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# LOW TEMPERATURE EFFECTS ON GUIDED WAVE STRUCTURAL HEALTH MONITORING SIGNALS

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**Abstract**. Structural Health Monitoring (SHM) has become a critical technology for maintaining the safety and performance of high-value structures, particularly those exposed to extreme environments such as cryogenic temperatures. Applications such as hydrogen storage tanks and aerospace components experience mechanical and thermal stresses that can degrade material properties, increase brittleness, and compromise structural integrity. In such conditions, traditional inspection methods may be impractical, whereas SHM provides a reliable means for real-time monitoring and early damage detection.
Among SHM techniques, guided wave (GW) methods are particularly promising for fiber-reinforced polymers, offering long-range coverage and high sensitivity to various defect types. However, GW signals are also sensitive to environmental and operational factors, including temperature, mechanical loads, and surrounding media (e.g., moisture, ice, gas), which can lead to signal variation unrelated to damage. Without proper compensation, these effects may obscure actual damage or result in false positives.
This study investigates the influence of cryogenic temperature and surrounding media on GW signal behavior in a unidirectional carbon fiber-reinforced polymer panel instrumented with co-bonded DuraAct™ piezoceramic transducers. The specimen is subjected to controlled thermal cycling from liquid nitrogen temperature to room temperature, while guided waves are recorded across a wide frequency range.
Results demonstrate distinct temperature and frequency-dependent behavior in both A0 and S0 wave modes. Amplitude and time-of-flight characteristics reveal strong interactions between temperature, transducer performance, and media boundary effects. These findings underscore the importance of environmental compensation in GW-SHM systems and highlight new opportunities for using wave behavior as a dual indicator of both structural health and environmental state.

**Key words:** Structural Health Monitoring, Low temperatures, DuraAct™, Guided waves.

## 1. INTRODUCTION

Structural Health Monitoring (SHM) has emerged as a promising technology for ensuring the integrity and safety of complex structures, particularly those operating under extreme environmental conditions. Components such as hydrogen storage tanks and aerospace structures are frequently exposed to cryogenic temperatures, which can adversely affect material properties, leading to increased brittleness and potential structural failures. In such scenarios, traditional inspection methods may be impractical or insufficient, making SHM a crucial tool for early damage detection and life extension of critical assets [1].

Composite materials, especially carbon fiber-reinforced polymers (CFRPs), are extensively used in high-performance applications due to their superior strength-to-weight ratios and adaptability. These materials are prevalent in sectors like aerospace and hydrogen energy, where components often operate under cryogenic conditions [2, 3]. Despite their advantageous properties, CFRPs are susceptible to damage mechanisms such as impact-induced delaminations, fatigue, and environmental degradation, which can compromise structural reliability [4].

Among various SHM techniques, guided wave (GW)-based methods have shown significant promise due to their sensitivity to damage and capability for long-range inspection, particularly in fiber-reinforced composites [5, 6]. Guided waves can propagate over considerable distances with minimal attenuation and are highly responsive to material discontinuities. However, the effectiveness of GW-SHM systems is influenced by external factors, including mechanical loads, ambient temperature, and surrounding media such as moisture or gaseous environments [7, 8].

Temperature effects are especially critical in cryogenic applications, where material properties like stiffness and residual stresses in CFRPs undergo significant changes. These variations can alter wave propagation characteristics, particularly in the transverse direction, where the polymeric matrix plays a dominant role [9]. Moreover, the performance of piezoelectric transducers, such as those based on lead zirconate titanate (PZT), can degrade at low temperatures due to changes in their dielectric and electromechanical properties [10, 11]. This degradation affects the reliability of SHM systems operating in cryogenic environments.

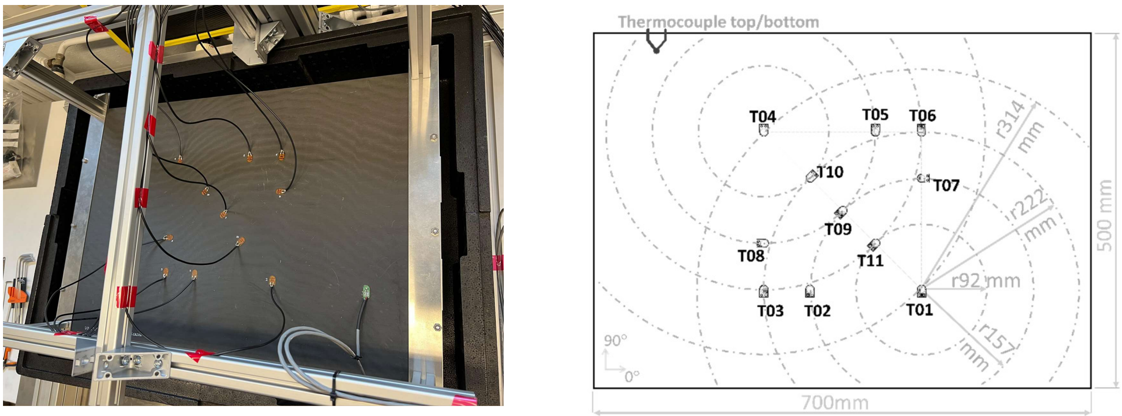
In this context, the present study aims to investigate the response of guided wave signals at cryogenic temperatures using co-bonded DuraAct™ transducers on a unidirectional carbon fiber-reinforced polymer (UD-CFRP) panel. The research focuses on evaluating how temperature and surrounding media influence guided wave propagation and transducer functionality. Measurements are conducted across various temperature states, with and without immersion in liquid nitrogen ($LN_2$), to analyze signal amplitude and time-of-flight (ToF) behavior comprehensively.

## 2. MATERIALS AND METHODS

### 2.1. Specimen configuration

The test specimen used in this study shown in **Figure 1 (a)** consists of a UD-CFRP panel integrated with co-bonded DuraAct™ transducers, to evaluate GW-SHM performance under cryogenic conditions. DuraAct™, developed by PI Ceramic GmbH, is a commercial piezocomposite acousto-ultrasonic transducer. It features a soft PZT piezoceramic (PIC255), placed between metallized electrodes and encapsulated within a polyester fleece-reinforced laminate, providing both electrical insulation and mechanical flexibility. Electrical connectivity is established through two solder points.

The UD-CFRP laminate is fabricated using HexPly® 8552-IM7 prepreg with a $[0]_{18}$ stacking sequence. Each ply has a nominal thickness of 0.125 mm, resulting in a panel measuring 700 mm × 500 mm. Eleven DuraAct™ transducers are strategically positioned on the laminate to establish signal propagation paths in three orientations: along the fiber direction (0°), perpendicular to it (90°), and diagonally (45°). Each path consists of one actuator and two sensors, spaced 157 mm and 222 mm apart, as depicted in **Figure 1 (b)**. After transducer placement, the laminate is autoclave-cured to achieve a final consolidated thickness of approximately 2.25 mm.




(a) (b)

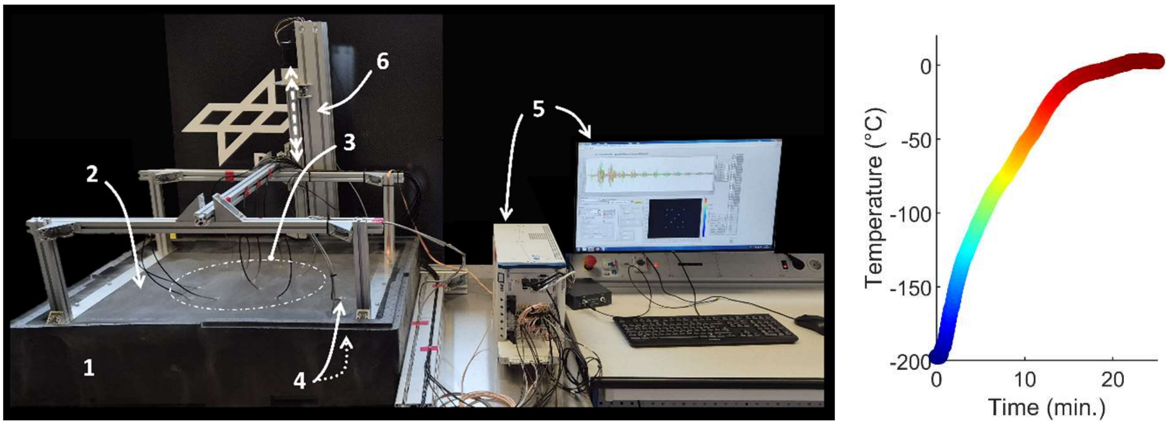
**Figure 1**: (a) Schematic of specimen configuration and (b) UD-CFRP panel with transducer network and thermocouples.

### 2.2. Thermal test set-up

The panel is mounted using aluminum clamps on both sides along the 90° axis and affixed to a lifting mechanism designed for precise vertical translation into and out of a $LN_2$ bath. This setup ensures the specimen remains perpendicular to the cryogenic liquid surface during immersion and withdrawal.

The transducer network is connected to a PXIe-based guided wave SHM acquisition system provided by National Instruments. Temperature monitoring is achieved using two thermocouples bonded to the top and bottom surfaces of the CFRP panel. The experimental configuration is illustrated in **Figure 2 (a)**.

During testing, the panel is submerged in $LN_2$ until thermal equilibrium is reached at approximately -197 °C. It is then gradually lifted and allowed to warm to ambient room temperature (~15 °C) under natural convection. Throughout this thermal cycle, guided wave signals are continuously recorded at excitation frequencies from 50 kHz to 250 kHz in 10 kHz increments. A representative temperature profile recorded from the top-surface thermocouple is shown in **Figure 2 (b)**.




(a) (b)

**Figure 2**: (a) Experimental setup showing: (1) cryogenic bath, (2) UD-CFRP panel, (3) transducer network, (4) thermocouples, (5) data acquisition system, and (6) lifting mechanism; (b) representative top-surface temperature profile during thermal cycling.

## 3. RESULTS AND DISCUSSIONS

### 3.1. GW signal temperature response

For the current study, guided wave excitation was performed using transducer 1 (T1), which generated a five-cycle Hanning-windowed sine burst with a peak voltage of 50 V. The signals acquired along the fiber direction of the UD-CFRP laminate by transducer 2 (T2) were processed through a multi-step chain comprising denoising, cross-talk removal, Hilbert transform-based envelope extraction, and peak estimation for each propagating mode. Maximum signal amplitudes and ToF values were extracted for both the A0 and S0 modes approximations across a frequency sweep from 50 kHz to 250 kHz, in 10 kHz increments, to evaluate dispersion characteristics under varying thermal conditions.

The A0 mode remained identifiable up to 150 kHz. Above this frequency, signal quality degraded due to mode overlap and reflection interference. Conversely, the S0 mode became discernible only above 100 kHz, as lower-frequency signals produced amplitudes too weak for consistent detection.

Amplitude behavior for the A0 mode depicted in **Figure 3 (a) (c),** followed a non-monotonic trend. As the temperature decreased from room temperature, amplitude initially increased, reaching a maximum near −60 °C. This increase is more pronounced as frequency increases. Below this temperature, amplitude declined sharply as temperature drops till −197°C equally in all frequency range. In contrast, ToF for the A0 mode depicted in **Figure 3 (b) (d),** remained relatively stable below −60 °C, with a slight decrease observed from room temperature to −60 °C.

When analyzing both amplitude and ToF trends together, two distinct behaviors emerge. From room temperature down to −60 °C, the increase in amplitude and decrease in ToF could be attributed to the thermal stiffening of the polymer matrix, reduced viscoelastic damping, and improved wave propagation efficiency. This effect specially affects A0 mode at higher frequencies (>70kHz) and has a lower impact at lower frequencies (<70kHz). However, below −60 °C, this coupling between amplitude and ToF diminishes, that could indicate that the reduction in amplitude is no longer linked to changes in structural wave speed or material dispersion. Instead, this behavior is most plausibly explained by temperature-induced degradation of piezoelectric performance in the DuraAct™ transducers. At cryogenic temperatures, the dielectric constant and piezoelectric coefficients (e.g., $d31$) of the soft PZT decrease substantially, reducing the effectiveness of wave generation and sensing [10, 11], and could result in the observed amplitude losses.

In addition to amplitude trends, the A0 mode also displayed a temperature-dependent shift in its frequency of maximum amplitude. At room temperature, the A0 mode showed a peak response around 65 kHz. As the temperature decreased, this peak shifted upward in frequency, settling near 90 kHz at −197 °C, albeit with diminished amplitude.

For the S0 mode, the amplitude response depicted in **Figure 4 (a) (c)** was distinctly different. Across the frequency spectrum, S0 amplitudes decreased monotonically as temperature dropped. This trend was most pronounced at higher frequencies where amplitudes are higher. Regarding S0 mode ToF depicted in **Figure 4 (b) (d)**, values remained consistent over temperature up to 200kHz where ToF starts to slightly decrease when lowering temperature with higher frequency.

When considering both amplitude and ToF trends together, behavior seems to be consistent to the behavior of A0 mode below −60 °C, where the reduction in amplitude could be explained due to the reduction of electromechanical coupling efficiency of the PZT piezoceramic when decreasing temperatures, rather than propagation-related loss mechanisms. The absence of changes in amplitudes and ToF close to room temperature in line with A0 mode, can be attributed to the S0 mode's dominance in in-plane axial displacements, are less affected by transverse stiffness alterations in unidirectional laminates while A0 mode has a greater influence in the out-of-plane components more dominated by matrix properties changes.

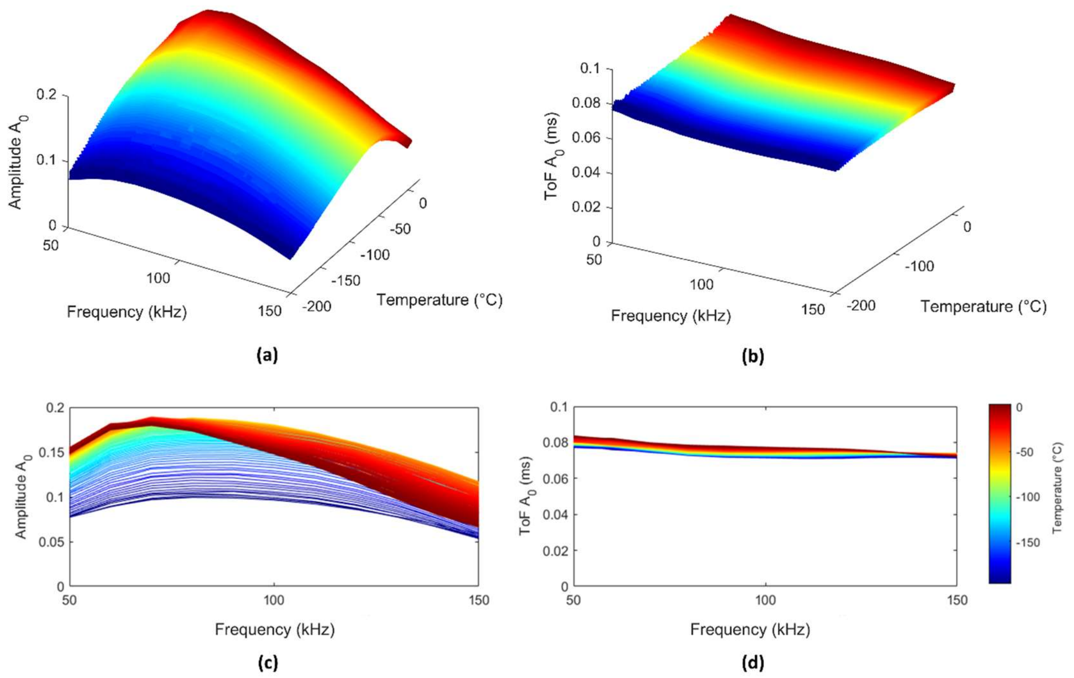



**Figure 3**: T1 to T2 (a) 3D representation of maximum amplitude spectrum of A0 mode over temperature, (b) 3D representation of ToF spectrum of A0 mode over temperature, (c) 2D representation of maximum amplitude spectrum of A0 mode over temperature and (d) 2D representation of ToF spectrum of A0

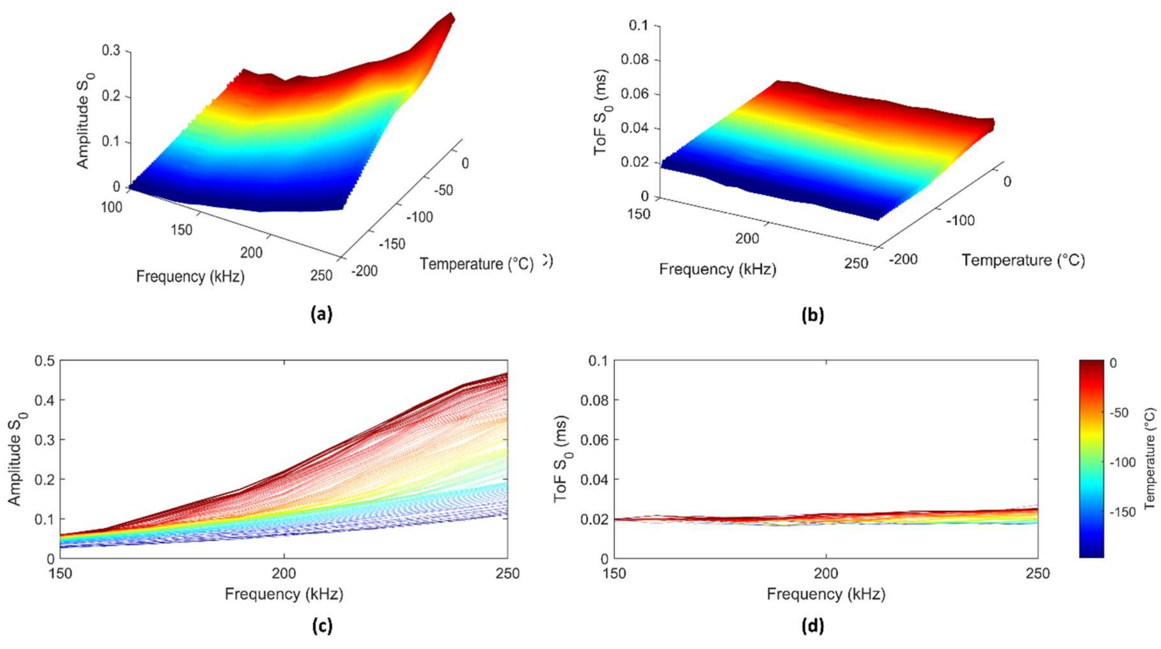



**Figure 4**: T1 to T2 (a) 3D representation of maximum amplitude spectrum of S0 mode over temperature, (b) 3D representation of ToF spectrum of S0 mode over temperature, (c) 2D representation of maximum amplitude spectrum of S0 mode over temperature and (d) 2D representation of ToF spectrum of $S_0$ mode over temperature

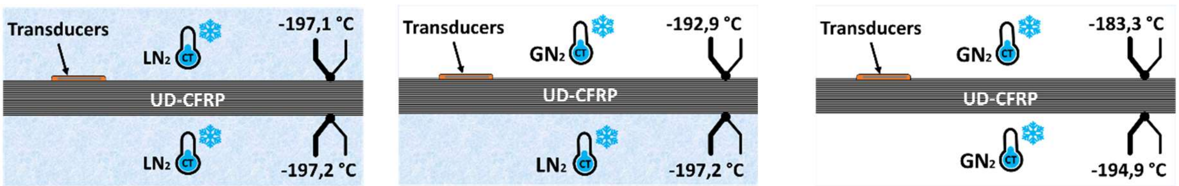
### 3.2. GW Adjacent media response

In addition to investigating the influence of temperature on guided wave propagation, this study examined the role of surrounding media, simulating realistic boundary conditions present in cryogenic storage applications, particularly in composite cryotanks containing both liquid and gaseous phases of cryogens. These structures often exhibit heterogeneous thermal environments, with partially submerged components encountering distinct heat transfer mechanisms and physical interactions depending on their immersion depth and phase interface.

To replicate such configurations, three test cases depicted in **Figure 5** were considered using the same UD-CFRP specimen:

- Fully Immersed in $LN_2$, with both transducer-equipped top and transducer-free bottom surfaces submerged.
- Partially Immersed, where only the bottom surface was in contact with $LN_2$ and the top remained exposed to gaseous nitrogen ($GN_2$).
- Fully Emerged, with the entire specimen suspended above the $LN_2$ bath in a $GN_2$ environment.

Thermocouple readings confirmed stable thermal gradients across the panel. In the fully immersed case, both surfaces stabilized near -197 °C. In the partially immersed configuration, the bottom surface remained at -197 °C, while the top was slightly warmer at -193 °C. The emerged panel recorded temperatures of approximately -195 °C and -183 °C at the bottom and top surfaces, respectively. These differences, though modest, create asymmetric thermal boundary conditions that can significantly affect guided wave propagation, particularly in anisotropic and multilayered materials like CFRP.




(a) (b) (c)

**Figure 5**: Schematics of the three configurations: (a) fully immersed, (b) partially immersed, and (c) fully emerged specimen.

Results depicted in **Figure 6** show that for the S0 mode, ToF remained essentially unchanged across all configurations, indicating that its wave speed was largely insensitive to whether the adjacent medium was $LN_2$ or $GN_2$. Amplitude showed minor increases in the emerged configuration, likely due to the slightly elevated surface temperatures rather than changes in damping or acoustic impedance. This supports the S0 mode's robustness to external medium effects, as its in-plane displacement profile minimizes interaction with environmental boundaries.

In contrast, the A0 mode displayed more pronounced sensitivity to immersion conditions. Subtle variations in ToF between the immersed and emerged states suggest slight changes in group velocity, potentially influenced by asymmetric boundary stiffness or pressure effects (e.g., hydrostatic pressure in $LN_2$ versus the lower-density $GN_2$).

Amplitude variations in the A0 mode were notably larger. Fully immersed conditions consistently produced the lowest amplitudes, while the partially emerged and fully emerged configuration resulted in the highest. This trend can be attributed to several factors:

- Increased acoustic damping in $LN_2$ due to its higher density and thermal conductivity.
- Acoustic impedance mismatch at the CFRP–$LN_2$ interface, reducing wave transmission efficiency.
- Reduced transducer coupling efficiency under thermal contraction in $LN_2$.

Conversely, the $GN_2$ environment imposes less mechanical constraint and thermal loading, enhancing transducer coupling and signal reception.

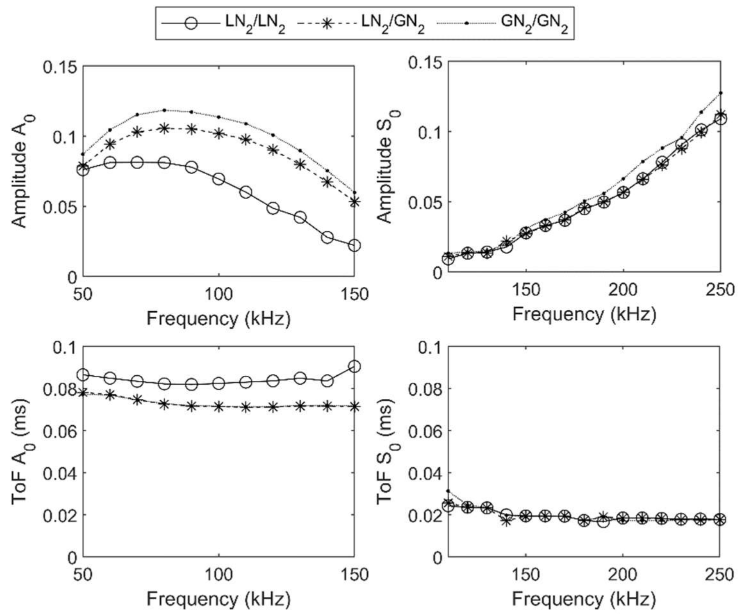



**Figure 6**: T1 to T2 signal comparison of A0 and S0 mode amplitude and ToF spectra across surrounding media configurations.

## 4. CONCLUSIONS

This study demonstrates that both cryogenic temperature and immersion state significantly influence guided wave behavior in UD-CFRP panels instrumented with DuraAct™ transducers.

The A0 mode shows strong sensitivity to temperature and immersion conditions, with amplitude increasing to approximately −60 °C that authors hypothesize that could be due to polymer stiffening and reduced damping, followed by a sharp decrease at r temperatures below −60 °C. This decline is thought to be primarily attributed to cryogenic degradation of piezoelectric performance in the transducers, rather than changes in material dispersion.

In contrast, the S0 mode exhibits stable ToF across all temperature and immersion conditions, following a monotonic amplitude variation over temperature. Authors hypothesize that this consistency could be due to the S0 mode's in-plane displacement nature, which is less influenced by changes in matrix stiffness or external boundary conditions.

Among the two wave modes, ToF measurements proved more robust for SHM in harsh environments, showing minimal sensitivity to electromechanical degradation and environmental variations. Amplitude, while more sensitive, provides valuable early indicators when corrected for environmental effects.

The upward shift in A0 amplitude peak frequency at cryogenic temperatures cannot be explained solely by thermal contraction of the transducer and further studies needs to carry out for a compressive understanding of the temperature effects on the dispersion characteristics and signal acquisition.

Immersion state plays a critical role, particularly for the A0 mode. Fully immersed conditions in $LN_2$ resulted in the lowest amplitudes. Conversely, emerged configurations yielded stronger signals, highlighting the need to account for surrounding media in SHM interpretations.

These findings have several important implications for SHM system design in cryogenic applications:

- Amplitude-based diagnostics, while sensitive, require environmental compensation and transducer performance tracking.
- ToF measurements provide a more stable diagnostic metric and are better suited for baseline tracking in long-term monitoring.
- Dual-mode strategies, leveraging the A0 mode's amplitude sensitivity alongside the S0 mode's temporal stability, may enhance the detection of early damage while maintaining robust operation across variable cryogenic environments.
- Immersion-sensitive behavior of the A0 mode opens possibilities for environmental sensing, such as liquid level detection or phase change monitoring, offering potential for dual-function SHM systems.

Future work should focus on:

- Developing adaptive signal processing techniques to normalize amplitude variations based on immersion configuration or thermal gradients.
- Exploring multi-frequency fusion of A0 and S0 responses to balance sensitivity and robustness in extreme conditions.

Together, these insights lay the groundwork for more resilient, accurate, and multifunctional SHM systems in next-generation cryogenic structures.

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