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Damage detection at cryogenic temperatures in composites using piezoelectric wafer active sensors

Giola Santoni-Bottai and Victor Giurgiutiu

Abstract
An experimental evaluation of the structural health monitoring capability of piezoelectric wafer active sensors on composite structures at cryogenic temperatures is presented. The piezoelectric wafer active sensor–based electromechanical impedance and the pitch–catch methods were first qualified for cryogenic temperatures using piezoelectric wafer active sensor–instrumented composite specimens dipped in liquid N2. Subsequently, damage detection experiments were performed on laboratory-scale composite specimens with (a) impact damage and (b) built-in Teflon patches simulating in service delaminations. Finally, a comprehensive damage detection test was performed on a full-scale specimen subjected to pressure and cryogenic temperature cycles. Based on these tests, we conclude that piezoelectric wafer active sensor–based structural health monitoring methods show promise for damage detection in composite materials even in extreme cryogenic conditions. Recommendations for further work are also included.

Keywords
Piezoelectric wafer active sensor, damage detection, composite structures, cryogenic temperature, nondestructive evaluation, structural health monitoring

Introduction
Structural health monitoring (SHM) is an emerging technology with multiple applications in the evaluation of critical structures. The goal of current SHM research is to develop a monitoring system that is capable of detecting and identifying various damage modes during the service life of the structure with minimal human intervention. Numerous SHM approaches have been proposed1–4; they can be broadly classified into two categories: passive SHM and active SHM. Passive SHM methods, such as monitoring strain, acceleration, and acoustic emission, are relatively mature methods but have limited utility because they can only infer the presence of damage from the passive measurements but cannot directly interrogate the structure to detect the damage. Active SHM methods are currently of more interest because of their ability to interrogate a structure and detect damage presence, location, and intensity. One of the promising active SHM methods utilizes arrays of piezoelectric wafer active sensors (PWASs) bonded to a structure that can both transmit and receive ultrasonic elastic waves to achieve damage detection.5–7 When used to interrogate thin plate structures, PWAS transducers are effective Lamb wave transducers. The PWAS transducers couple their in-plane motion with the Lamb wave particle motion on the material surface. The in-plane PWAS motion is excited by the applied oscillatory voltage through the $d_{31}$ piezoelectric coupling. Optimum excitation and detection happen when the PWAS length is an odd multiple of the half wavelength of particular Lamb wave modes. The principle of wave generation through PWAS is fundamentally different from that of conventional ultrasonic transducers. Conventional ultrasonic transducers act through surface tapping, applying vibrational pressure to the object’s surface. PWASs, on the other hand, act through surface pinching and are

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strain coupled with the object’s surface. This allows PWAS to have a greater efficiency in transmitting and receiving ultrasonic guided wave compared to conventional ultrasonic transducers.

Due to the increased use of composite materials in numerous types of structures, particularly in aerospace structures, it is important to prove that an active SHM system is capable of reliably detecting composite material damage. For example, one of the most troubling forms of damage in laminated composites is the low-velocity impact damage. This type of damage may leave no visual traces but can generate subsurface delaminations, which may significantly reduce the structural strength. Internal delaminations in composite structures may also result from mechanical and thermal cycling; if not detected at an early stage, these delaminations may lead to a catastrophic failure of the composite structure.

The present article investigates the use of PWAS to generate and sense ultrasonic guided waves to detect damage presence in composites. Section “State of the art” reviews the state of the art in PWAS-based damage detection and the different methods being used. Section “Cryogenic operability and survivability experiments” presents operability and survivability experiments that prove that PWAS-based SHM methods can operate on specimens subjected to cryogenic temperature (CT). Section “Damage detection experiments on laboratory specimens” demonstrates how a PWAS-based SHM system can detect low-velocity impact damage and built-in delaminations at both room temperature (RT) and CT. Section “Damage detection on full-scale composite specimen subjected to cryogenic and pressure cycling” presents results of a comprehensive test in which a full-scale composite specimen instrumented with PWAS transducers was subjected to pressure and CT cycling. This test showed that a PWAS-based SHM system is able to withstand and survive cryogenic thermal cycles under cycling pressure loading while performing meaningful damage detection tasks.

As most of the space applications are moving toward composite material, a new set of experiments was determined to validate the SHM system for space application on composite structures. The structural components for space applications are subjected to high loads and extreme low temperatures, that is, $T = -185\, ^\circ C \, (-300\, ^\circ F)$.

**Pitch–catch method**

Pitch–catch method (Figure 1(a)) can be used to detect structural changes that take place between a transmitter transducer and a receiver transducer. The detection is performed through the examination of the Lamb wave amplitude, phase, dispersion, and time of flight in comparison with a baseline signal corresponding to a “pristine” condition. Typical applications include (a) corrosion detection in metallic structures, (b) diffused damage in composites, (c) disbonds detection in adhesive joints, (d) delamination detection in layered composites, and so on. The pitch–catch method can also be used to detect the presence of cracks from the wave signal diffracted by the crack.

**Pulse–echo method**

The use of Lamb wave pulse–echo methods with embedded PWAS follows the general principles of conventional Lamb wave NDE. A PWAS transducer attached to the structure acts as both transmitter and detector of Lamb waves traveling in the structure. The wave sent by the PWAS is partially reflected at the crack. The echo is captured at the same PWAS acting

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**State of the art**

Significant research effort has been invested in studying the possibility of using in situ ultrasonic nondestructive evaluation (NDE) methods for the development of SHM systems. Wave propagation methods were used for detection of cracks, corrosion, and disbonds in stiffened metallic panels. Also, the ability to detect cracks under bolts and rivets was investigated. It was found that successful damage detection can be achieved using wave propagation methods (pitch–catch and pulse–echo methods) as well as the electromechanical (E/M) impedance method.

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**Figure 1.** PWAS-based in situ damage detection methods: (a) pitch–catch method, (b) pulse–echo method, and (c) E/M method.

PWAS: piezoelectric wafer active sensor; E/M: electromechanical.
as receiver (Figure 1(b)). For the method to be successful, it is important that a low-dispersion Lamb wave is used. The selection of such a wave is achieved through the Lamb wave tuning methods.\textsuperscript{5}

**E/M impedance method**

The E/M impedance method is an active damage detection technique complementary to the wave propagation methods. E/M impedance method gives structural dynamics identification at hundreds of kilohertz and low megahertz.\textsuperscript{13} Because high frequency implies small wavelength, PWAS-based E/M impedance spectroscopy (EMIS) is able to detect subtle changes associated with the presence of incipient damage, which would not be detected by conventional modal analysis sensors that operate at much lower frequencies.

The E/M impedance principles are illustrated in Figure 1(c), where the left side represents the electrical transducers and the right side represents the structure offering to the interrogating PWAS, a frequency-dependent mechanical impedance. \( Z_{\text{str}}(\omega) = -\omega^2 m(\omega) + i\omega c(\omega) + k(\omega)/i\omega \). Hence, the impedance measured by the impedance analyzer is a combination of the intrinsic PWAS impedance \( Z_{\text{PWAS}}(\omega) = 1/i\omega C \) and structural impedance \( Z_{\text{str}}(\omega) \), that is

\[
Z(\omega) = Z_{\text{PWAS}}(\omega) \left[ 1 - k_3^2 \frac{Z_{\text{str}}(\omega)}{Z_{\text{PWAS}}(\omega) + Z_{\text{str}}(\omega)} \right] \quad (1)
\]

where \( k_3^2 \) is the E/M coupling coefficient of the PWAS material. The E/M impedance method is applied by scanning a predetermined frequency range in the hundreds of kilohertz band and recording the complex impedance spectrum. By comparing the impedance spectra taken at various times during the service life of a structure, meaningful information can be extracted pertinent to structural degradation and the appearance of incipient damage. Previous work (e.g. Ref. 14) has shown that the E/M impedance method can be very effective in detecting incipient damage in aerospace-like structures.

**PWAS–Lamb wave tuning**

Lamb wave theory is extensively documented in a number of textbooks.\textsuperscript{15–17} The Lamb wave equations for an isotropic media can be expressed through two potential functions and the longitudinal and shear wave velocity characteristic of the material. The shear horizontal (SH) wave can be studied separately because it is decoupled from the pressure (P) and shear vertical (SV) waves. For the case of a plate with free boundaries, the P and SV waves are coupled and their interaction generates the Lamb wave. Lamb waves modes can be symmetric and antisymmetric with respect to the mid-surface. Closed-form analytical solutions exist and the Lamb wave speeds can be found as transcendental roots of the Rayleigh–Lamb characteristic equation. Lamb waves are dispersive because the wave speed changes with frequency. For a given plate, a threshold exists below which only the fundamental guided-wave modes (A\( _0 \), S\( _0 \), and SH\( _0 \)) exist. For laminated composite plates, closed-form solutions do not exist and the solution to the problem has to be obtained numerically using the transfer matrix, the global matrix, the stiffness matrix, or other approaches.\textsuperscript{18–24}

Commonly used Lamb wave transducers for ultrasonic NDE are piezoelectric wedge transducers; the wedge angle and transducer frequency can be designed to excite particular Lamb wave modes as needed for structural interrogation. These wedge transducers are bulky and are not appropriate for aerospace SHM applications. PWAS transducers are much smaller than wedge transducers and can be used for SHM applications, but they are broadband and hence excite all the Lamb wave modes present at a given frequency-thickness product. The simultaneous presence of two or more Lamb wave modes increases the difficulty of the damage detection process. The ability to excite a single wave mode would be useful for effective damage detection. Through PWAS–Lamb wave tuning,\textsuperscript{25} one can selectively reject certain Lamb wave modes and amplify others by judiciously combining PWAS size and excitation frequency. The PWAS–Lamb wave tuning concept is based on the strain response formula

\[
e_{\xi}(x, t) = -i \frac{\alpha t_0}{\mu} \sum_{\xi} \left( \sin \xi a \frac{N_2(\xi a)}{D_2(\xi a)} \right) e^{i\xi x - \omega t} + \frac{1}{i\omega} \sum_{\xi} \left( \sin \xi a \frac{N_1(\xi a)}{D_1(\xi a)} \right) e^{i\xi x - \omega t} \quad (2)
\]

where \( a \) is the PWAS half-size, \( \xi \) is the wave number, whereas superscripts A and S signify antisymmetric and symmetric modes. (The other Lamb wave analysis notations, which can be found in Ref. 25 or in Ref. 26, p.327, equation (99), were not included here for brevity.) The PWAS–Lamb wave tuning process can be articulated as follows: It is apparent from equation (2) that if the product \( \xi a \) equals an odd multiple of \( \pi/2 \), then the function \( \sin \xi a \) takes extreme values and the associated Lamb wave mode is maximized. Conversely, if the product \( \xi a \) equals an even multiple of \( \pi/2 \), then \( \sin \xi a \) vanishes and that particular Lamb wave mode is rejected. This tuning concept was developed in Ref. 25 for straight-crested Lamb waves; subsequently, it was extended in Ref. 27 to circular-crested Lamb waves. Experimental confirmation of this tuning concept was
also provided.\textsuperscript{25,27} Lamb wave tuning has also been observed with PWAS mounted on anisotropic composites;\textsuperscript{28} an extension of equation (2) to composite laminates has recently been attained.\textsuperscript{29} Pitch–catch experiments performed on composite materials using one PWAS transmitter and several PWAS receivers placed at various angular directions with respect to the composite material fiber orientation showed that in composite materials, the tuning depends on wave propagation direction.\textsuperscript{28} In another experiment, round PWAS transducers (7 mm in diameter, 0.2 mm in thickness, American Piezo Ceramics APC-850 material) were bonded to a quasi-isotropic composite plate. Three waves were detected: $S_0$, $A_0$, and $SH_0$. Rejection of the $A_0$ mode was observed at certain frequencies when the $A_0$ packet almost disappears and the $S_0$ packet becomes maximized. However, the actuation of a pure $S_0$ mode in quasi-isotropic was not entirely possible because the $SH_0$ mode also appeared because of the intrinsic coupling in the quasi-isotropic composite material.

**Cryogenic operability and survivability experiments**

The basic element used for damage detection in these experiments was a round PWAS transducer (7 mm in diameter, 0.2 mm in thickness, American Piezo Ceramics APC-850 material). In a previous study,\textsuperscript{30} we proved that the piezoelectric material APC-850 and the PWAS transducers are able to retain their operational abilities after exposure to cryogenic conditions. To reproduce cryogenic conditions, we used containers filled with liquid $N_2$, which ensure a temperature around $-200^\circ C$. Free PWAS resonators as well as PWAS transducers attached to metallic plates were submerged in the liquid $N_2$ container, kept there for 10 min, and had their E/M impedance signature taken. Then, they were returned to RT and had the E/M impedance signature taken again. The process was repeated for 10 times with good results.\textsuperscript{30}

In this study, we used a similar approach but with the focus on composite material specimens. In addition, we also augmented the experiments with pitch–catch measurements besides the E/M impedance measurements. The experiments performed in this study are listed in Table 1. The set of experiments were divided into two groups. The aim of first set of experiments was to determine the CT operability of a PWAS-based SHM approach for composite materials. The aim of second set of experiments was to perform damage detection with a PWAS-based SHM system operating on composite specimens subjected to cryogenic conditions.

The adhesive layer between the PWAS and the structure and solder material used to connect the PWAS electrodes to the electric wiring was carefully selected. The selected adhesive was the two-component Vishay M-Bond AE-15 with an operating range down to $-270^\circ C$ ($-450^\circ F$). The selected solder was indium-based 97In3Ag with good performance at CT. (Sn/Pb solder was not used because it was previously found\textsuperscript{30} that it becomes brittle and fragile at CT.)

A strip of unidirectional carbon/epoxy composite material was used to test the PWAS pitch–catch operability at CTs. Figure 2(a) shows the specimen with several PWASs attached to it; Figure 2(b) shows the experimental setup.

Figure 3 shows the impedance signatures.\textsuperscript{30} From the data recorded, it can be seen that the SHM system impedance curves did not change significantly after submersion in liquid $N_2$; the peak amplitude and their relative frequency location seem to remain the same throughout the experiment.\textsuperscript{30}

<table>
<thead>
<tr>
<th>Table 1. Summary of experiments discussed in this article</th>
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<tbody>
<tr>
<td><strong>Cryogenic operability and survivability experiments</strong></td>
</tr>
<tr>
<td>Specimen</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Unidirectional composite strip</td>
</tr>
<tr>
<td>1</td>
</tr>
<tr>
<td><strong>Cryogenic damage detection experiments</strong></td>
</tr>
<tr>
<td>Specimen</td>
</tr>
<tr>
<td>----------</td>
</tr>
<tr>
<td>Lap joint</td>
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<tr>
<td>Thick plate</td>
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<tr>
<td>Cylindrical specimen</td>
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</table>
Figure 4 shows pitch–catch wave propagation before, during, and after submersion of the specimen in liquid nitrogen. The data collected showed that the PWAS was able to send and receive signal at CTs. However, when the specimen was submerged in the liquid nitrogen, the amplitude of the wave packet decreased. This behavior is consistent with studies performed elsewhere, which showed that fluid coupling can reduce the Lamb wave propagation velocity and amplitude.31 In this study, it is apparent that the effect of submerging the specimen into liquid N2 is twofold: (a) effects that are due to fluid loading and Lamb wave leakage and (b) effects that are due to CT. In our article, the focus has been on the latter effects, that is, on how the CT might influence the performance of the PWAS transducers. The data shown in Figure 4 indicate the following: (a) PWAS transducers are still active at CTs and are able to transmit and receive guided Lamb waves into the specimen and (b) nonetheless, a specimen with pitch–catch PWAS attached to it behaves differently at RT after exposure to CT by submersion in liquid N2 than before submersion. Figure 4 shows that the wave amplitude after submersion is lower than before submersion. (When submerged in liquid N2, the wave amplitude is even lower because of the additional wave leakage effect.) We are not sure at this stage why this reduction in performance happens after submersion in liquid N2 and return to RT, but we believe that it is not due to a degradation in piezoelectric properties of the piezoceramic material because separate tests performed on free PWAS transducers indicated that there is no performance degradation to the piezoelectric material after cryogenic exposure through submersion in liquid N2.30 Hence, we believe that the decrease in performance could be attributed to a degradation of the adhesive bond between the PWAS and the specimen due to the differential coefficient of thermal expansion (CTE) between the two materials. This aspect needs further investigation; we plan to do it...
as soon as practically possible if further funding is available; we will report such new results in a future communication.

In brief, the amplitude of the wave packets at RT after submersion in liquid nitrogen did not return to the original amplitudes. However, the amplitudes of the wave packets were greater than those of the specimen submerged in liquid $N_2$, because the wave excited by the PWAS leaked into the liquid when the specimen was submerged in liquid $N_2$.

**Damage detection experiments on laboratory specimens**

*Composite specimen types*

The PWAS ability to perform damage detection SHM on composite specimens under cryogenic conditions was verified on three test specimen types. The first type of specimen was a composite lap joint. The geometry of the specimen is shown in Figure 5. The specimen was made of two composite plates of $305 \times 230$ mm$^2$ ($12'' \times 9''$), and the plates were bonded together with an overlap of 100 mm ($\sim 4''$). Two PWAS pairs were installed as indicated in Figure 5. The following tests were performed: (a) damage detection at RT with PWAS pair 1 and (b) damage detection at CT with PWAS pair 2.

The second type of specimen was a thick composite plate (Figure 6). The composite plate had a dimension of $305 \times 230$ mm$^2$ ($12'' \times 9''$). To simulate delamination damage, the specimen was fabricated with 16 Teflon patches of different sizes located inserted between various plies. The four patches of interest in the experiments are marked as A, B, C, and D in Figure 6.

The four patches had different dimensions and different thickness-wise locations (Table 2). Patches A and B had a diameter of $\sim 6.35$ mm (0.25''), patch C had a diameter of $\sim 19$ mm (0.75''), and patch D had a diameter of $\sim 13$ mm (0.5''). Patches A and C were located close to one of the surfaces while patches B and D were closer to the mid-plane. Two experiments were performed on the specimen: (a) patch damage detection at RT and (b) patch damage detection at CT.

The third specimen type was a full-scale composite specimen of cylindrical shape. The specimen was thermomechanically cycled to CT of about $-185^\circ C$ ($-300^\circ F$) and peak strains around 7000 microstrain. This section discusses the laboratory tests performed on the first and second specimen types. The tests performed on the third specimen type are discussed in the next section.

**Damage index calculation**

The data collected in the experiments were analyzed using a damage index (DI). The DI is a scalar number that reveals the difference between sequential readings (impedance spectrum or wave packets) due to the damage accumulation. Ideally, the DI should only capture the changes in the signal that are directly related to the damage presence, while not being influenced by

<table>
<thead>
<tr>
<th>Step</th>
<th>Patch name</th>
<th>Patch dimension (mm)</th>
<th>Patch location</th>
<th>PWAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>04–01</td>
<td></td>
<td>04–07</td>
</tr>
<tr>
<td>2</td>
<td>A</td>
<td>6.35</td>
<td>Close to surface</td>
<td>05–00</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>19</td>
<td></td>
<td>05–08</td>
</tr>
<tr>
<td>3</td>
<td>B</td>
<td>6.35</td>
<td>Close to the mid-plane</td>
<td>03–02</td>
</tr>
<tr>
<td></td>
<td>D</td>
<td>13</td>
<td></td>
<td>03–06</td>
</tr>
</tbody>
</table>

PWAS: piezoelectric wafer active sensor.
variations due to normal operation conditions (i.e. statistical difference within a population of specimens, and expected changes in temperature, pressure, ambient vibrations, etc.). To date, several simple DI formulae have been proposed, for example, root mean square deviation (RMSD), mean absolute percentage deviation (MAPD), and correlation coefficient deviation (CCD). In this work, we have used RMSD defined as

\[
RMSD = \sqrt{\frac{\sum_{i=1}^{n} \left( \text{Re}(S_i) - \text{Re}(S_0) \right)^2}{\sum_{i=1}^{n} \left( \text{Re}(S_0) \right)^2}}
\]

where \(S_i, i = 1, \ldots, n\), is the sampled signal and superscript 0 denotes the initial (baseline) state. Thus, the symbol \(S_0\) represents the baseline signal. The RMSD equation (3) yields a scalar number, which is zero initially and increases as the signal becomes more and more different. The advantage of using a simple DI formula is that no data preprocessing is needed, that is, the data obtained from the measurement equipment can be directly used to calculate the DI. The DI was used to assess the severity of the damage in each test run. Several readings were taken of the undamaged (baseline) condition and of each damaged configuration in order to assess the statistical spread. The resulting DIs were plotted as “box plots” representing the mean value plus/minus a standard deviation.

**Impact detection on composite lap joint**

The composite lap joint was subjected to impact damage. The impact damage was applied to the plate using the impactor shown in Figure 7.

The impactor had a hemispherical tip of ~13 mm in diameter and its weight was 391 g. The impactor weight could be increased by adding barrels (Figure 7(b)). Each barrel weighted 500 g; a total of three barrels could be added to the impactor.

The impactor used in our experiments had a total weight of 1391 g. Two different impact damage states were created at each site by dropping the impactor from different heights. The first impact damage state had an impact energy level of 6 ft lb (~16 J) and hit the plate at about 11 ft/s (3.35 m/s); the second impact damage state had an impact energy level of 12 ft lb (~16 J) and hit the plate at about 16 ft/s (~5 m/s).

A total of 11 readings were taken in the undamaged baseline configuration, 10 readings were taken after the impact with energy level of 6 ft lb, and 10 readings were recorded after the impact at 12 ft lb (see Table 3). The first reading in the set of baseline readings was used as the reference reading for the DI analysis.

The location of the PWAS and the impact sites on the lap joint are shown in Figure 5. Two pairs of PWAS were installed on one side of the lap joint; each pair of PWAS was bonded close to one of the edges of the joint. The distance between the PWAS transducers was ~200 mm (8”). We used the Lamb wave tuning method to select the frequencies at which there was only one mode present. We found such conditions at 54 and 318 kHz. The wave speed at 54 kHz was 1175 m/s, with wavelength of 21.8 mm. The wave speed at 318 kHz was 3065 m/s, with wavelength of 10 mm.

Figures 8 to 11 show the plot of the RMSD values for the baseline (step 1), the first damaged condition (step 2), and the second damaged condition (step 3). Figure 8 shows the plots of the DI values for two different frequencies. Both low and high frequencies were able to detect impacts at 6 and 12 ft lb with a significance level of 99%.

From Figure 8, we see that the absolute difference at low frequency between steps 1 and 2 is much higher than at high frequency. This indicates that lower frequencies are more sensitive to impact damage at RT than the high-frequency excitations. The explanation for this phenomenon is as follows. For impact damage, the structural damage is a delamination in the composite layup; the presence of the delamination changes significantly the local flexural stiffness of the specimen. As indicated by the tuning principle, lower frequencies tend to excite more predominantly the pseudo-flexural antisymmetric wave mode, which is more sensitive to this type of damage than the pseudo-axial symmetric wave mode excited at higher frequencies. This explains our observation that the low frequencies are more sensitive to this type of damage than the high frequencies.

Similar tests were performed using the PWAS system for damage detection on the lap joint at CTs. Two frequencies were selected through tuning: 60 and 318 kHz. The wave speed at 60 kHz was 1410 m/s with wavelength of 23 mm. The wave speed at 318 kHz was 3065

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**Figure 7.** Impactor for impact damage: (a) base impactor with hemispherical tip, (b) barrel, and (c) impactor assembled.
m/s with wavelength of 10 mm. The data were collected at temperatures below −150°C.

Figure 9 shows the plots of the DI values for the two different frequencies. Both low and high frequencies were able to detect the impacts with a significance level of 99%. At CTs, the low and high frequencies show a similar sensitivity to the impact damage. We do not have at this stage an explanation to why the difference in detection sensitivity between different frequencies, as observed at RT, did not also appear at CTs.

In brief, the PWAS-based pitch–catch method was able to detect impact damage in composite lap-joint specimen at CTs with reasonable sensitivity.

### Simulated delamination detection on thick plate composite specimen

Nine PWAS transducers were installed on the thick specimen (Figure 6). The experiments were performed to

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**Table 3. Summary of impact test parameters on lap-joint specimen**

<table>
<thead>
<tr>
<th>Readings</th>
<th>Energy ft lb (J)</th>
<th>Velocity ft/s (m/s)</th>
<th>Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>00–10</td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>11–20</td>
<td>6 (~8)</td>
<td>11 (~3.35)</td>
<td>2</td>
</tr>
<tr>
<td>21–30</td>
<td>12 (~16)</td>
<td>16 (~5)</td>
<td>3</td>
</tr>
</tbody>
</table>

**Figure 8.** DI values for different damage levels (PWAS pair 00–02) at RT on the composite lap-joint specimen: (a) excitation frequency at 54 kHz and (b) excitation frequency at 318 kHz.

DI: damage index; PWAS: piezoelectric wafer active sensor; RT: room temperature.

**Figure 9.** DI values for different damage levels (PWAS pair 00–02) at CT on the composite lap-joint specimen: (a) excitation frequency at 54 kHz and (b) excitation frequency at 318 kHz.

DI: damage index; PWAS: piezoelectric wafer active sensor; CT: cryogenic temperature.
detect the presence of simulated delamination (Teflon patches) inserted during specimen manufacture. The readings taken with PWAS pairs P04–P01 and P04–P07 were used as baseline readings because there were no patches in the wave path between these PWAS pairs. Two experiments were performed on the specimen: (a) patch detection at RT and (b) patch detection at CT.

The thick plate specimen was scanned at two different frequencies: 60 and 318 kHz. The wave speed at 60 kHz was \(\sim 2680\) m/s with the wavelength of \(\sim 45\) mm. The wave speed at the high frequency of 318 kHz is not available.

Figure 10 shows the DI values for the thick plate specimen at RT. From the analysis of the DI values, we see that the low frequency is more sensitive to the patch thickness-wise location, especially when the patches are large (Figure 10(c)). The high frequency was more sensitive to the patch presence, but it is not affected by the patch dimension.

A similar experiment was conducted at CT. Readings were taken with temperatures below \(-150^\circ\)C. We used a different low frequency (75 kHz) because the CT caused a shift in the frequency of the maximum amplitude of the \(A_0\) mode. Figure 11 shows how DI index changed with the different steps. We found that there was significant difference between the steps; the PWASs were able to detect the presence of the patches. From the DI values, we determined that both frequencies could detect the presence of the patches; however, at 318 kHz, there was greater sensitivity to patch presence. The DI difference between steps 2 and 3 is always smaller than between steps 1 and 2. We can conclude that the depth or the dimension of the patches did not affect significantly the DI values at CT.

![Figure 10. Thick composite plate at RT: (a) excitation frequency at 60 kHz, delaminations A and B; (b) excitation frequency at 318 kHz, delaminations A and B; (c) excitation frequency at 60 kHz, delaminations C and D; and (d) excitation frequency at 318 kHz, delaminations C and D. DI: damage index.](https://www.sagepub.com)
Damage detection on full-scale composite specimen subjected to cryogenic and pressure cycling

The cylindrical specimen used for this experiment was a container that could be filled with liquid nitrogen and then emptied cyclically during the test. The specimen could also be cyclically subject to internal pressure of about 2500 lbf/in².

A PWAS transducers network was installed on the specimen as shown in Figure 12. The specimen area permitted for sensor installation was limited to four longitudinal columns located at 90° increments around the tank. Based upon this constraint, the PWAS transducers were installed as shown in Figure 12: 16 pairs of PWAS were installed along four rows at 90° increments; electrical ground connections were installed close to PWAS 16, PWAS 7, and PWAS 31.

The sensors were installed using a vacuum curing blanket. The adhesive used was the two-component Vishay AE-15, which has an operating temperature range down to −270°C (−420°F) and an elongation capability of 2% (20,000 microstrain) at −195°C (−320°F), which is far more than the expected maximum test strain (9000 microstrain). SWG 34 copper wire was used to connect the PWAS; the solder was 97In3Ag, which is known to behave well at low temperatures. The test lasted 4 days; impedance readings for each PWAS were taken at the beginning and end of each day. Table 4 reports the scans taken and the test environment for both pitch–catch and impedance data collection.

There were a total of six cycles with strain above 4000 µm/m and temperature below or equal to −185°C (−300°F). There were a total of seven cycles with strain above 4000 µm/m, and there were a total of three cycles with temperature below −185°C.
The status of each PWAS was visually checked before the test started; it was found that all PWAS transducers were properly bonded to the specimen. Capacitance and impedance readings were taken to check the integrity of the PWAS transducers and wiring. The capacitance readings were all within the range required. The impedance readings (Figure 13) showed PWAS 16 had a problem in the solder connection. Repair action was taken, and a new wire–PWAS connection was put into place.

After the recording of the last data (Reading 29 in Table 4), visual inspection was performed on the SHM system. Of the 32 PWAS transducers installed, five presented a wire disconnection due to the solder disconnection from the PWAS (Figure 14(a)); one was broken with the wire attached to the detached part of the PWAS (Figure 14(b)); one was broken with the wire still on the part of the sensor attached to the structure (see Figure 14(c)). The tube exploded a few pressure cycles after these images were taken.

**Impedance readings**

For each PWAS, six impedance readings were taken in the frequency range of 1–500 kHz at each stage during the test. During postprocessing, plots of the real part of E/M impedance were drawn. The real part of E/M impedance, Re(Z), measured at the PWAS terminals reflects with fidelity the mechanical impedance of the structure at the PWAS location.26

Hereunder, we report the graph of the six impedance readings for PWAS 0. Impedance 0 corresponds to the impedance taken before the test was started. Impedance 1 was taken after one cycle at 5000 μm/m and one cycle at temperature below –185°C. There is no much difference between these two readings. Impedance 2 was taken when the specimen was at ambient temperature and without load. The reading was taken the day after impedance 1 was taken; there was no loading change in between. Impedance 3 was taken with the specimen at about –169°C and after three cycles at about 6000 μm/m. Impedance 4 was taken while the tank was filling with liquid nitrogen and without load. (This reading was taken the next day after impedance 3 was taken). Impedance 5 was taken at the end of the test at RT and with no load. (Note that the tube was brought to RT between impedance readings 3 and 4.) Between impedance curves 4 and 5, the SHM system has withstood other three cycles with strain above 6000 μm/m.

Figure 15 indicates that after a few cycles at high microstrain levels, the E/M impedance spectrum reveals a new resonance frequency at about 100 kHz. This resonance frequency is evident only when the structure is not subjected to load and critical temperatures (impedance curves 4 and 5). The same behavior could be seen in all the PWASs that were still active.

The impedance curves 1 and 3 are similar to the baseline curve 0. The impedance curves 4 and 5 are very different because they show a new resonance frequency at around 100 kHz. This resonance frequency is evident only when the structure is not subjected to load and critical temperatures (impedance curves 4 and 5). The same behavior could be seen in all the PWASs that were still active.

The pitch–catch readings data were collected at two frequencies. The frequencies were determined through PWAS–Lamb
wave tuning. We found the maximum of the $A_0$ mode at 45 kHz. For the $S_0$ mode, we selected the frequency, 165 kHz, at which the $S_0$ mode achieves a maximum while the $A_0$ and $SH_0$ modes stay at low values.

We noticed that if the tube was under high loading and at CT, then the pitch–catch analysis could not be performed because the wave amplitude was too attenuated and not visible.

Figure 16 shows the pitch–catch results between PWAS 2 and PWAS 4 with at ambient temperature and with the tube at rest. Due to the composite material properties and layup, the waves propagating longitudinally along the cylindrical specimen have higher wave speeds than those propagating circumferentially or obliquely. For this reason, the first wave packet in Figure 16 is very close to the initial burst. For pitch–catch along the circumferential direction (e.g. PWAS 2 → PWAS 10), the wave speed was smaller by $\sim 40\%$. For oblique pitch–catch (e.g. PWAS 2 → PWAS 12), the wave speed decreased even more by $\sim 46\%$. Hence, in these cases, the first wave packet was easier to identify and process for DI calculation.

Since all the analyzed data appeared qualitatively similar, we discuss here only a couple of cases: (a) the circumferential pitch–catch PWAS 2 → PWAS 10 (Figure 17), and (b) the oblique pitch–catch PWAS 2 → PWAS 12 (Figure 18). Figure 17(a) shows the circumferential pitch–catch with the wave propagating from PWAS 2 to PWAS 10. The wave amplitude of the $A_0$ mode decreases as the number of fatigue and thermal cycles increases. While the wave amplitude of the baseline reading (Reading 0) is about 0.14 mV, the wave amplitude of the last reading (Reading 29) is about

### Table 4. Test sequence for impedance

<table>
<thead>
<tr>
<th>Reading</th>
<th>Strain ($\mu m/m$)</th>
<th>Temperature ($^\circ C$)</th>
<th>Reading</th>
<th>Strain ($\mu m/m$)</th>
<th>Temperature ($^\circ C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance 0</td>
<td>31</td>
<td>18–19</td>
<td>Few</td>
<td>$\sim$ –185</td>
<td></td>
</tr>
<tr>
<td>00–04</td>
<td>31</td>
<td>20</td>
<td>$\sim$ 6000/7000</td>
<td>$\sim$ –168</td>
<td></td>
</tr>
<tr>
<td>05</td>
<td>$\sim$ 2400</td>
<td>$\sim$ –177</td>
<td>21</td>
<td>$\sim$ –169</td>
<td></td>
</tr>
<tr>
<td>06–07</td>
<td>$\sim$ 2400</td>
<td>$\sim$ –177</td>
<td>22</td>
<td>$\sim$ –169</td>
<td></td>
</tr>
<tr>
<td>08</td>
<td>Few</td>
<td>$\sim$ –188</td>
<td>23</td>
<td>$\sim$ –129</td>
<td></td>
</tr>
<tr>
<td>09</td>
<td>4000/5000</td>
<td>$\sim$ –188</td>
<td>6000/7000</td>
<td>$\sim$ –189</td>
<td></td>
</tr>
<tr>
<td>Impedance 1</td>
<td>$\sim$ –154</td>
<td>24</td>
<td>Few</td>
<td>$\sim$ –189</td>
<td></td>
</tr>
<tr>
<td>Impedance 2</td>
<td>31</td>
<td>25</td>
<td>$\sim$ 6000</td>
<td>$\sim$ –189</td>
<td></td>
</tr>
<tr>
<td>11–12</td>
<td>31</td>
<td>26</td>
<td>$\sim$ 300</td>
<td>$\sim$ –188</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Few</td>
<td>$\sim$ –190</td>
<td>27</td>
<td>Impedance 5</td>
<td>31</td>
</tr>
<tr>
<td>14</td>
<td>$\sim$ 5000</td>
<td>$\sim$ –185</td>
<td>28</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>$\sim$ 6000</td>
<td>$\sim$ –185</td>
<td>29</td>
<td>31</td>
<td></td>
</tr>
<tr>
<td>16–17</td>
<td>$\sim$ 6000</td>
<td>$\sim$ –185</td>
<td>31</td>
<td>31</td>
<td></td>
</tr>
</tbody>
</table>

**Figure 14.** Visual inspection of the broken PWAS or connection after the test (after Reading 29 in Table 4). (a) PWAS 1 broken, (b) PWAS 12 disconnected, and (c) PWAS 18 broken and PWAS 19 disconnected.

PWAS: piezoelectric wafer active sensor.

**Figure 15.** Impedance change collected with PWAS 0 during the thermal and pressure cycling experiment.

PWAS: piezoelectric wafer active sensor.
0.06 mV. The variation in amplitude is also shown by the change in DI values (Figure 17(b)). Similar results were obtained for oblique pitch–catch PWAS $2 \rightarrow$ PWAS $12$ (Figure 18).

The decrease in wave amplitude with number of cycles was observed in all PWAS readings. This phenomenon could, in principle, be due to either (a) a structural change of the tube material or (b) a degradation of the PWAS capability to transmit and/or receive signals. However, we believe that the first assumption applies because both the pitch–catch signals and impedance readings indicate that the PWAS transducers seem to be functioning well. Hence, we believe that the observed changes are due to degradation of the composite material under thermomechanical cycling, thus indicating that the PWAS transducers are able to perform SHM functions at CT.

**Figure 16.** Pitch–catch at ambient temperature and zero load for PWAS $2$ transmitter and PWAS $4$ receiver (longitudinal wave propagation) at different history times ($A_0$ tuning at $45$ kHz). PWAS: piezoelectric wafer active sensor.

**Figure 17.** Pitch–catch at ambient temperature and no load for PWAS $2$ transmitter and PWAS $10$ receiver ($A_0$ tuning at $45$ kHz): (a) wave packet (circumferential wave propagation) at different history times and (b) plot of DI values. PWAS: piezoelectric wafer active sensor; DI: damage index.

**Figure 18.** Pitch–catch at ambient temperature and no load for PWAS $2$ transmitter and PWAS $12$ receiver ($A_0$ tuning at $45$ kHz): (a) wave packet (oblique wave propagation) at different history times and (b) plot of DI values. PWAS: piezoelectric wafer active sensor; DI: damage index.
Similar results were obtained for $S_0$ tuning at 165 kHz. Figure 19 presents the results for circumferential pitch–catch PWAS 2 to PWAS 10 at 165 kHz. Although the wave amplitude is small, the noise-to-signal ratio is still quite acceptable; hence, it was possible to recognize the same amplitude reduction with the increase in the number of cycles as for $A_0$ tuning at 45 kHz.

**Summary and conclusions**

This article has presented how PWAS can be used to detect damage in composite structures at CT. PWAS transducers are lightweight and inexpensive; they enable a large class of SHM applications such as embedded guided-wave ultrasonics, that is, pitch–catch, pulse–echo, phased arrays, and high-frequency modal sensing, that is, the E/M impedance method. The focus of this article has been on the ability of PWAS-based SHM system to survive and operate at low temperatures and sustain the thermal and mechanical cycling. This article illustrates several experiments that prove how the PWAS transducers are effective for detecting multiple types of damage (impact damage and delaminations) in complex composite materials. In particular, results were shown for damage detection of impact damage on a composite lap-joint specimen at room and CT, and detection of simulated delaminations in a composite thick plate at room and CT. These results indicate that a PWAS transducers would be effective and reliable for SHM of composite structures at cryogenic environmental conditions.

In the last part of this article, a full-scale experiment was presented. A full-scale composite specimen of cylindrical shape was subjected to high-strain cycles and CT cycles. The test finished with the specimen bursting under pressure after a considerable number of high-pressure low-temperature load cycles. Most of the PWAS transducers proved to be working till the end of the test. However, they indicated damage initiation and progression during the test. The impedance readings showed a new resonance peak at about 100 kHz, after the first two cycles at high strains. It is not possible to assess with certainty whether the new resonance is due to a structural change in the tube or to a PWAS—bond degradation. However, we believe that it was due to a structural change in the tube during the test because (a) a new resonance peak appeared in the impedance readings after several high load–low temperature cycles and (b) the pitch–catch readings showed consistently a DI increase with the increase in the number of high load–low temperature cycles due to decrease in wave amplitude and appearance of phase shifts. The PWAS system has detected a structural change after four high strains cycles and three cryogenic cycles. The experiment conducted also shown good survivability of the PWAS-based system under both harsh environmental condition (extreme cold temperatures, aging, and liquid contact) and extreme loads.

This article has only presented a preliminary investigation aimed at determining whether PWAS transducers can be used for damage detection at CT. In this investigation, we have shown that a PWAS-based SHM system could be used with the specimen at CT and under cycling between RT and CT. We have shown that the signal processing algorithms developed for damage detection at RT can be also used for damage detection at CT. However, further investigation is needed because this study has not yet addressed some fundamental
issues associated with CT. For example, are the piezoelectric behavior of PWAS, the mechanical performance of composite structures, and the bonding between PWAS and composite structures sensitive to temperature fluctuation down to CT? If yes, how much and how severe is this dependence? In principle, if the changes are negligible, the algorithms developed at RT would be expected to also function at CT. If the changes are not negligible, then how large are they? When did the changes happen substantially on the route from RT down to CT? These are common issues that affect the applications of various SHM techniques based on piezoelectric elements down to CTs (and also up to elevated temperatures). Such studies need to make the object of further research and future communications.

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**References**


