onto the structural substrate through a deposition technique followed by, annealing, electroding and poling.