GW-MUSIC focusing algorithm with high accuracy for composite damage diagnosis

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Abstract. The Guided Wave (GW)-based Multiple Signal Classification (MUSIC) method for damage imaging in composite structures offers high-resolution and flexible sensor array placement, demonstrating the considerable potential for precise damage localization. However, the application to aircraft composite structures, characterized by complex structural features, presents substantial challenges. These include pronounced anisotropy and diminished scattered signals from damaged sites. This paper presents a GW-MUSIC focusing algorithm for composite damage diagnosis. This method, designed for high localization accuracy, combines an anisotropy-compensated strategy to mitigate anisotropy while focusing on amplifying signals. Experimental validation on a composite structure demonstrated significant enhancements in localization precision, affirming the method's efficacy.

Keywords: Composite structures; damage localization; GW-MUSIC focusing algorithm; anisotropy compensation.

Introduction

The MUSIC algorithm excels in identifying signal origins across various fields such as radar, sonar, and seismic surveying by leveraging directional scans [1-3]. It operates by collecting emissions through an array of sensors and forming a covariance matrix from these signals, highlighting the time delay correlations between different sensors [4]. Small eigenvalues' eigenvectors define a noise subspace. By calculating the steering vector at each scan point, based on signal time delays to the array, and assessing its orthogonality against the noise subspace, the algorithm pinpoints signal sources.

Yuan [5], Engholm [6], and Yang [7] initially applied the MUSIC algorithm to structural health monitoring (SHM) [8-12] for pinpointing impact locations using guided wave signals from impacts. They started with a far-field approach using a linear uniform

Several studies have utilized the MUSIC algorithm for damage localization in structures. Yuan and team first [15] applied the near-field 2D-MUSIC algorithm to assess damage on carbon fiber reinforced plates. Zuo and colleagues [16] enhanced damage localization by correlating scattered and residual signals within the 2D-MUSIC framework, focusing on simulated damages on composite plates. Bao and Yuan [17] developed a technique using transmitter beamforming to address guided wave attenuation, amplifying wave signals from corrosion damage with sequential sensor activation in a linear array, effectively monitoring metal surface corrosion. Yang's group [18] combated dispersion in guided waves on aluminum plates with a forward-propagation-free focusing MUSIC algorithm, optimizing phase alignment for pinpointing damage. However, research mainly on simulated damage in simple metal specimens exists, with a limited exploration into composite structures' damage imaging using the MUSIC algorithm.

Composite structures are preferred in aerospace for their lightweight and high strength [19-20]. However, these structures are vulnerable to diverse damages that can degrade their performance [21-23]. Applying the GW-MUSIC algorithm for damage localization in these structures presents challenges [24-27]: high signal attenuation due to material damping, structural components, and geometric variations lowers the signal-to-noise ratio. Additionally, structural heterogeneity and multi-layer composition complicate wave propagation, with low signal-to-noise ratios often overshadowing the damaged signal. This complicates noise subspace estimation and signal-noise differentiation. Moreover, the inherent anisotropy of composites can lead to errors in phase delay calculations, affecting the accuracy of steering vectors. These factors collectively diminish the MUSIC algorithm's localization precision in complex composite structures.

A GW-MUSIC focusing algorithm is proposed to address the challenges of structural anisotropy and weak scattered signals, enhancing damage imaging accuracy. An experimental investigation was conducted on a composite structure. The results confirm the effectiveness of the method in accurately localizing damage.

The paper structure is as follows: Section 1 presents the GW-MUSIC focusing algorithm for imaging damage in composites. Section 2 explores damage experiments, detailing damage localization. Section 3 concludes the study.

1. GW-MUSIC focusing algorithm

This section introduces the GW-MUSIC focusing algorithm for composite damage diagnosis.

1.1 Anisotropy compensation

This section presents an array error compensation method that leverages impact events at predefined locations as auxiliary sources. This approach eliminates the need for additional PZT sensors on structures. An adaptive threshold method is then used to accurately estimate the practical Time of Flight (TOF) from the array signals generated by impact responses. Furthermore, phase delay perturbations are calculated by comparing the practical TOF with the theoretical TOF, as outlined in Equation (3). This comparison is crucial for calibrating the steering vectors within the MUSIC algorithm. Fig. 1 provides a flow diagram illustrating the array error compensation process.
The method outlined below illustrates the estimation of sensor phase errors for a sensor array. To simulate the auxiliary source, an impact event at a known direction $\theta$ is introduced within the structure. The sensor array then captures the impact response array signals. Given that the guided wave is frequency-dispersive and the impact response signals are broadband, it is essential to extract narrow-band signals. These signals, sharing the same central frequency as those excited by the active guided wave method, are specifically isolated using the Shannon wavelet transform.

After extracting the narrow-band array signals, the practical TOF between the impact and each element in the sensor array is determined, denoted as $t_q^*$. Considering the unknown response signal at the impact location, the practical time delay is then calculated

$$ t_q^* = t_q^c - t_q^0, \quad q = G, \cdots G $$

The theoretical time delay $t_q^c$ for guided wave travel between paths $F_j-A_0$ and $F_j-A_q$ is calculated using Equation (2).

$$ t_q^c = \sqrt{C_j^2 + h_q^2 - 2C_j h_q \cos \theta - C_j} $$

where $h_q$ denotes the $q^{th}$ sensing element's horizontal coordinate and $v$ is the guided wave velocity with the central frequency of $\omega_0$.

Accordingly, the theoretical time delay is subtracted from the practical time delay, resulting in the determination of the time delay error for the sensor array along direction $\theta$.

$$ \Delta t_q(\theta) = t_q^c - t_q^* $$

Typically, the time delay error for each direction can be estimated by applying impact events from $0^\circ$ to $180^\circ$ around the sensor array. Once these time delay errors are determined, the phase errors of the sensor array can be calculated.

$$ \Phi(\theta) = \text{diag} \left\{ e^{i\omega_0 \Delta t_1} \cdots e^{i\omega_0 \Delta t_i} \cdots e^{i\omega_0 \Delta t_n} \right\} $$

In Eq. (4), 'diag' transforms array elements into a diagonal matrix.

In damage localization, the potential damage direction is matched against $\theta$, selecting the nearest match to correct errors in calculating the array’s steering vectors.
1.2 Enhancing signal through focusing

When monitoring complex composite structures, the focusing MUSIC method monitors potential damage. Fig. 2 shows that each element in array R sequentially acts as an actuator, emitting guided waves from left to right. Array S’s sensors then pick up the damage-scattered waves. The scattered damage signals captured by the \( q \)th sensor are labeled \( A_q'(t), \ldots, A_p'(t) \), defined by the difference between the monitoring and baseline signals.

The proposed method locates unknown damage in the monitoring area by calculating the distance from each excitation source to the search location \((r, \theta)\), as defined in Eq. (5), using a search process.

\[
 r^j = \sqrt{(d^j - r \cos \theta)^2 + (l - r \sin \theta)^2}
\]

where \( r^j \) denotes the distance from the \( j \)th excitation source \( R_j \) to the search location, with \( d^j \) as its horizontal coordinate, positioned at \((d^j, l)\).

The relative TOF \( t'_j \) to the search location \((r, \theta)\) from the \( j \)th excitation source is calculable,

\[
 t'_j = \frac{r^j - r^0}{v}
\]

\[ \text{Fig. 2. Amplification setup with enhanced focusing.} \]

Relative TOF values enable the amalgamation of scattered damage signals from every excitation source, as demonstrated in Eq. (7).

\[
 T_q(t) = T_{qG}(t)e^{-imq'G} + \ldots + T_q(t)e^{-imq'} + \ldots + T_q(t)e^{-imqG}
\]

The sensing element \( A_0 \) serves as the reference, with its received signal represented as

\[
 T_{0}(t) = u(t)e^{i\omega t - \frac{2\pi \ell}{v}}
\]

where \( u(t) \) represents the amplitude of the damage scattered signal from Eq. (7), with \( r \) the distance to the reference PZT \( A_0 \). The signal weakens at undamaged areas but strengthens at the damaged location, enhancing the signal's amplitude as intended.

The noise subspace used for damage localization is derived by computing the covariance matrix of the focusing signal. \( U_n \) represents the noise subspace, constituted by eigenvectors linked to the signal’s smaller eigenvalues.

Given the frequent inevitability of background noise, the observed array signal in near-field conditions is depicted as
\[ S(t) = A(r, \theta)T_\theta(t) + N(t) \]  
where \( N(t) \) represents the background noise and Eq. (10) defines the array steering vector \( A(r, \theta) \) at position \( (r, \theta) \).

\[ A(r, \theta) = [a_G(r, \theta), a_{G+1}(r, \theta), \ldots, a_0(r, \theta)]^T \]  
where \( a_q(r, \theta) \) denotes the phase delays from positional variations of the sensing elements.

\[ a_q(r, \theta) = e^{j\omega \tau_q}, \quad q = -G, \ldots, G \]  
where the time delay is calculated as follows:

\[ \tau_q = \frac{r - \sqrt{r^2 + q^2 d^2 - 2rqd \cos \theta}}{v} \]  
Additionally, to adjust for structural anisotropy, measured array phase errors are used to assess the array steering vector, as indicated in Eq. (13). In this process, phase errors measured via a calibration source and aligned with the closest search direction are chosen. These selected phase errors are then utilized to correct the steering vector:

\[ A'(r, \theta) = \Phi(\theta)A(r, \theta) \]  
The spatial spectrum is then calculated as

\[ P_{\text{MUSIC}}(r, \theta) = \frac{1}{A^H(r, \theta)U_N U_N^H A'(r, \theta)} \]  
where "H" represents the conjugate transpose operation.

2. Composite structure damage localization

In this section, the effectiveness of the GW-MUSIC focusing algorithm for damage localization on the structure is evaluated.

2.1 Experimental setup

The experimental setup, illustrated in Fig. 3, includes an integrated scanning system paired with a reinforced composite plate. This scanning system generates excitation signals and acquires response signals from the piezoelectric transducer. During the damage diagnosis experiments, the system operated in active monitoring mode. The excitation involved a 3-cycle tone burst at an amplitude of ±70 V, with the central frequency set at 40 kHz to predominantly generate A0 mode guided waves. Data was captured at a sampling rate of 30 MHz with 10,000 data points. The composite plate measures 90 cm by 90 cm by 0.3 cm and features two T-stiffeners along its longitudinal axis to enhance structural integrity. The lay-up sequence of the plate is [45/0/-45/90/0/45/0/-45/0] s.
The adjacent PZT elements are spaced 12 mm apart, with each element having an 8 mm diameter and 0.48 mm thickness. The excitation and sensing arrays are labeled R₃ to R₃ and A₃ to A₃, respectively.

2.2 Damage diagnosis on the composite structure

This section describes the application of the proposed method for diagnosing damage in a composite structure. The process begins with the measurement of array phase errors, followed by an experimental procedure to evaluate the diagnostic effectiveness of the algorithm.

Utilizing the methodology outlined in Section 1.1, the array phase errors are assessed. The method targets a specific type of simulated damage, implemented using bonded masses. Initial measurements of phase errors across the array are taken. The scanning process then covers areas ranging from 0 to 30 cm in distance and from 0° to 180° in direction, with search increments of 0.1 cm and 1°, respectively. Within this setup, Array R serves as the actuator while Array A functions as the sensor.

The localization of simulated damage is illustrated in Fig. 4. The effectiveness of the proposed method is demonstrated in Figure 5, showing a maximum angular localization error of less than 3° and a maximum distance localization error of less than 1.4 cm.

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Fig. 4. Damage positions on the composite structure.
3. Conclusions

This study introduces a novel approach, the GW-MUSIC focusing algorithm, for imaging damage in composite materials. The proposed method first compensates for phase errors caused by structural anisotropy and then enhances the scattered signals from the damage using a focusing algorithm. To validate this innovative MUSIC-based damage imaging technique, damage experiments were conducted. Experimental results demonstrate significant enhancements in imaging localization accuracy, successfully pinpointing damage within complex composite structures.

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References


