Sociedad Mexicana de Ingeniería Mecánica
Fecha de recepción: 02-06-2024
Fecha de aceptación: 29-07-2024

Beamforming for Structural Health Monitoring Using Guided Waves

Monitoreo de condición estructural usando conformado de haces con ondas guiadas

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Abstract

Ultrasound can travel in mechanical guides such as beams, plates, and tubes. In nondestructive inspection, guided ultrasonic waves have been attractive because they can cover larger areas compared to traditional point-by-point ultrasonic test techniques. However, they come with a challenge: they are non-stationary, multimode dispersive waves, making signal analysis difficult. This problem has been addressed using mode discrimination, identifying regions of low dispersion, and applying signal processing techniques. This work gives a brief summary of the state-of-the-art in guided wave signal processing and imaging using shear guide waves. We discuss our current research on beamforming as a mean to provide an easy-to-observe detection and identification method of signals. Results on signal analysis of guided wave propagation in plates using small, flexible patches and sensor arrays are presented both numerically and experimentally. It is shown that beamforming is possible using guided waves and can be used to localize discontinuities in a large inspected plate.

Resumen

El ultrasonido puede viajar en guías mecánicas como vigas, placas y tubos. En la inspección no destructiva, las ondas ultrasónicas guiadas han sido atractivas porque pueden cubrir áreas más grandes en comparación con las técnicas tradicionales de prueba ultrasónica punto por punto. Sin embargo, presentan un desafío: son ondas dispersivas multimodo no estacionarias, lo que dificulta el análisis de la señal. Este problema se ha abordado mediante la discriminación de modos, la identificación de regiones de baja dispersión y la aplicación de técnicas de procesamiento de señales. Este trabajo presenta un breve resumen del estado del arte en el procesamiento de señales e imágenes de ondas guiadas utilizando ondas de guía de corte. Discutimos nuestra investigación actual sobre el formado de haces (beamforming) como un medio para proporcionar una detección e identificación de señales fácil de observar. Se presentan resultados de laboratorio sobre el análisis de señales de propagación de ondas guiadas en placas utilizando parches pequeños y flexibles y arreglos de sensores, tanto numérica como experimentalmente. Los resultados demuestran que el beamforming es posible utilizando ondas guiadas y puede utilizarse para localizar discontinuidades en una gran placa inspeccionada.

Keywords:
Guided waves, Flexible PZT patches, SH waves, Beamforming, Structural Health Monitoring

Palabras clave:
Ondas guiadas, Parches PZT flexibles, ondas SH, formado de haces, Monitoreo estructural

Introductión

The human desire to see beyond the visible has led to the development of nondestructive evaluation (NDE) techniques, which enable us to assess the condition of various materials and systems without affecting their later use. Modern NDE methods often use ultrasound, with inspection frequencies ranging from 0.1 MHz to 25 MHz, and typically involve equipment such as signal generators, transducers, coupling media, signal processing units, and display devices. NDE employing ultrasonics can be divided into two main techniques: bulk wave propagation and guided waves (GW). Both methods use discontinuities as reflectors, reflecting some of the energy traveling through the system, allowing the identification of structural defects by measuring the reflected waves. Due to the abundance of plate-like structural configurations, Lamb waves have been the subject of several investigations. Guided waves are particularly attractive in NDE due to their ability to inspect larger areas compared to traditional point-by-point bulk wave techniques, although their non-stationary, multimode dispersive nature makes signal analysis challenging.

Lamb waves are commonly used in detection techniques due to their easy generation and detection, sensitivity to discontinuities, and long-range capability [1,2]. However, they face challenges such as dispersion and multimode propagation, making it difficult to discern defect signals due to interference from other factors. In contrast, the fundamental mode of SH waves (SH0 waves) in an isotropic plate is non-dispersive, simplifying signal interpretation. SH0 waves are less affected by surrounding fluids and have extended inspection

DOI: 10.59920/RIMTD.20244S

distances due to their in-plane particle displacement. They also experience less mode conversion at defects or boundaries, reducing signal complexity, and are suitable for inspecting curved structures with minimal reflections. However, the limited use of SH0 waves may be due to challenges in exciting pure SH0 waves with piezoelectric transducers and difficulties in coupling.

The efficiency of evaluating structural defects is closely linked to the capability of wave generation and detection by transducers. Recent advancements in transducer technology, such as the use of piezoelectric and epoxy material fibers to create highly flexible and lightweight patches, have led to the development of transducers with improved performance. Examples of such transducers are the macro-fiber composite (MFC) transducers developed by NASA, which have been employed and studied in various applications [3,4]. Studies have investigated the directivity of Lamb and SH modes using MFC transducers, as well as the orientation effect of the fibers in the generation of SH modes [5-7]. MFCs are manufactured by sandwiching rectangular thin piezo-ceramic rods between layers of adhesive, electrodes, and polyamide film [8]. A method for modeling the wave field and directivity of MFC transducers for using a semi-analytic approach was developed in [9,10]. This work focuses on SH waves because their pure in-plane displacement makes them less affected by surrounding fluids. This translates to longer travel distances, ultimately improving the inspection range. Additionally, SH waves have less mode conversion at defects, reducing signal complexity. The fundamental mode of SH waves (SH0) in isotropic plates is non-dispersive, making signal interpretation easier. They are also appropriate for inspecting curved structures. The interactions of SH waves with various types of discontinuities have been studied numerically and experimentally [11]. These studies have shown the complexities involved in accurately detecting and characterizing these discontinuities. Consequently, the need to improve detection has driven advancements in beamforming methods for ultrasound imaging of solid plate-like structures. Beamforming techniques have become essential for effectively addressing the wave interactions and improving the resolution and accuracy in damage location [12,13]. The advancements in conventional beamforming methods for ultrasound imaging of solid plate-like structures have been driven by the need to address challenges related to correlated signals and dispersion [14-16].

Despite significant efforts in the field, challenges related to correlated signals and dispersion in cylindrical structures remain unresolved, highlighting the need for continued research and advancements in SH wave generation and beamforming techniques for localization of discontinuities.

This study explores the generation of SH waves using flexible actuators that could be coupled to curved structures (Fig. 1 (a)). However, when the pipe's thickness-to-radius ratio is low, the problem can be treated as guided waves propagating in a plate, as shown in Fig. 1 (b). This simplifies the problem by assuming an equivalent unwrapped hollow cylinder. Here, we are proposing to generate SH waves on the surface of a plate using an array of directional and flexible actuators to focus the wave energy on a desired direction for inspection of discontinuities or flaws. Reflections from discontinuities will be gathered with a sensor array of quasi-omnidirectional transducers, and the reflected signals will be processed using a beamforming algorithm.

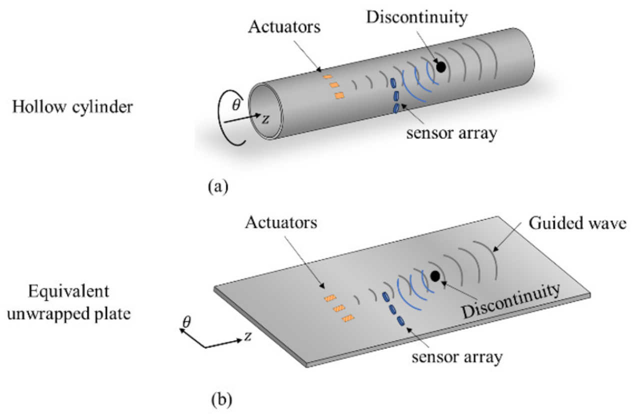

Figure 1 – Description of problem simplification, (a) wave propagation in a cylindrical system to discontinuity detection (b) approach of modeling the cylinder as an unwrapped plate.

The aim of this work is to employ a beamforming algorithm for the detection and localization of discontinuities using the fundamental SH0 nondispersive mode generated by an array of flexible PZT patches, and the reflected signals received by a linear array of sensors. Our specific objectives include: 1) to calculate the wave field of the SH0 mode generated by the array of actuators, 2) designing an experimental setup with a linear array for transmitting and receiving the SH0 wave, and 3) apply a beamforming algorithm to determine the direction of discontinuities detected by the flexible sensors.

This work is organized as follows: In section 2, a summary of the state-of-the-art guided waves is presented, describing the types of guided waves and their differences from bulk waves, as well as the phenomenon of dispersion. Section 3 discusses beamforming techniques used in NDE using ultrasound. Section 4 discusses the acoustic field generated by flexible MFC transducers and how we can predict it, along with the application of beamforming, explaining the basis of the algorithm used. Finally, in Section 5 the experimental setup is described and the results of applying beamforming and beam steering for the localization of discontinuities are presented.

Ultrasonic Guided Waves for Inspection

Conventional ultrasonic inspection techniques involve manually positioning the transducer at each location to be analyzed, known as point-by-point inspection (Fig. 2(a)). This method, while effective, can be time-consuming and

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ISSN 2448-5837

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labor-intensive. To address these challenges, various enhancements to the point-by-point inspection method have been developed. These improvements include the use of robotic scanners for automatic inspection and the implementation of transducer arrays for pipe inspection, among others [17, 18].

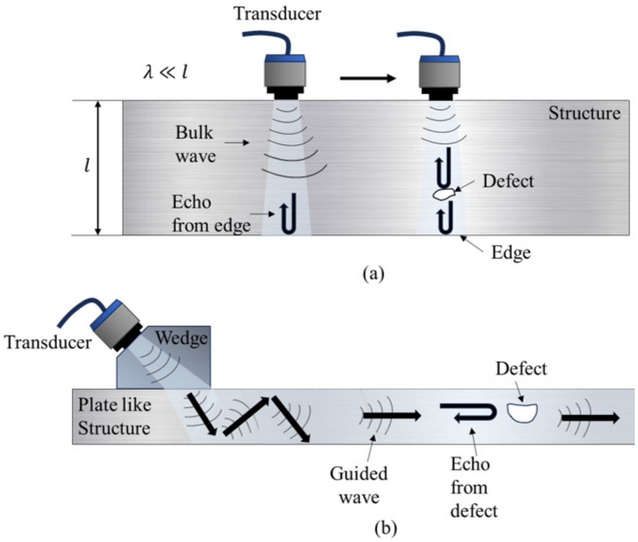


Figure 2 – Inspection using ultrasound, (a) point by point using bulk waves (b) scanning from a single location using guided waves in plate-like structures.

The techniques based on point-by-point inspection, which is time-consuming, especially for large structures. In bulk wave inspection, the transducer must be moved along the surface to collect data, whereas with guided waves the structure can be inspected from a single probe position. On the other hand, GW based on ultrasonic techniques can travel long distances on mechanical guided structures such as plates or pipes [19].

The principal advantages of using guided waves (GW) analysis techniques include the ability to inspect long distances from a single position, eliminating the need to scan the entire object. These techniques often provide greater sensitivity and a better assessment of the material's health compared to standard localized ultrasonic inspections. Ultrasonic GW can inspect hidden structures, underwater structures, coated structures, and structures buried under soil or encapsulated in insulation and concrete, making them ideal due to their mode sensitivity over long distances. Additionally, GW inspection is cost-effective, simple, and rapid, as it requires minimal preparation, such as not needing to remove insulation or coating along the length of the structure, except at the transducer's location [20]. A depicted comparison of bulk wave and guided wave ultrasonic inspection is shown in Figure 2. The figure illustrates two methods of ultrasonic evaluation in solid structures. In image (a), traditional ultrasonic bulk wave evaluation with normal-beam excitation is depicted, where a transducer emits ultrasonic waves perpendicular to the material's surface, covering a small area, especially when the sound wavelength (λ) is much smaller than the material thickness (l). In Figure 2(b), guided wave inspection with angle-beam excitation is shown, where the transducer emits waves at an angle, allowing the waves to propagate along the structure and cover a larger area. In theory, this method could be less time consuming for detecting discontinuities and internal defects throughout the structure. A general comparison is given in Table 1.

Table 1 – Ultrasonic bulk versus guided wave propagation.

	Bulk	Guided
Phase velocity	Constant	Function of frequency
Group velocity	Same as phase velocity	General not equal to phase velocity
Pulse shape	Nondispersive	General dispersive

In the bulk wave case, waves are modeled as vibrations propagating through infinite space without considering physical boundaries. A major challenge with guided waves (when boundaries are assumed) is the presence of multiple vibration modes, leading to various wave velocity values dependent on frequency. In contrast, bulk wave propagation exhibits a frequency-independent wave velocity.

A theoretical prediction of the propagation characteristics of GW can be obtained by applying the theory of elasticity in wave mechanics, with Navier's equation and a constitutive equation like the Hooke's law, and assuming harmonic solutions, and we can derive the dispersion curves for a structure. These curves, which plot phase velocity versus frequency, describe how waves propagate through the material. So consequently, frequency components of the wave packet will travel at different velocities distorting the original input signal along its propagation [21]. This phenomenon is called dispersion. A graphic example is shown in Fig. 3.

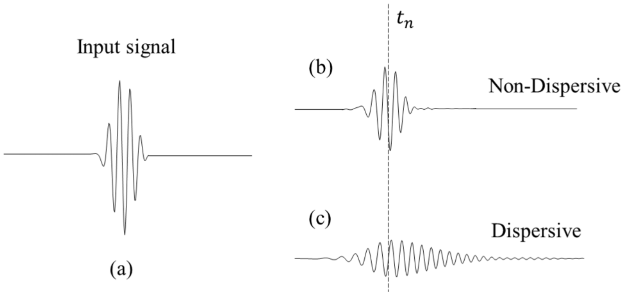


Figure 3 – Example of dispersion (a) input signal, (b) non-dispersive (bulk) waves, (c) dispersive wave.

Fig. 4 presents the phase and group velocity dispersion curves for an aluminum plate made of 6061 alloy. These curves illustrate how the phase velocity of guided waves varies with frequency. These curves show how the group velocity, which represents the velocity at which the wave information travels, varies with frequency. Like the phase velocity curves, different propagation modes are illustrated, highlighting the group velocities at various frequencies. Different modes of wave propagation are represented, showing the characteristic velocities for each mode at varying frequencies. Lamb waves, which have no particle motion in the direction orthogonal to the illustrations depicted in Fig. 2, and SH waves which do involve this type of particle motion, are the two types of waves that can be generated.

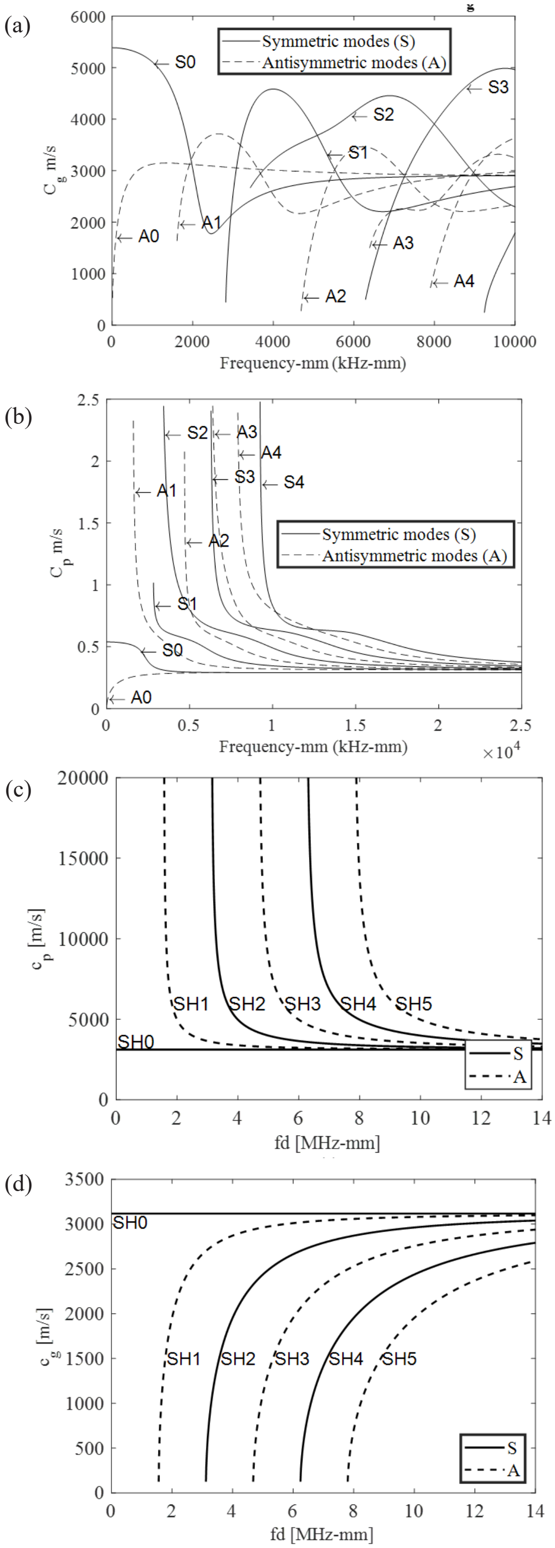
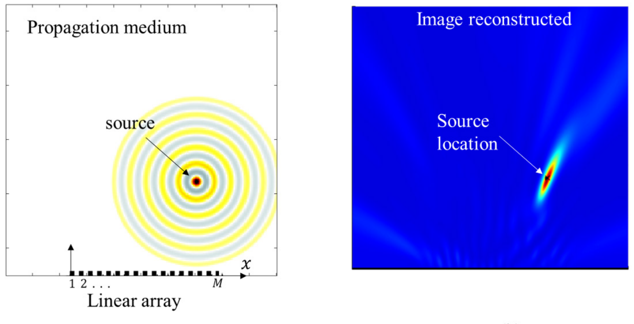


Figure 4 – Dispersion curves for guided waves in an aluminum plate 6061. Lamb waves dispersion curves for (a) phase, and (b) group velocity, and (c) phase and (d) group velocity for SH dispersion curves.

Dispersion curves are crucial for understanding wave propagation characteristics in a plate. Due to the complex behavior of GW, obtaining accurate dispersion curves is essential. Analyzing, processing, and obtaining relevant information for interpretation is complex. Furthermore, controlling and analyzing GW is challenging, but recent advancements in computational capacity allow the implementation of new signal processing algorithms and new opportunities for developing better inspection techniques have emerged, leading to better interpretation of readings obtained through ultrasonic GW inspection.

The correct interpretation of readings obtained through ultrasonic inspection is crucial for the correct detection or monitoring of engineering structures. Transducer arrays, which consist of a set of individual elements that produce a focused acoustic field, offer a method to address this challenge. A transducer array consists of a set of individual elements that produce an acoustic field in a specific direction. Transducer arrays (for example using phase array) can propagate a wide range of acoustic fields and are commonly used to produce bulk waves and guided waves [22]. Also, the received acoustic waves can be algorithmically processed by beamforming using the signals received by an array of sensors. Using this technique, it is possible to reconstruct an image showing the source locations. An example of the implementation of this technique is shown in Fig. 5.



(a) (b)

Figure 5 – Image reconstruction of a point source assuming bulk waves, (a) propagation medium and simulated source, (b) image reconstructed of the source location using beamforming.

Beamforming using an array of transducers

Beamforming is a signal processing technique used to enhance the directionality and quality of transmitted or received signals in applications like wireless communication, radar, sonar, and audio processing. Adaptive algorithms, including delay-weight-and-sum, frequency selectivity, and transducer design, improve resolution, reduce processing time, and mitigate dispersion effects. Hybrid algorithms combining various methods and optimization techniques, such as random chaotic walk search, address limitations and reduce computational costs [15].

ISSN 2448-5837

ISSN 2448-5837

Beamforming involves manipulating the phase and amplitude of signals from an array of sensors to create a focused beam in a particular direction, while suppressing interference and noise from other directions. The fundamental principle behind beamforming is interference and wave superposition.

There are several popular adaptive beamforming algorithms used in practice, including delay-and-sum beamforming, minimum variance distortionless response (MVDR) beamforming, and linearly constrained minimum variance (LCMV) beamforming. Delay-and-sum beamforming is a basic algorithm (eq. 1) that delays the signals from each sensor or antenna to align them in time and then sums them to create a beam in a particular direction [12,14].

$$z(t)=\frac{1}{M}\sum_{m=0}^{M-1} w_m y_m\left(t-\Delta_m\right) \qquad (1)$$

Where M is the number of sensors, and for each signal taken y_m, a delay Δ_m and an amplitude weight w_m are applied. The delay is adjusted to focus the detection on signals propagating in a specific direction θ. The aperture function of a beamforming array depends on a combination of factors, including the topology and layout of the array, the number of sensors, the frequency of the input signal, and the physical properties of the sensors. Understanding and optimizing these parameters are crucial for achieving desired beamforming performance in various applications. For an assumed array of M point actuators and physically equal sensors, the aperture function is shown in Fig. 6. Which controls the beamforming output, and it determines how the array's beam is shaped and, consequently, its performance.

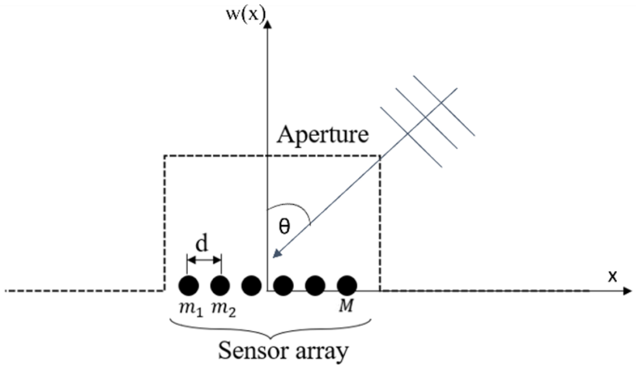


Figure 6 - Sensor array with uniform spacing and corresponding aperture function (dashed line) receiving a plane wave from a specific direction.

A widely used alternative algorithm is MUSIC (Multiple Signal Classification) that has gained popularity due to its high resolution and capability to handle multiple sources in the presence of noise. The MUSIC algorithm is a subspace-based approach that uses the spatial properties of signals to estimate the direction of arrival (DOA) of multiple signals. The basic idea of MUSIC is to project the received data onto two orthogonal subspaces: the signal subspace, which captures the information of the desired signals, and the noise subspace, which represents the noise and interference. The DOA estimates are then obtained by identifying the peaks in the spatial spectrum computed from the eigenvalues of the noise covariance matrix projected onto the noise subspace, see [25] for further details.

Generation and directivity of SH waves using an array of MFC actuators

To generate and focus GW on a given direction requires controlling the directivity of an array of actuators. Using both numerical simulations and experiments, it is demonstrated that the directivity of an array of actuators can be modified. This allows scanning and focusing the acoustic beam to specific regions on the inspected structure. Consider an infinitely extended isotropic plate of uniform thickness $l=2b$, with an array of rectangular MFC patches bonded on its top surface, at $x_3=+b$ as shown in Fig. 7. Note that the origin of the coordinate system is located at the plate's mid-plane. The stress distribution produced by the MFC source through its piezoelectric vibration is of three-dimensional nature; therefore, a full three-dimensional analysis is required to describe the experimental measurements presented later. A method to predict the directivity of an array of sensors for guided waves is described in [9,10].

A summary of the main steps to determine the acoustic field (directivity) of SH wave generated by an array of MFCs is summarized as follows:

- To specify the shape of the actuator or array of actuators bonded to the surface isotropic thin plate of uniform thickness, as described in Fig. 7.
- SH modes dispersion expressions: For a given frequency ω the displacements are calculated from the wave equation using as boundary condition the stress distribution functions.
- To determine the stress distribution function by implementing FEM for a piezoelectric actuator bonded to the surface of the plate.
- The directivity is calculated by the product of each angular component of the Polar Fourier transform of the stress distribution by the dispersion relation from the analytical solution.

By following these steps, the semi-analytical method combines analytical and numerical approaches to accurately estimate the directivity of the wave field generated by an array of MFCs with arbitrary shape actuation.

Fig. 8 depicts Finite Element Method (FEM) stress distribution functions σ_{31} and σ_{32} of a a) MFC and b) and c) arrays of 2 and 3 MFCs arranged in a linear topology. The MFCs are represented as rectangular shapes, arranged in a linear pattern, with a particular orientation. Each MFC is represented by rectangular elements with varying colors indicating the stress levels. The FEM analysis provides insights into the electromechanical behavior of the MFCs, revealing areas of high and low stress concentrations. These functions are essential for the semi-analytical proposed method. The contour plots show varying stress levels in different areas of the MFC, indicating stress concentration or distribution patterns.

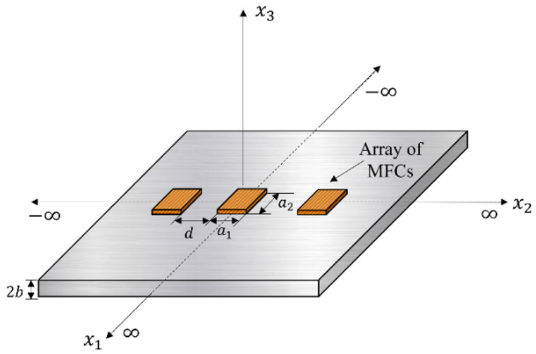


Figure 7 - An isotropic plate with an array of MFC patches attached at its center.

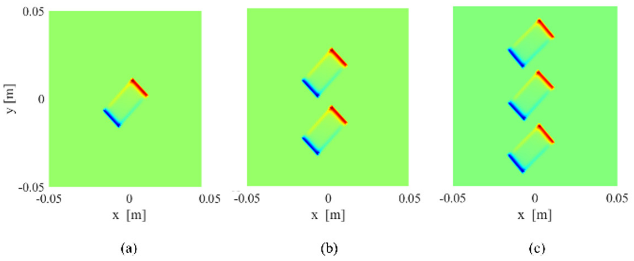


Figure 8 - Stress distributions of a) a single MFC, and linear arrays of b) 2 and c) 3 MFCs.

Fig. 9 shows the directivity for SH0 mode obtained using a semi-analytical method proposed in [9] for various MFCs configurations: 1 MFC, 2 MFCs and a linear array of 3 MFCs. The beam pattern of the MFC, indicating the directionality and intensity of the emitted or received signals can be observed. The directivity pattern is shown in a polar plot with azimuth angles, providing information about the beam width, main lobe, and side lobes of the array's beam pattern. The beam pattern reflects the array's ability to focus or steer the signals in a specific direction.

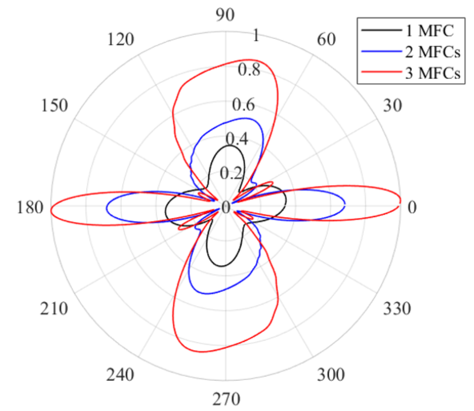


Figure 9 - Directivity patterns for a single MFC and arrays of 2, and 3 MFC at a frequency of 50 kHz.

The semi-analytical method involves solving the wave equation and obtaining analytical expressions for the directivities of arrays with 1, 2, and 3 MFCs. These directivities represent the ability of the array to focus energy on a particular direction. The results of the semi-analytical method show that the directivity increases with the number of MFCs in the array. Specifically, the array with 3 MFCs in a linear configuration exhibits higher directivity compared to arrays with 1 or 2 MFCs. This indicates that the array of 3 MFCs can focus more energy on a particular direction, which makes it suitable for experimental tests aimed at locating a discontinuity.

Results and analysis

The experimental configuration for generation (using an array of MFC actuators) and capture of reflected signals by another array of PZT-SH sensors for subsequent signal processing using MUSIC beamforming algorithm is shown in Fig. 10. Three MFC transducers (MFC-2814-P1) were attached to an Aluminum plate with a thickness of 2 mm. The array of MFCs was excited with a 4-cycle tone burst and a central frequency of 90 kHz by a function generator. SH0 waves were detected by an array of commercial shear wave transducers (PZT-SH transducers) with a frequency of 1 MHz and 0.5" in diameter. The captured signals were post-amplified and post-processed in MATLAB environment.

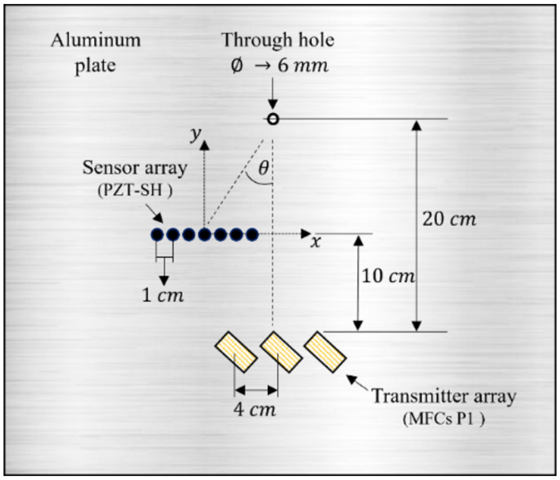


Figure 10 – Experimental configuration, showing the locations of the receiver and transmitter linear arrays.

An array of three MFCs 2814-P1, are used to generate and focus the beam of non-dispersive SH0 mode in a specific direction. An artificial discontinuity in the form of a through hole is introduced in the direction of interest. The array of MFCs (type P1) is positioned at a fixed distance from the specimen surface, and the angle of incidence, denoted as θ, is varied during the experiment. To capture the echo from the through-hole, a separate array of seven SH piezoelectric (PZT) sensors is placed on the specimen surface. The received signals from the PZT sensors are recorded for further analysis. The beamforming algorithms described above, Delay and Sum (DAS) and MUSIC, were implemented to

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process the recorded signals and locate the artificial discontinuity.

Fig. 11 displays the set of signals captured by the seven SH piezoelectric sensors for an incident angle of 15° during the experimental investigation. The figure shows the direct SH0 signal captured by the sensors, as well as the echoes from the through hole and the edge of the plate. The figure provides a visual representation of the signals captured by the sensors, illustrating the complex nature of the interactions between the incident SH0 wave and the artificial discontinuity in the form of a through hole, as well as the reflections from the edge of the plate.

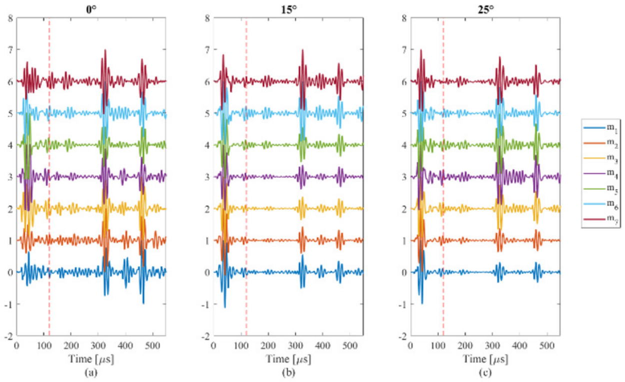

Figure 11 – Signals captured by the array of sensors for incident angle of a) θ=0°, b) 15°, and c) 25°, where the red dashed line indicates the expected arrival time of the echo from discontinuity.

Fig. 12 shows an example of the output of the DAS beamforming algorithm for two scenarios: when the sum of delayed signals occurs in the correct direction (black) and when it occurs in the incorrect direction (blue).

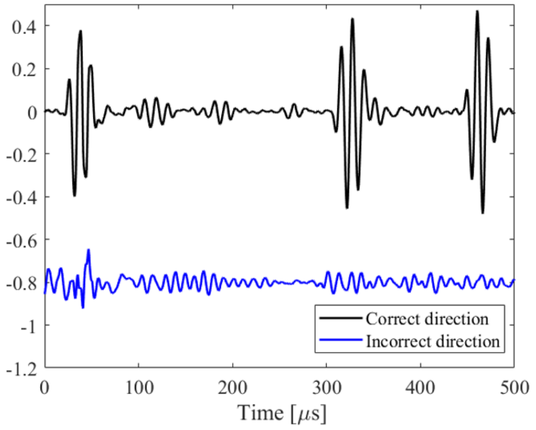

Figure 12 – Beamforming Delay and Sum output for correct and incorrect directions.

In the experiments, the angle θ was varied in discrete steps, 0°, 15°, and 25°, to investigate the effect of the incident angle on the accuracy and resolution of the beamforming algorithms in locating the artificial discontinuity. The results of the DAS and MUSIC algorithms are analyzed and compared for each angle θ. The beamforming results, including the beamforming images generated by DAS and MUSIC, are presented in Fig. 13.

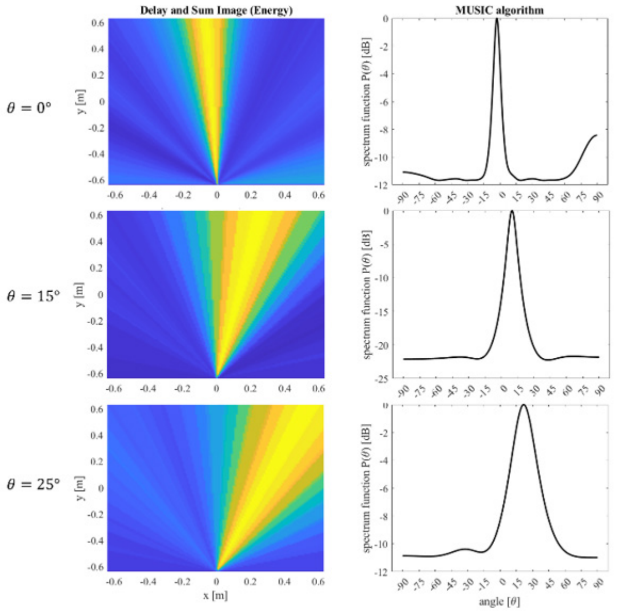

Figure 13 – Beamforming results for artificial discontinuity localization using DAS and MUSIC algorithms at different incident angles a) θ=0°, b) 15°, and c) 25°.

Conclusion

The fundamental shear horizontal (SH0) acoustic plate wave mode is a non-dispersive vibrational mode with potential applications in non-destructive health monitoring of plate-like engineering structures. In this study, rectangular patches of flexible piezoelectric (PZT) transducers were utilized to excite SH0 waves, as these patches are better suited for surfaces with smooth waviness compared to hard piezoceramic transducers. The complex directivity pattern of different patch array configurations on a thin plate was estimated using a semi-analytical method. An experimental setup was built in the laboratory to propagate and detect small discontinuities in an aluminum plate. The excited SH0 waves were propagated and interacted with an artificial through-hole discontinuity, and the scatter signals were collected by a linear array of piezoelectric SH sensors. The results demonstrated that the proposed beamforming algorithms, Delay-and-Sum (DAS) and Multiple Signal Classification (MUSIC), could localize the discontinuity using an array of flexible Macro Fiber Composite (MFC) transducers directed towards a specific target. These findings highlight the potential of utilizing flexible PZT transducers and advanced beamforming algorithms for effective SH0 wave-based non-destructive health monitoring of plate-like structures. In future work will explore the imaging reconstruction to determine not only the direction but also the position of discontinuities.

Acknowledgements

The authors gratefully acknowledge the financial support provided by CONAHCYT program for the Ph.D. scholarship of Esteban Guerra-Bravo.

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ISSN 2448-5837