HIGH-TEMPERATURE INTELLIGENT COMPOSITES

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Abstract

Recently there is an increasing need for high-temperature polymer matrix composites (PMCs) in aerospace applications, but due to complex internal damage types plus imperceptible defects in composites, overweight designs are commonly required to ensure reliability for composite structures. Different structural health monitoring (SHM) techniques have been developed to overcome the inefficient design issues in composite structures, but for high-temperature composites, the harsh curing/working environments make current structural health monitoring techniques difficult to be implemented. In this work, we have demonstrated that with our intelligent diagnostics algorithm and temperature compensation model, the newly developed high-temperature piezoelectric sensors (BS-PT) not only can survive the harsh curing conditions required for high-temperature PMCs, but also can be potentially utilized in high-temperature intelligent sensor systems to achieve SHM in a larger temperature range.

1 Introduction

Composite materials have been used in aerospace applications more and more frequently in recent years because of their superior strength-to-weight ratios and high chemical stability. However, standard polymer matrix composites (PMCs) cannot withstand high temperature environments above the glass transition temperature of their resin system (around 180℃). Therefore high temperature PMCs, with heat-resistant resin systems such as bismaleimide (BMI) and polyimide become increasingly important, especially in the development of high-speed aircraft and reentry vehicles where entire craft is exposed to extreme thermal environments.

A primary concern of using composites for aerospace applications is the complex failure modes of composites. Different types of internal damage are not easy to be detected, observed and distinguished. Without an estimated location, traditional non-destructive evaluation (NDE) techniques are time-consuming and labor intensive for inspecting damage. If an impact is suspected in service, it could lead to considerable operation cost, and more seriously, if an impact occurs without notice it could lead to un-anticipated structural failure. The current practice of including significant margins of safety in design leads to heavy inefficient structures.

In order to reduce maintenance and enhance reliability, researchers have been developing different diagnosing sensory systems to achieve structural health monitoring (SHM) that make composites “intelligent,” which means that composite structures can have the ability to automatically detect impacts, detect damage and further predict their lifetime for future maintenance consideration.

Current passive SHM systems are capable of detecting impacts, determining their location and reconstructing the impact load. Additionally acoustic ultrasound (AU) based active SHM systems are capable of detecting and locating multiple forms of damage in composites by comparing propagated signals to baseline data; however, this baseline data changes with temperature. In real structures it is desirable to detect damage at a range of temperatures. Existing systems are not capable of this without tremendous databases of reference data taken at multiple temperatures. Furthermore, current SHM hardware is not capable of withstanding temperatures greater then approximately 150℃.

High curing temperatures (above 300℃) required for high-temperature PMCs can completely de-functionalize the lead zirconate titanate (PZT) based piezoelectric sensors used in both passive impact detection systems and AU active systems.
This paper presents ongoing research to overcome these issues. This work includes temperature compensation algorithms that work with developed diagnostic systems to greatly reduce the number of necessary baseline data points required in systems with significant temperature variations enabling accurate reconstruction of useful sensor signals. Ongoing work also includes the development of high-temperature piezoelectric material system, promising to overcome the temperature limits of current commercial piezoelectric elements.

2 Development of a High-Temperature Intelligent Sensory System

2.1 Intelligent Damage Diagnostics System

As stated above, an intelligent structure is a structure that it is able to assess its current damage state via damage diagnostics, and based on this information estimate its remaining useful life through prognostic models to accommodate for more efficient maintenance schedules. Composite materials damage mechanics are very complex due to their anisotropic properties. Two of the main damage types that lead to failure are matrix micro-cracks and inter-laminar delaminations. Matrix micro-cracks first develop in the matrix through the ply thickness direction, creating stress concentration at the plies' interfaces. As more cracks develop, the interfacial stress increases up to a point where delamination is initiated and is propagated along the ply interface. Many models for damage propagation and transition from matrix micro-cracks to delamination have been proposed [1-4]. Assessing the current damage state of the structure can be achieved through knowledge of the current damage type (matrix micro-cracks or delamination) and its extent. In the case when only matrix micro-cracks are present, delamination initiation can be prevented. If it is known that delamination has already developed, delamination propagation could be avoided.

Fatigue tests and experiments have been designed and performed on composite plates with surface mounted piezoelectric sensor networks (SMARTLayer®) to acquire sensor data as a function of damage progression [5, 6]. X-ray images of the composite plates were taken throughout the experiment to correlate diagnostic signals to damage type and quantity. Within the signal parameters affected, it was found that while some parameters are very sensitive to delamination only, there was only one parameter that was sensitive to matrix micro-cracks increase. This same parameter is affected by delamination, so in order to trust the matrix micro-cracks' parameter, a supervised learning classification algorithm was implemented to classify whether an actuator to sensor path has developed both matrix micro-cracks and delamination or matrix micro cracks only [6]. After classification, the parameter was used to quantify matrix micro-cracks per path. The delamination sensitive parameters were used to diagnose the location and extent of delamination by implementing a modified version of the pitch catch damage imaging algorithm [5]. Work in progress is focusing on linking the damage diagnosis information gathered from the methods developed above and using them as inputs into a Fatigue Progressive Failure Analysis [7] and expanded for cyclic loads [8-9], a flowchart is presented in Fig. 1.
This work focuses on data acquisition and interpretation when the structure is at room temperature in an unloaded condition. The following sections will explain how changes in temperature can change the sensor and sensed signal; and describe the current efforts to overcome these challenges.

2.2 Temperature Compensation Model

The underlying principle for any structural damage diagnosis is to compare the current state of the structure with the reference undamaged state. Such comparisons are usually carried out by monitoring changes in high frequency acoustic waves transmitted through the structure. These acoustic ultrasound waves are generated and detected with arrays of piezoelectric devices either embedded within or mounted on the surface of a structure. One of the widely accepted challenges in the field of AU SHM is to perform accurate damage diagnosis even in the presence of changing environmental conditions especially due to ambient temperature. This issue is typically addressed through referencing enormous amounts of data taken through temperature variations with high resolution. The lack of physical insight severely constrains the practical implementation of these data driven strategies [10-12].

The temperature compensation model developed at the Structures and Composites Laboratory at Stanford University addresses the problem by understanding the role of physical parameters that affect the wave propagation due to the changes in the ambient temperature. A simple system identification model, relating the changes in the sensor signal to the changes in physical properties, is generated from a set of very few experimental measurements [13]. The model is then used to compensate baseline sensor signals so they appropriately represent a signal at the proper temperature. The generated signal from the model is then used for environmental compensation and fed to the diagnostics algorithm for accurate damage diagnosis.

2.3 High-Temperature Piezoelectric Materials

In order to deploy SHM systems through a wide range of temperatures, it is crucial to develop hardware that can function at those temperatures in addition to temperature-compensated diagnostics algorithms. The key to this is the development of sensor systems that can survive the harsh curing conditions and the extreme working environments of high temperature composites. The current limitation in SHM systems is the PZT-based piezoelectric element. After exposure to temperatures higher than the depoling temperature of the piezoelectric elements, the piezoelectric sensor responses will be greatly reduced, if it exists at all, and no more signals can be sent or received by the actuator/sensor arrays for further monitoring.

State of the art PZT-based transducers can only survive temperatures up to about 200℃, which is not sufficient for the proposed integration with high-temperature PMCs. Therefore, a new high-temperature piezoelectric material system is required and its material properties are critical for generating strong/clear enough signals across the structure.

For most of the piezoelectric material systems, higher temperature tolerance usually comes with lower piezoelectric response due to the fact that stronger chemical bonds provide better stability at high temperatures but also suppress the actuation amplitude of molecules in the unit cell. Recently, after a series of studies on different combination components with $PbTiO_3$, Eitel *et al.* found that the combination of $BiScO_3$ and $PbTiO_3$, or Bismuth Scandate Lead Titanate (BS-PT) is a promising material system for high-temperature piezoelectric actuator/sensor applications [14].

Other studies have also shown that microstructure configurations and chemical stoichiometry ratio can be used to enhance BS-PT properties for further high-temperature applications [15-17]. Based on the previous knowledge about BS-PT properties, experimentation with different stoichiometry of BS-PT solid solution systems was performed at in the Structures and Composites Laboratory at Stanford University to further improve the material properties.

3 Experimental Results

3.1 Temperature Compensation Tests

The effects of changes in ambient temperature on the PZT sensor signals are investigated with a 2mm-thick aluminum plate (18"x12") shown in Fig. 2. The PZT Smart® transducers are attached to the surface of the aluminum plate using 'Hysol 9696' thin film adhesive. The PZT transducers are actuated with 'Burst 5' (5-peaks Gaussian tone-burst) signal type at 250 kHz. The signals are collected in pitch-catch mode wherein one transducer acts as an actuator while the rest of them act as sensors. The sensor signals are collected from the test specimen inside an oven at different controlled ambient temperatures. The upper limit of testing temperatures for this study is restricted to 95°C due to the constraints on the component level, primarily amongst them being the adhesive which gets softer at higher temperatures leading to a lot of attenuation on the wave propagation.

Fig. 3. shows the comparison between two signals from the same actuator-sensor pair collected at two different temperatures. As seen in Fig. 3., there are observable changes in the amplitude of signal peaks as well as the time at which they arrive at the specific sensor location. Fig. 4. shows the comparison between the reconstructed sensor signal from the model with the experimental sensor data collected at 60ºC. It can be observed that the model output matches quite well with the experimental sensor signal. The temperature compensation model

for high temperature composites is being developed using similar approach. An overall idea about temperature compensation for damage detection is shown in Fig. 5. The improvement in diagnostic capabilities under different thermal environment emphasizes the need of an efficient and reliable temperature compensation strategy.

3.2 High-Temperature Depoling Tests

Conventional Solid-State Reaction method is used to fabricate BS-PT transducers. Pellet samples are prepared in 1/4 inch in diameter with 15:1 diameter-to-thickness ratio to ensure that radial vibration mode dominates. The piezoelectric responses (piezoelectric coupling coefficient, d_{33}, pC/N) of all the polarized samples are measured with a YE2730 d_{33} meter (APC International Ltd.) at room temperature first, and then, measured again at room temperature after heat-treatments at different temperatures for both commercial PZT-based (PZT-5A) sensors and in-house fabricated BS-PT sensors. The in-house developed BS-PT sensors have even stronger piezoelectric response (d_{33} ~ 540 pC/N) than the commercial ones (d_{33} ~ 500 pC/N). After staying in different thermal depoling environments for two hours, as shown in Fig. 4, commercial PZTs can only maintain functions until 200℃ while our modified BS-PT material system can remain active up to 350 ℃ with significant decrease in piezoelectric response. After thermal depoling treatment at around the critical depoling temperature, our BS-PT sensors can still hold over 80% of their original piezoelectric response (d_{33} ~ 440 pC/N), which is sufficient for future high-temperature SHM applications..

3.3 Preliminary Signal Propagation Tests

For demonstrating potential functionality of BS-PT in SHM system, an array of in-house developed BS-PT actuators/sensors are attached to a backing glass plate. Various actuation frequencies and voltages are applied to BS-PT actuators, and signals propagating through the backing structure are received by BS-PT sensors along different detecting paths at different distances with a commercially available SHM digital-to-analog converter (Acellent Technologies Inc.) for data acquisition. Fig. 7. shows one baseline signal received by one sensor that is 9 cm away from the actuator using a 5-peak-burst waveform at 500 kHz. Compared with commercial PZT-based sensors, BS-PT sensors can also generate similar voltage amplitudes upon receiving structural LAMB waves. In this test, BS-PT sensors can produce clear voltage signals even when the actuator is around 20 cm away. At similar actuation voltages, BS-PT actuators/sensors show promising potentials to achieve real damage detection capabilities.

4 Conclusions and Future Work

This paper presented the current research efforts to build intelligent composite structures that will be functional and provide accurate results at high temperature ranges. Development of intelligent diagnostic algorithms and temperature compensation models was discussed. A newly developed high-temperature piezoelectric sensors (BS-PT) was presented and preliminary results show that not only it can survive the harsh curing conditions required for high-temperature PMCs, but also can potentially be utilized for AU SHM in higher temperature ranges. Ongoing research will focus on miniaturization and integration optimization of the high-temperature BSPT sensor/actuators and development of other high temperature network hardware in order to minimize possible property degradation of the host composite structures and enable full functionality at elevated temperatures.

References

[1] H. Choi "Damage in graphite/epoxy laminated composites due to low-velocity impact" *Dissertation, Department of Aeronautics and Astronautics, Stanford University,* 1990.

[2] B. Harris "*Fatigue in composites*" Woodhead Publishing (2003).

[3] P. Johnson, F-K. Chang "Characterization of matrix crack-induced laminate failure- Part I: Experiments" *Journal of composite materials*, Vol.35, No.22, 2003.

[4] P.W.R Beaumont, R.A. Dimant, and H.R. Shercliff "Failure processes in composite materials: getting physical" *Journal of material science,* Vol 41, pp 6526-6546, 2006.

[5] C. Larrosa, V. Janapati, S. Roy, F-K. Chang "In-situ damage assessment of composite laminates via active sensor networks" *The 2011 Aircraft Airworthiness and Sustainment Conference*, San Diego, CA, 2011

[6] C. Larrosa, V. Janapti, V. Lonkar, S. Shankar, F-K. Chang "Damage classification and Quantification in composite laminates" *The 8th International Workshop on Structural Health Monitoring*, Stanford, CA, 2011

[7] I. Shahidand, F.-K. Chang "Progressive failure analysis of laminated composites subjected to in-plane and shear loads" *Dissertation, Department of Aeronautics and Astronautics, Stanford University,* 1993.

[8] I. Mueller, C. Larrosa, S. Roy, A. Mittal, K. Lonkar, F.-K. Chang "An integrated health management and prognostic technology for composites airframe structures" *The annual conference of the Prognostics and Health Management Society*, 2009.

[9] I. Mueller, C. Larrosa, S. Roy, F.-K. Chang "An integrated diagnostic to prognostic SHM technology for structural health management" *The 7th International Workshop on Structural Health Monitoring*, 2009.

[10] Y. Lu, J. Michaels "A methodology for structural health monitoring with diffuse ultrasonic waves in the presence of temperature variations" *Ultrasonics* Vol.43, pp 717-731, 2005.

[11] A. J. Croxford *et al.* "Efficient temperature compensation strategies for guided wave structural health monitoring" *Ultrasonics* Vol.50, pp 517-528, 2010

[12] G. Konstantinidis *et al.* "The temperature stability of guided wave structural health monitoring systems" *Smart Mater. Struct.* Vol. 15, pp 967–976, 2009.

[13] S. Roy *et al.* "Physics based temperature compensation strategy for structural health monitoring" *The 8th International Workshop on Structural Health Monitoring,* Stanford, CA, 2011

[14] R. Eitel *et al.* "New High Temperature Morphotropic Phase Boundary Piezoelectrics Based on Bi(Me)O3–PbTiO3 Ceramics" *Jpn. J. Appl. Phys.* Vol. 40, No. 10, pp 5999-6002, 2001

[15] R. Eitel *et al.* "Preparation and Characterization of High Temperature Perovskite Ferroelectrics in the Solid-Solution (1-x) $BiScO_3$–x $PbTiO_3$" *Jpn. J. Appl. Phys.* Vol. 41, No. 4A, pp 2099-2104, 2002

[16] S. Chen *et al.* "Thermal Stability of (1-x) $BiScO_3$–x $PbTiO_3$ Piezoelectric Ceramics for High-Temperature Sensor Applications" *J. Am. Ceram. Soc.*, Vol. 89, No. 10, pp 3270-3272, 2006

[17] A. Sehirlioglu, A. Sayir, F. Dynys "Doping of $BiScO_3$–$PbTiO_3$ Ceramics for Enhanced Properties" *J. Am. Ceram. Soc.*, Vol. 93, No. 6, pp 1718-1724, 2010

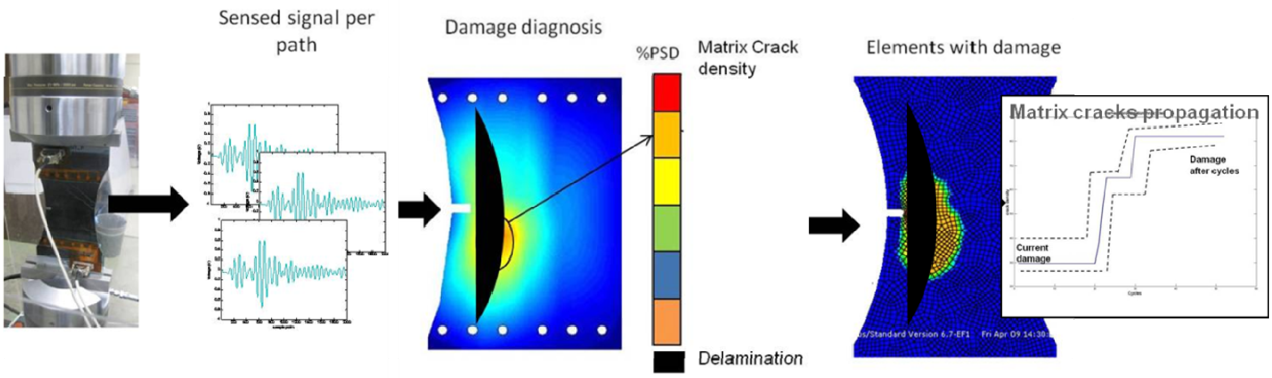

Fig. 1. Experimental data acquired from piezoelectric sensors, data interpretation into damage diagnosis, the current state is used as input for a fatigue progressive failure analysis' matrix-micro-cracks increase.

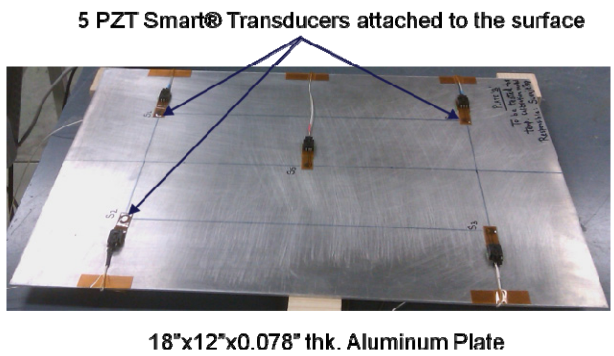

Fig. 2. Aluminum Plate with PZT Smart Transducers

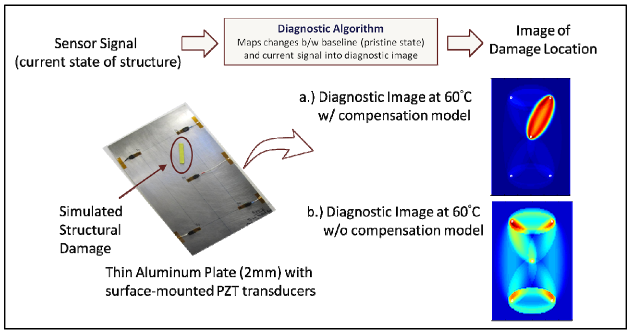

Fig. 5. Imaging of a simulated structural damage using sticky tape on aluminum plate kept at 60ºC inside the oven a.) Imaging with compensation model and b.) Imaging without compensation model

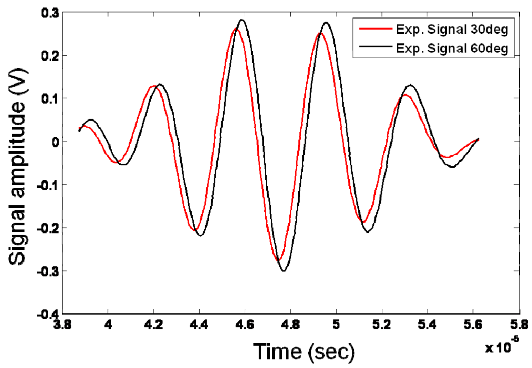

Fig. 3. Comparison of experimental sensor signal measured at two different temperatures 30ºC vs. 60 ºC

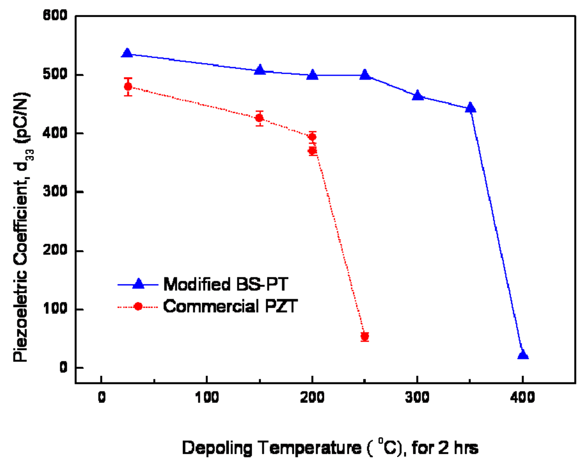

Fig. 6. Results of thermal depoling tests for commercial PZT-based sensors and BS-PT sensors.

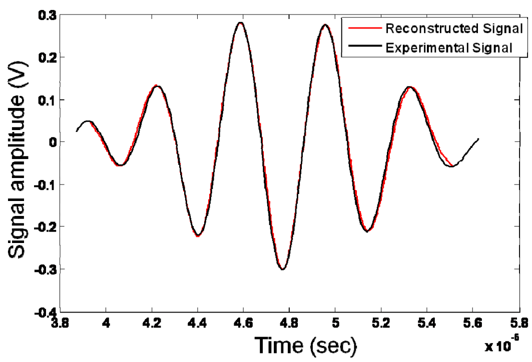

Fig. 4. Comparison of reconstructed sensor signal & experimental sensor signal measured at 60°C

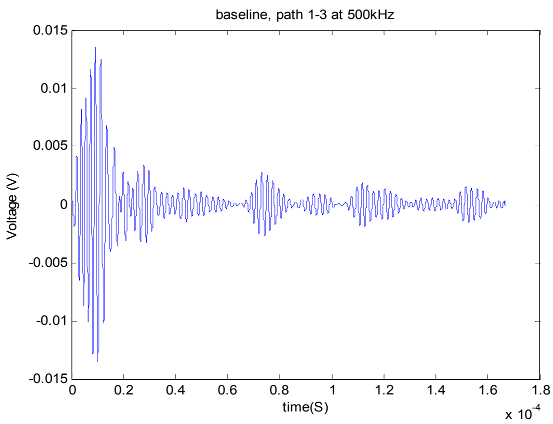

Fig. 7. Signals received by BS-PT sensor