

Damage Identification of Composite Laminate Impact Delaminations with Dual-Tone Steady-State Ultrasonic Excitation and Nonlinear Signature Analysis

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ABSTRACT

Composite layered materials offer many engineering advantages including high strength-to-weight ratio, tailorable material properties, and high fatigue resistance. Detection of small intra-layer delaminations that occur during manufacturing or while in the service environment are critical to ensure that the structure maintains its designed performance. Nondestructive evaluation (NDE) methods, such as ultrasonic testing, can identify hidden defects and damage, but detection can be challenging because the separated layers often remain in physical contact and prevent ultrasonic waves from scattering. Simultaneous multi-frequency excitation has the ability to incite contact acoustic nonlinearities and unique ultrasonic scattering patterns which can be observed within the ultrasonic signatures of the harmonics and mixing frequencies.

Acoustic steady-state excitation spatial spectroscopy (ASSESS) is a full-field ultrasonic NDE inspection technique. ASSESS implements a steady-state ultrasonic excitation using a transducer and rapidly measures a structure's surface velocity response using a laser Doppler vibrometer (LDV). The measurement product is a complex-valued wavefield response mapped to the surface geometry.

This research investigates the presence of nonlinear signatures in a dual tone ASSESS measurement of a composite laminate panel with three impact delaminations. From a single measurement, complex velocity wavefield maps are calculated at the two excitation frequencies and additional harmonic and mixing frequencies. Contact acoustic nonlinearity signatures are identified as changes in response amplitude over certain frequencies. Spatial and temporal frequency and image processing methods are applied to individual wavefield images to identify damage locations.

INTRODUCTION

Nondestructive evaluation (NDE) is an inspection process that evaluates a specimen for defects and damage without destroying it. Many methods of NDE exist, including

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visual inspection, ultrasonic testing, and imaging, but not all are suitable for every application and material. Many methods are physically intrusive, require component disassembly, are time consuming, and cannot identify obscured internal defects and damage. Ultrasonic testing is a non-intrusive inspection method that excites a specimen at high frequencies to obtain information about the internal structure; the acoustic wave behavior and interactions can be used to determine the presence of internal defects, damage, and estimate material properties.

Carbon fiber reinforced polymers (CFRPs) are layered composite materials used in many modern applications, including the aerospace and automotive industries. CFRPs have a high strength-to-weight ratio and are created by successively adhering layers of material to achieve desired material properties. Interlayer defects, such as delaminations and disbonds, may occur during the manufacturing process or while the component is in use. These internal defects are often not visible from the surface but significantly reduce the strength of the material, increasing the risk of catastrophic failure.

Ultrasonic inspection methods of composite materials often target linear features in the response to locate large delaminations and thickness changes. Other research shows that the wavenumber of a CFRP can be estimated from a single tone steady-state excitation [1-3], frequency sweep [4], or tone burst [5], to indicate delaminations from the wavenumber estimation or signatures from the measurement. Such linear processing methods are limited to identifying large defects; potentially missing small defects that may be precursors to larger failures. Transient excitation methods can provide detailed defect characterization, but are time consuming and small defects may still be missed.

Some defects can generate a nonlinear response from ultrasonic excitation. For example, cracks and delaminations can “open and close” due to contact acoustic nonlinearities (CANs) and present as unique nonlinear defect signatures [6]. CANs generally present as higher harmonic generation, wave mixing, and an increase in sidebands due to elastic wave distortion. Research shows that implementing a three-tone transient excitation from a single transducer and tracking the amplitude of the third order combined harmonics can be used to detect early fatigue cracks with high sensitivity [7]. Additionally, higher order harmonics and sidebands can be used to track amplitude shifts to indicate CANs that appear when bolt torque decreases [8].

Harmonic frequencies are an integer multiple of the main base frequency (Equation 1). Mixing frequencies are multiples of the sum or difference between two main frequencies (Equation 2). For nonlinear responses (i.e. delaminations causing a local change in stiffness evident in changes to scattering behavior), the amplitudes of both harmonic and mixing frequencies increase as energy transfers from the main frequencies to the mixing frequencies [6].

$$f_n = nf \quad \{n \in \mathbb{Z} \mid n > 0\} \quad (1)$$

$$f_{mix} = |mf_1 \pm nf_2| \quad \{m, n \in \mathbb{Z} \mid m, n > 0\} \quad (2)$$

Acoustic Steady-State Excitation Spatial Spectroscopy (ASSESS) is a rapid nondestructive evaluation method that measures a specimen’s surface velocity response to a steady-state ultrasonic tone [1, 2, 9]. An LDV captures the out-of-plane velocity by rastering across the specimen’s surface, guided by a galvanometer mirror and a rotation stage. A LiDAR mounted above the mirror captures a point cloud of the specimen and surrounding areas for geometric perspective correction. The collected time history is

Where $v[x, y, t]$ is the temporal out-of-plane velocity indexed by measurement location $[x, y]$ and time t , f is the excitation, harmonic, or mixing frequency, and \hat{v} is the resulting complex-valued wavefield used for analysis in this paper.

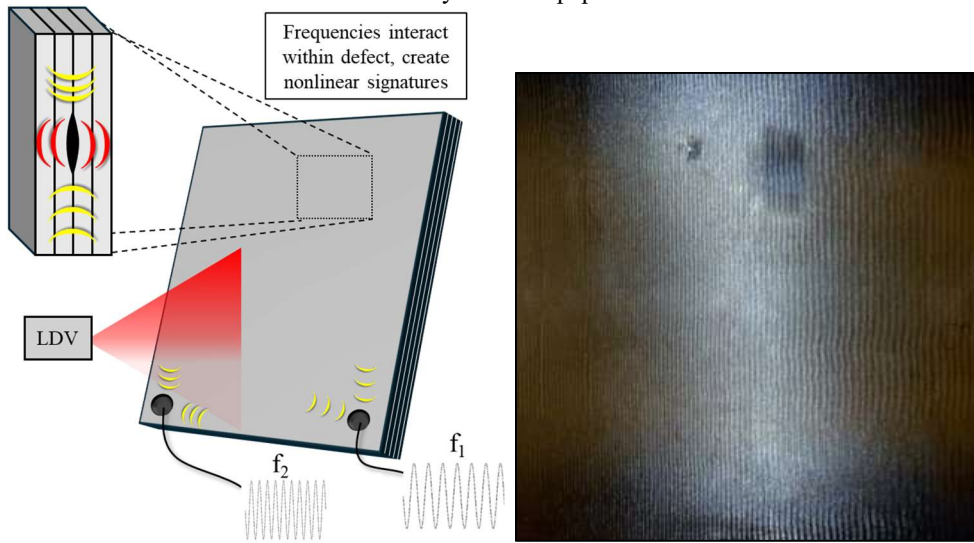


Figure 1. (left) ASSESS dual-tone measurement schematic, (right) photo of impacted CFRP panel.

All measurements were made on a composite specimen with dimensions of 38 cm x 38 cm x 7.35 mm.

External damage was visible on the non-impacted side for only region three of the three impacted locations (

Figure 2). Though the panel has large area delaminations, it will serve as a base test specimen to test the theory and demonstrate the capabilities of identifying mixing frequencies as damage signatures in this work, as the delaminations contain varying levels of depth separation and small cracks. Measurements of the specimen (also used in [1]) were divided into four regions: the main healthy region and three regions with impact damage.

Two ultrasonic transducers were clamped to the panel, one on each lower corner. A single ASSESS measurement was collected with simultaneous excitation using 7 volts (amplified) at 45 and 81.5 kHz applied to the specimen. It was discovered that lower excitation amplitudes were not sufficient for transferring energy into the mixing frequencies, and that maximum system excitation can excite the harmonics of the entire plate (not just the defect regions). The full measurement, segmented into pixels, then the inner product is taken with a complex exponential at the excitation frequency (Equation 3). The result is a single complex value at each pixel, resulting in a complex wavefield map.

$$\hat{v}[x, y] = \frac{1}{T} \sum_{t=0}^T v[x, y, t] e^{-j2\pi f t} \quad (3)$$

Figure 1 shows a diagram of an ASSESS measurement using two frequencies to excite CANs.

METHODS

Figure 2 shows the ultrasonic C-scan results of the panel (left) and the identified damage regions in the raw ASSESS wavefield response at 81.5 kHz (right).

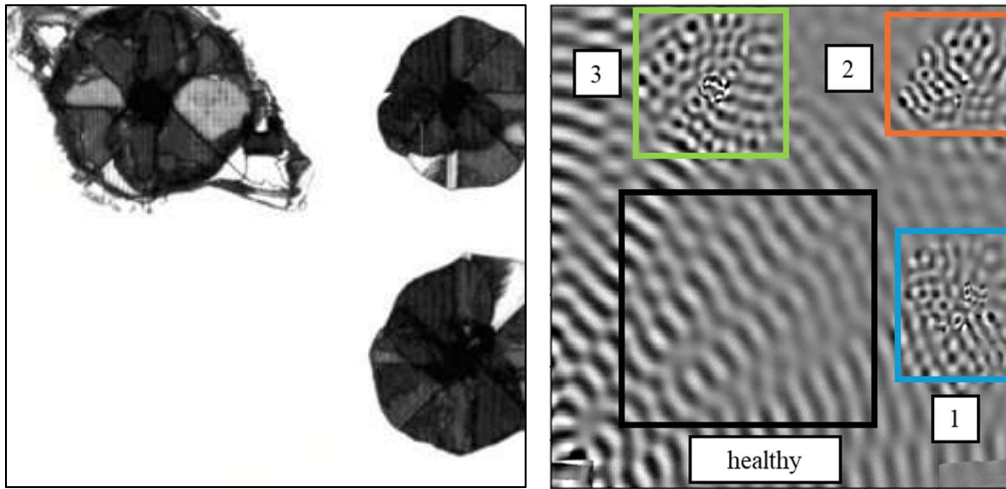


Figure 2. (left) C-scan of composite panel with impact delaminations; (right) regions for analysis overlaid on the real wavefield response map for 81.5 kHz excitation.

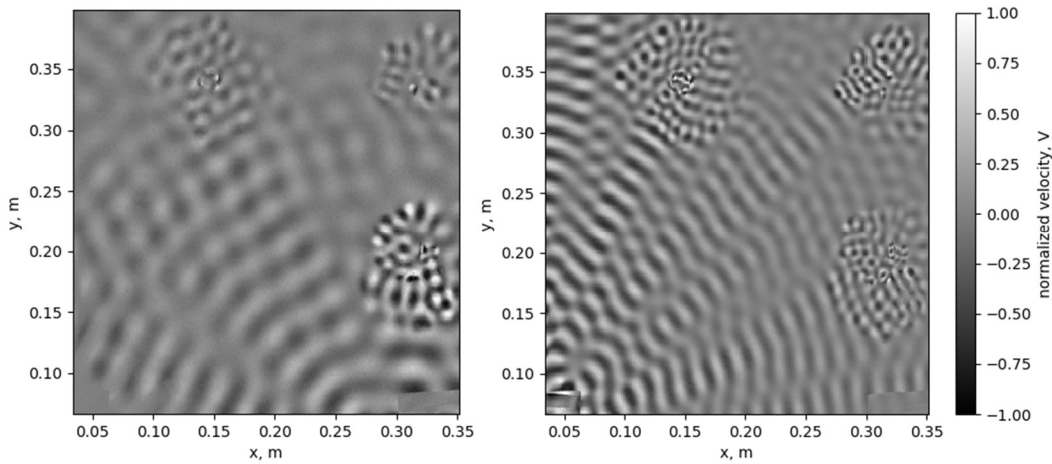


Figure 3. Raw real ASSESS measurement of two main frequencies: 45 kHz (left) and 81.5 kHz (right).

Figure 3, lasted 52 seconds with a sample rate of 2 MS/s and each pixel had a resolution of 0.95 mm x 0.95 mm.

RESULTS

Local wavenumber estimation was performed at the two main excitation frequencies (Figure 4) to demonstrate the linear analysis capabilities for damage identification. This method has been proven to reliably detect nonvisible internal delaminations relative to the entire measurement region [2]. However, there is currently no way to fully characterize the delaminations without obtaining the material dispersion curves, experimentally or analytically.

The out-of-plane velocity response was analyzed in the frequency domain by region to determine which mixing frequencies are sensitive to CANs. Figure 5 shows the average power spectral density (PSD) was calculated using 5,000 points, 50% overlap,

and frequency resolution of 400 Hz for each vertical scan line within the regions, and then averaged together across all scan lines. **Error! Reference source not found.** TABLE I provides details of the segmented time response used for these calculations. The damaged regions are witnessed to have a greater amplitude at higher frequencies than the healthy region in addition to extra peaks at select mixing frequencies. A subset of nine mixing frequencies were selected to be utilized to identify nonlinear responses for all three regions, shown in Figure 5 as dashed vertical lines.

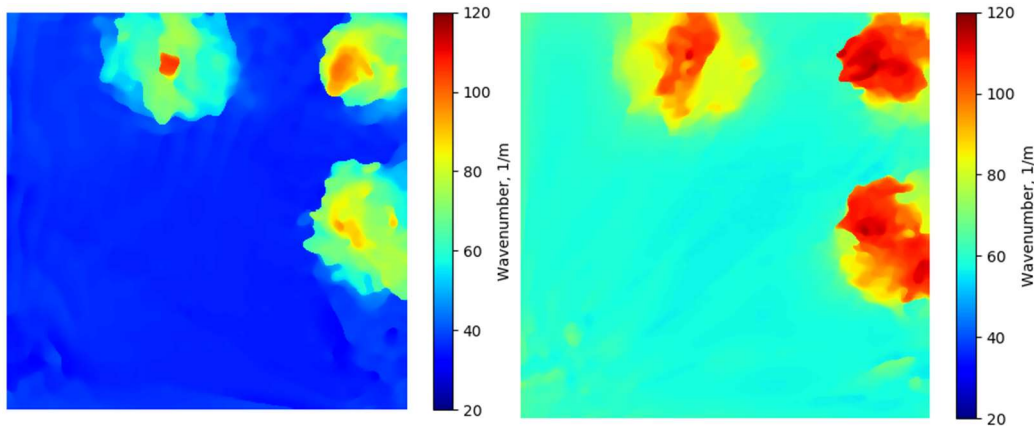


Figure 4. Linear wavenumber estimation at two main frequencies: 45 kHz (left) & 81.5 kHz (right).

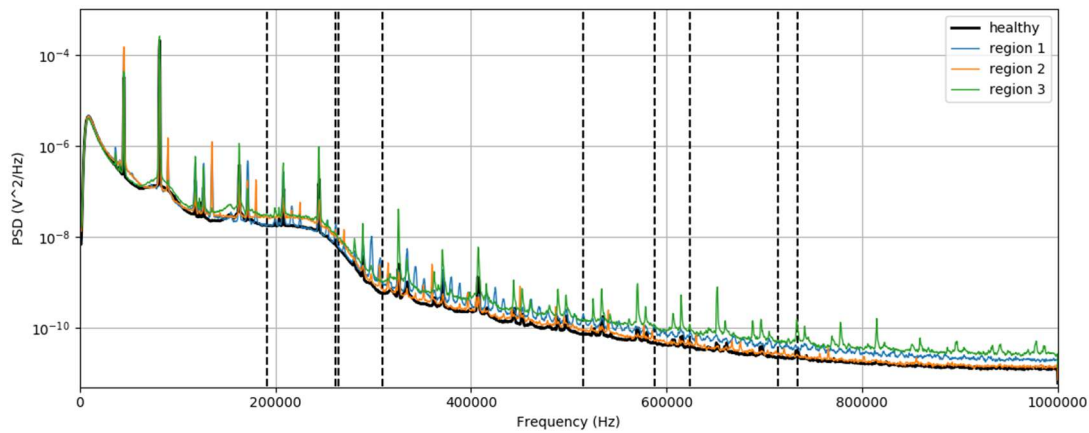


Figure 5. Power spectral density of healthy and damaged regions of composite impact panel. A subset of nine mixing frequencies used for further analysis are indicated with vertical dashed lines.

TABLE I. COLLECTION TIME PER REGION

Region	Scan lines	Samples per scan line	Time per scan line (s)	Time (s)
Healthy	185	87,500	0.0438	8.103
1	90	57,500	0.0288	2.592
2	100	47,500	0.0238	2.380
3	130	55,000	0.0275	3.575
Full Panel	459	228,000	0.1140	52.326

Wavefield maps were recalculated at the selected mixing frequencies using eq. 3, then the magnitude was calculated from the raw complex wavefield **Error! Reference source not found.** Figure 6 shows the full plate magnitude results for three frequencies and Figure 7 displays the magnitude of region 1 at all nine mixing and harmonic frequencies. The resulting wavefield magnitude features were summed and normalized by the overall maximum value to create a defect map localizing regions exhibiting a nonlinear response to the simultaneous dual-tone excitation (Figure 8).

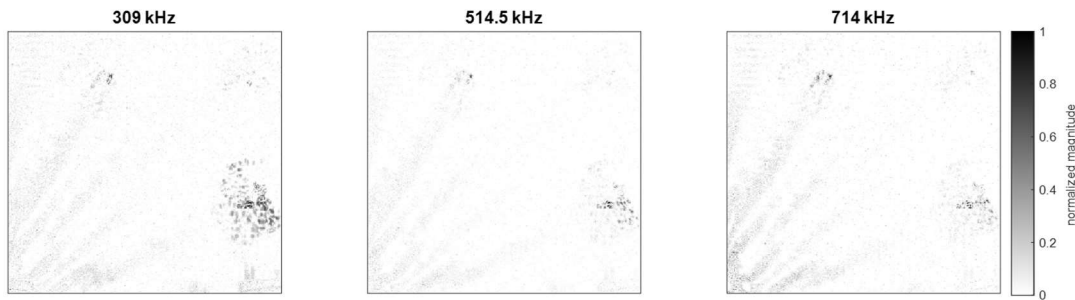


Figure 6. Normalized magnitude of the full plate at three selected mixing frequencies.

Specific areas within the identified impact regions had an increased magnitude at select mixing frequencies, which may correlate to damage size, depth, and location – modeling and additional experiments need to be implemented to fully understand that relationship. Additionally, there were repeated areas of increased magnitude on the lower left-hand side of the plate, originating where the 81.5 kHz transducer was attached. This phenomenon could indicate a performance difference in the transducers, potential nonlinear interactions with the clamp used to attach the transducer to the panel, or a nonlinear material response resulting from this specific excitation frequency.

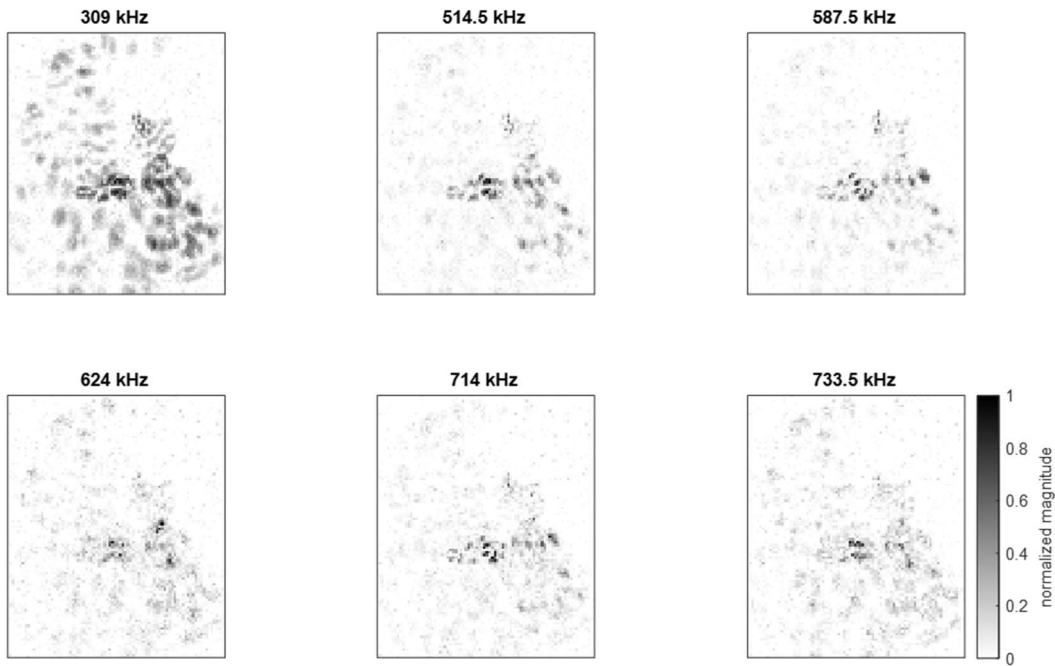


Figure 7. Normalized magnitude of region 1 at six of nine selected mixing frequencies.

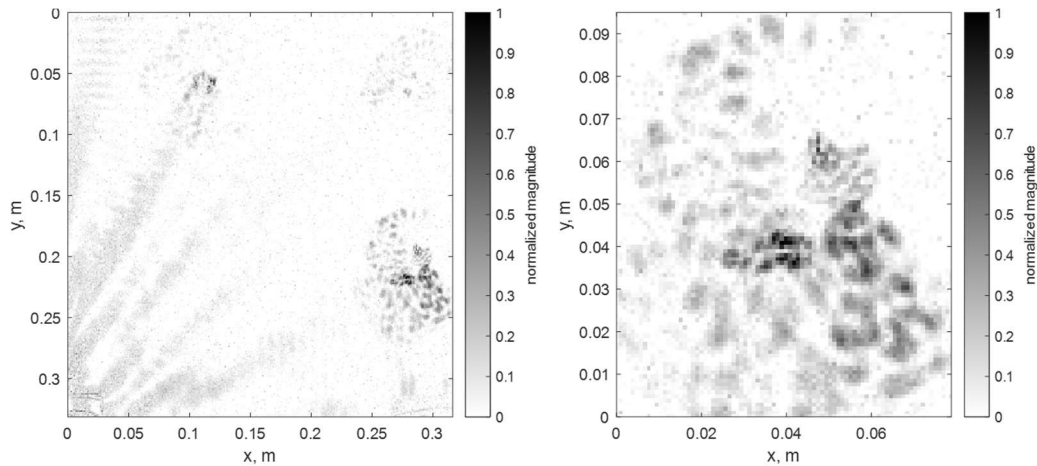


Figure 8. Normalized combined response magnitude using subset of mixing frequencies of (left) the entire plate, (right) region 1.

CONCLUSIONS

Although noticeable differences exist in the frequency and amplitude of the damaged regions, a peak above the healthy PSD does not directly indicate that the damaged regions will be visible in the magnitude feature. The largest region PSD peaks, between 30 and 150 kHz, had a significantly high magnitude presence in the undamaged region, obscuring the visual separation of the damaged regions. In contrast, the higher mixing and harmonic frequencies had minimal response within the undamaged regions, allowing for more visible separation of the damaged regions. Additionally, the spectrum results are heavily dependent on the selected bounds around the damaged regions. For

these reasons, the nine frequencies selected for processing were identified by analyzing the peaks in the spectrum and reviewing the corresponding magnitude feature for each frequency. To improve the calculated feature results, the region definition should be altered to more accurately bound the damaged regions, and additional signatures closely related to the frequency spectrum must be investigated. Additionally, the potential nonlinear signature emitted from the left transducer may be decreasing the expected magnitude separation between the healthy and damaged areas.

This research demonstrates that damage nonlinearities can be observed through energy transfer to higher mixing frequencies from a single, rapid, dual-tone, steady-state measurement. This method is roughly two orders of magnitude faster than traditional nonlinear signature collection techniques. Further research is needed to explore the relationship between the measurement parameters and nonlinear damage signatures, for example, how the excitation amplitude and selected excitation frequencies alter the recorded signatures. In future work, specific damage-sensitive wave modes could be targeted by altering the transducer geometry. After conducting signature discovery research, nonlinear wave processing methods and image processing techniques will be investigated to determine the best damage-sensitive features for defect and damage characterization.

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