

Transforming Sparse Piezoelectric Measurements into High-Resolution Damage Maps for Structural Health Monitoring

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ABSTRACT

Structural health monitoring of plate-like structures often relies on guided wave propagation to detect and locate damage. While full-field vibrometric measurements offer exceptional resolution and detail, their high cost and complexity make them unsuitable for widespread use in practical applications. In contrast, piezoceramic transducers provide a cost-effective alternative but are limited to collecting data at discrete points, leading to significant challenges in achieving high-resolution damage visualization. This paper addresses this gap by introducing a novel method to transform sparse piezoelectric measurements into high-resolution visual damage maps.

This paper presents a novel, image-processing-based method to reconstruct high-resolution damage maps from sparse piezoelectric measurements. The approach leverages emitter-receiver pairs to draw color-coded propagation paths, where intensity reflects the severity of damage detected along the wave trajectory. Unlike existing methods such as RAPID, the proposed framework is computationally lightweight, baseline-agnostic in terms of damage indices, and compatible with a wide range of signal features beyond Pearson correlation.

The proposed method utilizes an image-processing-based algorithm to reconstruct dense feature maps of damage presence. The approach leverages emitter-receiver pairs to draw color-coded propagation paths, where intensity reflects the severity of damage detected along the wave trajectory. The resulting visualizations closely mimic those obtained from full-field vibrometry, while significantly reducing data requirements and computational overhead.

To validate the method, experiments were conducted on an aluminum plate equipped with 8 signal transmitters and a laser vibrometer to measure wave propagation. Seven damage scenarios were tested, ranging from barely visible damage to a 17 mm flat-bottom hole. This proof-of-concept offers a practical and scalable solution for high-resolution SHM and serves as a foundation for more detailed quantitative studies presented in future work.

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INTRODUCTION

Structural Health Monitoring (SHM) is increasingly critical in fields like aerospace, where aging components face cumulative mechanical and environmental stress. Guided wave methods—particularly those using Lamb waves—are well-suited due to their long-range sensitivity to defects such as cracks, delaminations, and corrosion. Piezoceramic (PZT) transducers enable cost-effective deployment but provide sparse data, complicating high-resolution visualization [1–3].

Traditional signal-processing approaches rely on scalar damage indices or statistical features that require expert interpretation and offer limited spatial insight. This motivates the transformation of sparse guided wave data into spatially continuous maps, improving both human and algorithmic diagnosis [4].

This paper presents a proof-of-concept method that uses image-processing and signal fusion to produce interpretable, high-resolution damage maps from sparse measurements, with minimal hardware requirements.

STATE OF THE ART

From Pitch-Catch to Damage Indices — and the Limits of Localization

Guided wave SHM systems often use a pitch-catch setup, where one transducer emits a wave and another receives it after it propagates through the structure. Comparing received signals to a baseline from the undamaged state yields a scalar Damage Index (DI), indicating potential structural changes.

DIs are widely used due to their simplicity and low computational overhead, but they lack spatial resolution. A DI may signal that damage exists along a path, but not where it lies. This issue is critical in sparse sensor networks and complex geometries.

Localization methods like Time-of-Flight (ToF) or amplitude-based analysis can infer distance or defect type, but they degrade under noise, wave speed uncertainty, or environmental variation. Supervised machine learning offers an alternative, mapping features to damage via trained models, but it demands large, labeled datasets that are rarely practical in real-world SHM.

These challenges drive interest in unsupervised and interpretable approaches. One promising direction is damage mapping: converting sparse signal data into spatial visualizations of probable damage. These maps improve clarity for human operators and support automated analysis—bridging the gap between raw waveforms and actionable diagnostics.

Imaging Techniques for Guided-Wave-Based Damage Visualization

Imaging techniques in guided-wave SHM are designed to produce spatial representations of structural condition by combining information from multiple sensor pairs. These methods typically rely on aggregating the outputs of several pitch-catch paths, each contributing partial information about the structural state. The resulting image — often in the form of a two-dimensional map — highlights areas with high inferred damage probability or intensity. The resolution and accuracy of these maps depend on the number and configuration of sensors, the chosen signal-processing pipeline, and the fusion method used to construct the final visualization.

Among the more advanced techniques is Full Waveform Inversion (FWI) [5, 6],

which reconstructs material property distributions by iteratively minimizing the difference between measured and simulated wavefields. This method can yield highly accurate and detailed images of internal defects. However, it requires significant computational resources and an accurate model of the wave propagation environment — including knowledge of the structure’s geometry, material properties, and boundary conditions. As such, FWI is rarely practical outside of well-controlled experimental or simulation-based contexts.

A somewhat more accessible approach is the Synthetic Aperture Focusing Technique (SAFT), which synthesizes reflections collected from different angles and positions to construct an image of structural discontinuities. SAFT is conceptually similar to radar and ultrasonic imaging, and it is particularly effective in detecting point-like defects. However, it still requires high-frequency signals, precise time synchronization, and often dense sensor arrangements to achieve satisfactory image quality. [7]

A widely used and conceptually simpler imaging method is the Reconstruction Algorithm for Probabilistic Inspection of Damage (RAPID) [8,9]. In RAPID, a damage index is calculated for each emitter–receiver pair, and this value is projected into the monitored region — typically along the straight-line path between the two transducers or via elliptical isochrones derived from ToF assumptions. Each DI projection contributes a 2D probabilistic field that is summed with those from other paths to form a two-dimensional damage probability map. RAPID has proven effective in a variety of applications due to its straightforward implementation and compatibility with sparse sensor networks.

Despite its utility, RAPID has several inherent limitations. First, it assumes a relatively uniform or symmetrical sensor layout, which can be difficult to achieve in real-world structures. Second, it treats each DI projection in a static and geometry-constrained manner, without accounting for the temporal evolution of the wavefield. Third, the aggregation process is typically fixed and insensitive to context — making it challenging to adapt the method to different damage indices, environmental conditions, or inspection scenarios. These factors limit RAPID’s flexibility and may result in blurred or ambiguous damage maps, especially when sensor density is low or damage is complex.

Overall, imaging techniques in guided-wave SHM offer an important path forward for interpretable and scalable damage localization. However, current methods tend to trade off between accuracy, flexibility, and hardware requirements. There remains a need for practical imaging approaches that are sensor-layout-agnostic, capable of incorporating temporal signal structure, and easy to adapt to diverse damage indicators. The method proposed in this paper is a step in that direction, aiming to produce clear, high-resolution damage maps using minimal sensing infrastructure and lightweight image-processing algorithms.

IMAGE PROCESSING FOR ASSEMBLY OF A DAMAGE MAP FROM PITCH-CATCH VIBRATION DATA

The proposed method transforms sparse guided wave measurements into interpretable, high-resolution maps of structural damage. It operates on the fundamental principle of mapping signal deviations — captured through damage indices (DIs) — onto the physical domain using path-based projections between transducer pairs. The result produces

a spatial representation of signal deviations suitable for both manual inspection and algorithmic analysis. At its core, the method builds a structural state image by drawing straight-line segments between emitter–receiver pairs. Each segment is assigned a color intensity proportional to the detected signal deviation, thereby projecting localized damage indications into the spatial domain.

The reconstruction process begins by preparing the necessary input data: the Cartesian coordinates of the emitters and receivers, a set of baseline signals representing the undamaged state, and a set of current signals reflecting the structure’s present condition. For each emitter–receiver pair, a damage index (DI) is computed using a baseline-based function that quantifies the deviation between the current and reference signals. The damage index can be based on correlation loss, amplitude attenuation, or any other suitable metric such as energy entropy or kurtosis, depending on the signal feature of interest.

Following this, a straight-line path is drawn between the emitter and receiver coordinates. This path is assigned a grayscale or colormap intensity that reflects the magnitude of the corresponding damage index — with greater signal deviation resulting in higher visual intensity. All such paths are then sorted in descending order according to their damage indices. Drawing is performed sequentially: paths with the highest damage indices are rendered first, while those with lower values are overlaid afterward. This heuristic enables low-index paths, typically associated with undisturbed wave propagation, to overwrite earlier, longer lines and effectively mask noise or over-extended damage projections. This step is critical for enhancing spatial localization and minimizing false positive regions in the reconstructed image.

Once all paths have been drawn, a morphological closing operation is applied to the image to eliminate small gaps and reinforce the visual continuity of damage indications. Depending on the application, additional smoothing, filtering, or thresholding may be applied as a post-processing step to further improve image clarity and facilitate interpretation. The final output is a structural state image in which localized regions of high accumulated intensity correspond to areas most likely affected by damage.

Unlike RAPID, which aggregates damage indications and may produce false hotspots in regions traversed by many low-intensity paths, our method overlays lower-damage paths over stronger ones, effectively suppressing broad projections and reinforcing localization. This inversion of the typical additive logic allows sparse data to yield cleaner, more interpretable damage maps.

EXPERIMENTAL DESCRIPTION

The experimental validation was conducted on a flat 2024-T3 aluminum alloy plate (280 mm × 250 mm × 10 mm), equipped with twelve SMD05T04R111WL piezoceramic transducers (STEMINC Inc.) arranged in a rectangular grid. These transducers acted as guided wave emitters, while signal reception was simulated using high-resolution vibrometric measurements. Simulated damage was introduced via flat-bottom holes ranging from 3 mm to 17 mm in 2 mm increments, each representing a distinct structural condition. After drilling each hole, a new baseline scan was recorded to serve as the undamaged reference for that scenario. All holes had a fixed depth of 25% plate thickness.

A subset of PZT emitters was used to apply Hanning-windowed 300 kHz excitation signals. Due to the time-intensive nature of full-field scanning, only a limited number of excitations were performed per case.

Wave responses were captured using a Polytec PSV-500 laser vibrometer with a PSV-I-550 scanning head. The scan grid, placed on the plate's opposite surface, included 8613 points spaced 2.7 mm apart, enabling full-field wavefield visualization. To simulate sparse receiver data, a predefined subset of scan points was selected as virtual sensors. These signals were used as input for the proposed image-generation algorithm to evaluate its effectiveness in reconstructing interpretable damage maps from limited sensing.

DAMAGE MAPS OBTAINED FROM VIBROMETRIC SIGNALS

Figure 1 illustrates the key steps involved in constructing a feature map using the proposed method. In this example, a correlation-based damage index is used, with a single emitter and receivers positioned in a rectangular arrangement surrounding the specimen. The figure serves to demonstrate the principle of path drawing and sequential merging based on damage index values. As expected, when only one emitter is used, the damage localization is imprecise. The spatial resolution of the method depends not only on the number of receivers, but also on the number and distribution of emitters across the monitored area.

Figure 2 presents two examples of reconstructed feature maps obtained with different sensor placements. The perceived spatial resolution varies significantly between the two cases. In Figure 2(a), the damage is represented by a large affected region because no transmitter-receiver paths are available behind the damage that remain unaffected, leading to a broad damage indication. While the most visually consistent and localized reconstructions are obtained when sensors are distributed uniformly — for instance along a border or in a regular grid — the method is also compatible with non-uniform sensor layouts. This flexibility enables its application in scenarios where structural features, such as rivets, stiffeners, or welded zones, prevent arbitrary sensor placement.

Nevertheless, it should be noted that large distances between receivers can lead to artifacts in the reconstructed images, such as visible dents or voids in the damage map, as exemplified in Figure 3. These effects are more pronounced when sparse receiver configurations leave significant gaps between the areas covered by different propagation paths.

Finally, Figure 4 shows feature maps reconstructed for several different damage scenarios. In these examples, sensors were placed around the region where damage was expected to occur, simulating a monitoring strategy focused on "hot spots," as commonly practiced in aircraft structural health monitoring. The results indicate that the method is capable of detecting and localizing damaged areas. However, some false positive indications are present, particularly for smaller damages, reflecting the inherent challenges associated with sparse sensing and subtle damage signatures.

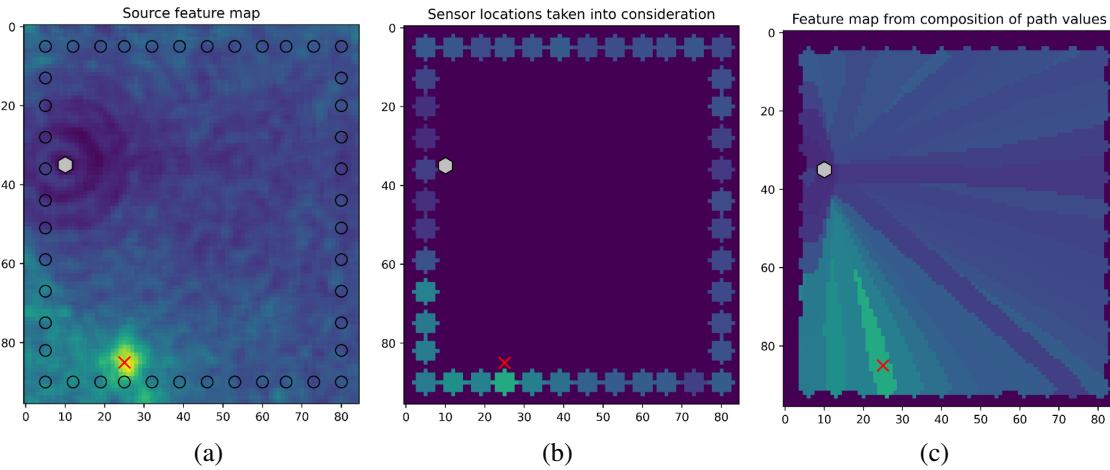


Figure 1. Feature map calculation stages - for one excitation sensor. Damage location marked with a red 'x': (a) dense feature map acquired using laser vibrometer; (b) simulated receivers' locations and (c) color-coded paths drawn and then merged using morphological closing

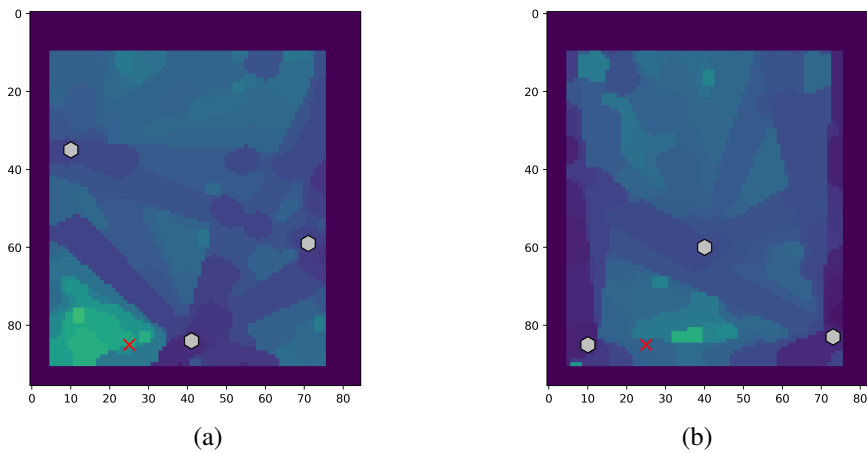


Figure 2. Feature maps calculated for different excitation sensors' locations

DISCUSSION AND CONCLUSIONS

While the RAPID approach has proven effective in a range of structural health monitoring scenarios—particularly due to its compatibility with sparse sensor layouts and straightforward implementation—it typically aggregates all damage indices into a cumulative damage map. This can, in some cases, produce broad or ambiguous indications when multiple low-magnitude signals overlap.

The method proposed in this paper takes a different but complementary approach: rather than summing contributions from all emitter–receiver paths, it prioritizes those with higher damage indices by rendering them first and allowing subsequent, lower-index paths to overwrite earlier ones. This ordering functions as a form of contextual filtering, where undisturbed wave paths suppress broad projections and help sharpen the localization of actual damage. While both methods offer valuable capabilities, this

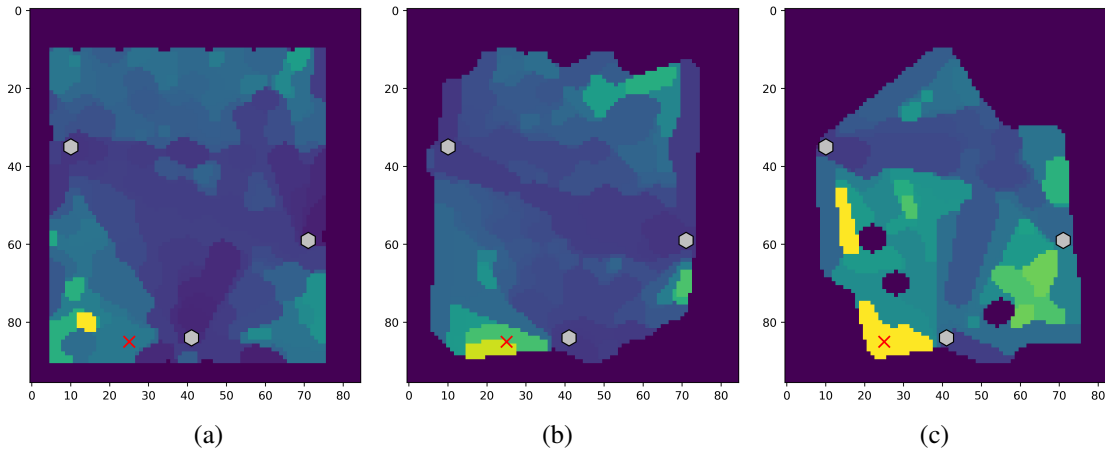


Figure 3. Feature maps resulting from different receiver arrangements: (a) grid, 49 sensors; (b) random, 49 sensors and (c) random, 16 sensors

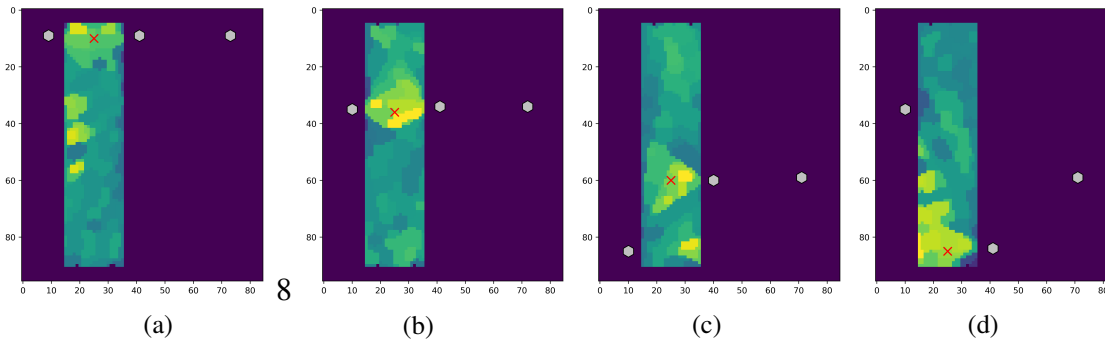


Figure 4. Feature maps calculated for different damage scenarios: (a) 11 mm, (b) 13mm, (c) 15 mm and (d) 17 mm; for 20 sensors located around the region where damage is expected to happen

rendering strategy can be particularly advantageous in scenarios where damage signals are strong but spatially sparse, and noise suppression is critical for interpretability.

The reconstruction method presented here addresses the problem of visualizing structural damage from sparse guided wave measurements through a direct, path-based projection strategy. By mapping damage indices onto straight-line segments between sensor pairs, the approach avoids reliance on complex physical models or probabilistic inference. This strategy does not depend on dense sensor grids or specific geometric layouts. While configurations with border-mounted receivers often yield clearer spatial representations, the method is applicable to arbitrary sensor arrangements.

Its computational simplicity and flexibility in handling different damage indices make it suitable for exploratory diagnostics or systems with limited sensing capacity. Rather than serving as a replacement for high-fidelity imaging techniques, the method offers a practical and interpretable alternative that may complement more advanced analyses in structural health monitoring.

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