

Generation of plate waves using electromagnetic acoustic transducer (EMAT) for defect detection in thin stain steel weld plate

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Abstract: This paper presents a non-contact ultrasonic inspection technique based on an electromagnetic acoustic transducer (EMAT) to generate plate (Lamb) waves for defect detection in thin stainless steel weld plates. The design and operating principle of a meander-coil (MC) EMAT for the efficient generation of plate waves in thin plates are discussed. Experiments were carried out on a 2-mm-thick stainless steel weld plate using a MC EMAT at a low excitation frequency of 500 kHz. At this frequency, the MC EMAT generated the fundamental symmetric (S_0) and antisymmetric (A_0) plate wave modes. The propagation characteristics and mode identification were analyzed using dispersion curves developed for the 2-mm-thick stainless steel plate. The experimentally observed wave modes were correlated with the theoretically predicted phase and group velocities. Artificial defects introduced in the weld region were subsequently inspected using the generated plate wave modes. The defect responses were analyzed in both the time and frequency domains to evaluate their detectability and characteristic signal features.

Keywords: Electromagnetic Acoustic Transducer, Meander coil, Plate waves, Dispersion curves, S_0 and A_0 modes, Stainless steel weld plate

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I. Introduction

Electromagnetic acoustic transducers (EMATs) are being increasingly investigated for non-contact, non-destructive testing (NDT) of electrically conductive and ferromagnetic materials [1-3]. Unlike conventional piezoelectric transducers, EMATs generate and detect ultrasonic waves via electromagnetic interactions, primarily the Lorentz force and/or magnetoelastic effects [4]. A major advantage of EMATs is their couplant-free operation, which eliminates variations and uncertainties associated with liquid couplants in conventional ultrasonic testing [5-7]. The non-contact nature of EMATs also enables ultrasonic measurements at elevated temperatures and in applications involving remote or difficult-to-access locations. Another important advantage of EMATs is their versatility in generating different ultrasonic wave modes by appropriately designing and configuring the excitation coil and permanent magnet [8-10]. By modifying the coil geometry, magnetic-field configuration, and excitation sequence, specific ultrasonic modes can be generated, including normal and angle-beam shear waves, horizontally polarized shear waves, Rayleigh waves, and Lamb or plate waves [11-14]. This flexibility allows the EMAT configuration to be tailored to the material, geometry, and specific inspection requirements, making EMATs a promising technology for a wide range of ultrasonic NDT applications [15-17].

Lamb waves, also referred to as plate waves or guided waves, are a class of ultrasonic guided waves widely used for the inspection and structural health monitoring (SHM) of plate-like structures, thin-walled components, and metallic materials [18]. Unlike conventional bulk ultrasonic waves, which generally propagate through the thickness or along a localized beam path, Lamb waves are guided by the boundaries of a plate. They can propagate over relatively long distances while interacting with defects and discontinuities throughout the material thickness [19]. This characteristic makes them particularly useful for NDT and SHM applications involving components that are difficult to access directly, including structures embedded in other materials, buried structures, and geometrically constrained components. Lamb waves exhibit complex particle motion extending across the entire thickness of the plate, and their propagation characteristics depend on the material density, elastic properties, plate thickness, and excitation frequency. Multiple propagation modes can exist, with the two fundamental mode families being symmetric (S) and antisymmetric (A), defined by the symmetry of particle motion about the plate's median plane [3]. The symmetric mode is predominantly associated with extensional deformation, involving alternating stretching and compression along the direction of propagation. In contrast, the antisymmetric mode is primarily associated with flexural deformation, with significant particle

motion normal to the plate surface. The fundamental modes, S0 and A0, are particularly important in practical NDT applications because they exhibit different propagation characteristics and sensitivities to structural defects [9, 19].

Thin stainless steel weld plates are widely used in engineering structures where high strength, corrosion resistance, and structural integrity are required with reduced material thickness [5]. They are commonly employed in various industries, including nuclear power plants, particularly in lightweight panels, piping components, pressure boundaries, and structural assemblies. Hence, a reliable volumetric NDT method is essential for testing the weld. In this work, the MC EMAT, comprising a meander coil and a permanent magnet, was developed to excite the fundamental S0 and A0 wave modes in a 2 mm-thick stainless steel weld plate. The generated plate waves were used to investigate their interaction with artificial defects of different depths introduced in the weld region. The defect responses were recorded and analyzed in both time and frequency domains. Time-domain signals were evaluated to identify defect-induced reflections and amplitude variations, while frequency-domain analysis was used to characterize changes in spectral components. The study demonstrates the potential of MC EMATs for non-contact plate wave generation and defect detection in stainless-steel welds.

II. Physical principle of MC EMAT

An EMAT generally consists of a high-frequency coil and a permanent magnet or electromagnet that provides a static magnetic field. When an alternating electrical current at the desired ultrasonic frequency is supplied to the coil, a time-varying electromagnetic field is generated in the vicinity of the specimen surface. This alternating magnetic field induces eddy currents (J_e) within the near-surface region of the electrically conductive material according to the principle of electromagnetic induction. The induced eddy currents interact with the static magnetic field (B_s) produced by the permanent magnet. The interaction between these two fields produces the Lorentz forces (L_f) within the conducting material, which can be expressed as [1, 2]

$$L_f = J_e \times B_s \quad (1)$$

The direction and magnitude of the Lorentz force depend on the orientation and strength of the induced eddy current and the static magnetic field. These forces are transferred to the material lattice, producing periodic mechanical stresses at the excitation frequency. Consequently, ultrasonic elastic waves are generated and propagate through the specimen. The same electromagnetic coupling principle can also be used in the receiving mode, where the interaction between the propagating ultrasonic wave and the magnetic field induces motion of the conducting material, resulting in a measurable electrical response in the receiver coil. Thus, EMATs can perform both ultrasonic generation and detection without direct mechanical coupling to the test component [20-22].

The performance of an EMAT is strongly dependent on the geometrical characteristics of the excitation coil and the application of the magnetic field. In particular, the coil geometry, conductor spacing, number of turns, excitation frequency, lift-off distance, magnetic flux density, and orientation of the magnetic field influence the spatial distribution of the Lorentz force and, consequently, the efficiency of the generated ultrasonic waves. For plate or guided-wave applications, the periodicity or pitch of the coil is an important design parameter, as it can be chosen to match the wavelength of the desired guided-wave mode at a particular operating frequency. Two commonly used EMAT coil configurations are the spiral and meander coils. The spiral coils are generally used to generate bulk ultrasonic waves in bulk materials. In contrast, the meander coils are particularly suitable for generating angle beam shear waves and guided wave modes such as Rayleigh, and plate waves [23-25]. In an MC EMAT, the alternating current flows through a series of parallel conductor segments, with the current direction periodically changing. The resulting spatially periodic Lorentz forces provide an efficient mechanism for exciting guided waves with a selected wavelength and propagation direction. This feature makes the meander-coil configuration particularly attractive for selective excitation of plate wave modes in thin plates. The physical principle of MC EMAT leading eddy current and Lorentz force distributions on a 2 mm thickness stainless plate is shown as a schematic in Figure 1.

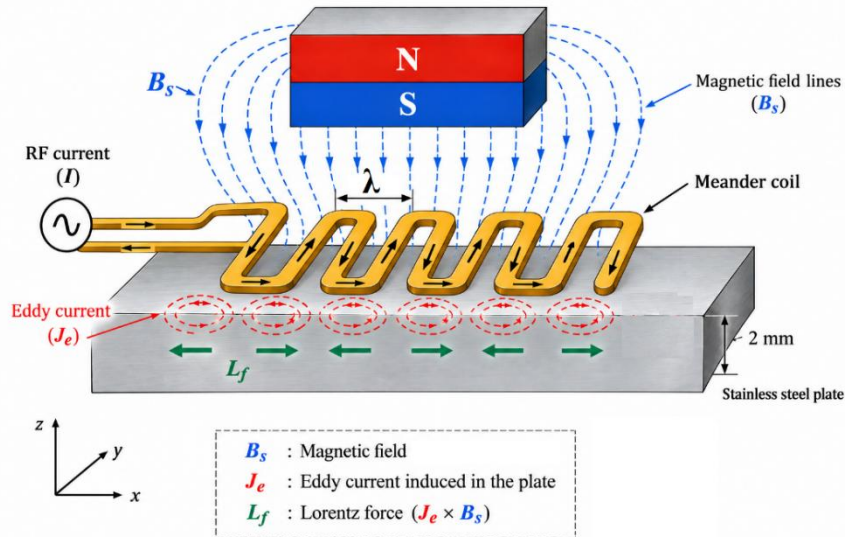


Figure 1. Schematic of a meander coil EMAT showing the distributions of magnetic field (B_s), eddy current (J_e) and Lorentz force (L_f) inside a 2 mm thick stainless steel plate.

III. MC EMAT for Plate waves

The MC EMAT configuration was chosen based on the coil geometry, excitation frequency, magnetic field orientation, and coil lift-off to efficiently generate the fundamental S0 and A0 plate wave modes in a thin stainless steel weld plate. In this work, a set of MC EMATs was developed to test a 2-mm-thick stainless steel weld plate using the fundamental plate-wave modes. The developed EMAT, shown in Figure 2, consists of a permanent magnet providing a normal biasing magnetic field and a flexible meander coil having a periodicity (λ) of 3 mm. The coil periodicity determines the spatial periodicity of the induced electromagnetic excitation and, consequently, plays an important role in controlling the wavelength and frequency characteristics of the generated plate waves. By appropriately selecting the coil periodicity and excitation frequency, the desired fundamental plate wave modes can be efficiently generated and propagated along the plate.

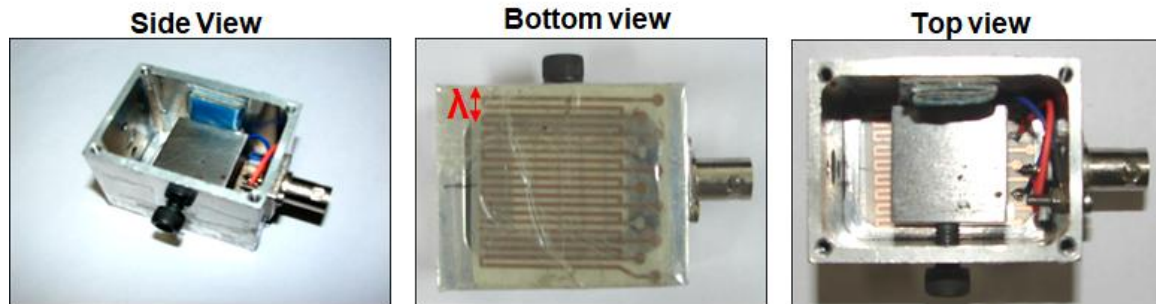


Figure 2. Photographs of the developed MC EMATs were used to generate the fundamental plate wave modes.

The flexible meander coil offers significant advantages, such as the ability to conform to mildly curved or uneven surfaces while maintaining a small, controlled lift-off. The coils were fabricated using flexible printed circuit board (PCB) methods, enabling precise control of the conductor dimensions, inter-coil spacing, and meander geometry. A 170 μm -thick polyester-based flexible laminate with a 50 μm -thick copper layer was employed, resulting in an overall coil thickness of approximately 220 μm . This flexible construction also facilitates the fabrication, handling, and positioning of the transducer on the test surface. Sintered neodymium iron boron (Nd-Fe-B) permanent magnets were used to provide the required static magnetic field. Each magnet measured 25 $\times$ 25 $\times$ 15 mm and provided a nominal magnetic flux density of approximately 0.32 T.

IV. Experimental Details

The schematic diagram of the experimental setup used to generate and detect plate waves in a thin plate is shown in Figure 3. To get a high-power RF tone burst, a gated amplifier was used in conjunction with a waveform generator and a gating modulator, and the output was supplied to the transmitter MC EMAT. A waveform generator produced a continuous sine wave with an amplitude of 1 V_{pp}, which was fed to a gated

amplifier that amplified it only during the gating pulse. A broadband preamplifier was used to amplify the signal received by the EMAT receiver. The amplifier output was fed to a digital oscilloscope to view the received signals. The oscilloscope was interfaced with a personal computer to record and process the acquired signals. 50-ohm cables were used to interconnect all instruments to minimize signal loss. Before starting the experiment, all the instruments were checked and their performance calibrated.

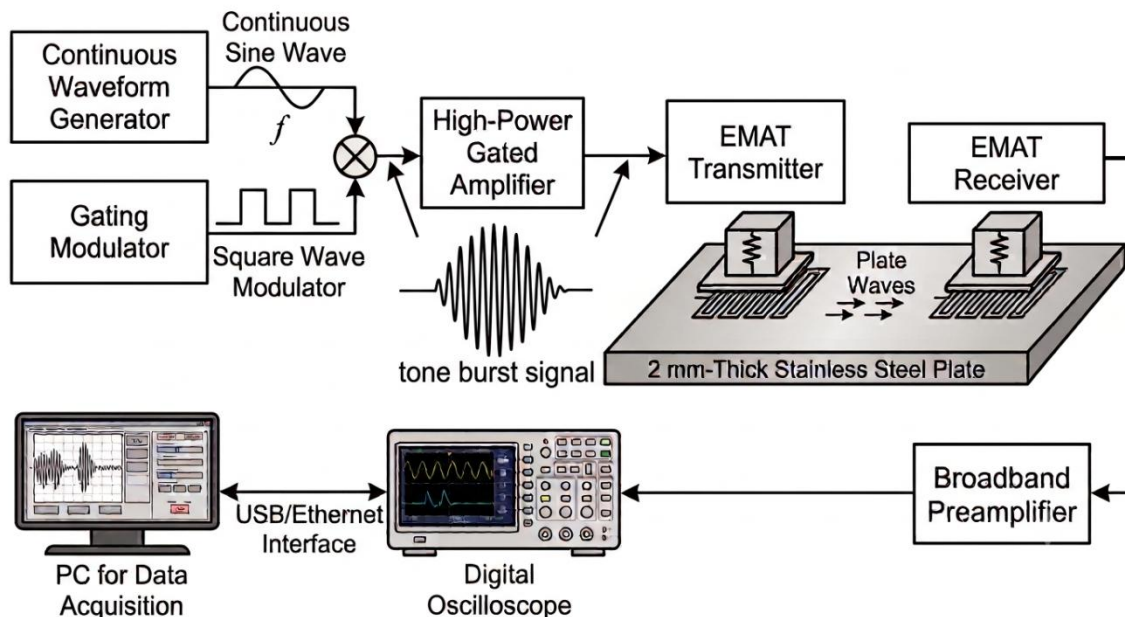


Figure 3. Schematic diagram of the experimental set-up

The experiments were performed using the through-transmission configuration, in which the transmitting and receiving MC EMATs were mounted on the same surface of the plate. A peak current of approximately 50 A with a pulse duration of 4 μ s was supplied to the transmitter MC EMAT. The generated and transmitted acoustic signal was detected using the receiver MC EMAT of identical configuration. The oscilloscope sampling rate was set to 10 MHz, and a receiver gain of 40 dB was used throughout the measurements. The high-pass and low-pass filter frequencies were set to 100 kHz and 3 MHz, respectively. The same EMAT system and measurement configuration were subsequently used to test the stainless steel weld plate. Two stainless-steel plate specimens, each 2 mm in thickness, were used in this study: one unwelded plate and one welded plate. Two artificial defects were introduced into the plate's weld region using electrical discharge machining (EDM). The defects were designated as Defect A and Defect B. Defect A had dimensions of 20 mm in length, 1 mm in width, and 0.5 mm in depth, whereas Defect B had dimensions of 20 mm in length, 1 mm in width, and 1 mm in depth. The two defects were positioned laterally apart within the weld region.

V. Results And Discussion

Preliminary measurements were conducted on a 2-mm-thick unwelded stainless-steel plate to evaluate the wave-generation characteristics of the developed EMATs. The MC EMATs were designed with a coil periodicity of 3 mm, chosen to exceed the plate thickness and satisfy the spatial excitation conditions required for efficient generation of plate-wave modes. The suitability of the developed MC EMAT configuration for exciting the desired wave modes was initially assessed through theoretical dispersion curves. For this purpose, the group and phase velocity dispersion curves were calculated for the 2 mm-thick stainless steel plate over a range of frequencies. The dispersion characteristics were used to identify the propagating plate-wave modes and to determine the frequency at which the fundamental S0 and A0 modes could be preferentially excited [26]. The dispersion analysis confirmed that, in the low-frequency regime, the developed MC EMAT configuration can effectively generate the fundamental S0 and A0 plate waves. The calculated group and phase velocity dispersion curves for the 2 mm-thick stainless steel plate are presented in Figure 4.

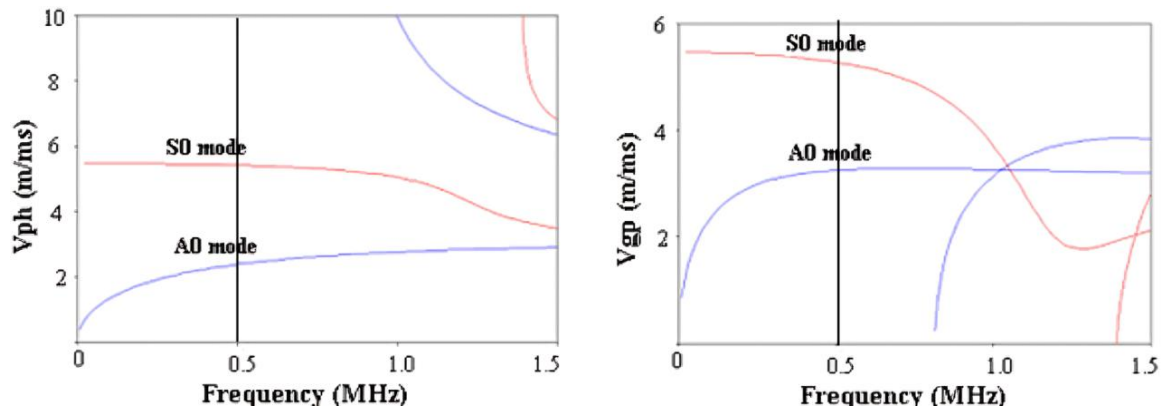


Figure 4. Phase and group velocity dispersion curves for 2 mm Stainless steel plate

5.2. Generation of plate wave modes

Although the developed MC EMAT can generate guided plate waves over a relatively wide frequency range, the excitation frequency was optimized based on the dispersion characteristics shown in Figure 4. An excitation frequency of 500 kHz was selected for the present study, where the group and phase velocities of the fundamental S0 and A0 modes exhibit relatively low dispersion. Operation at this excitation frequency enables the generated plate-wave modes to propagate with minimal frequency-dependent distortion, thereby facilitating reliable identification and characterization of the fundamental modes in experimental measurements. Figure 5 shows the schematic representation of the experimental measurement configuration used for the generation and detection of the fundamental S0 and A0 modes.

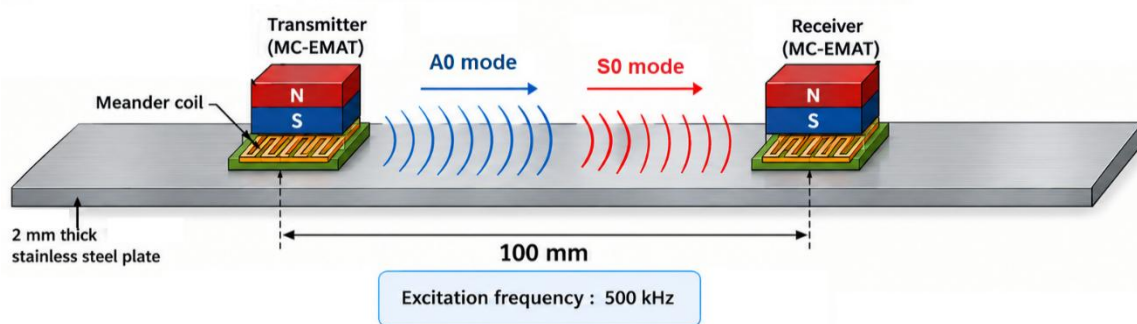


Figure 5. Experimental set-up for the generation of plate waves on a 2 mm thick stainless steel plate

The transmitting MC EMAT was excited at 500 kHz, and the receiving MC EMAT was positioned at a separation distance of 100 mm from the center of the transmitter. The receiver was aligned along the propagation axis of the wave front generated by the transmitting EMAT to ensure efficient detection of the guided plate wave modes. This fixed transmitter–receiver separation was maintained throughout the measurements to provide consistent propagation conditions and facilitate comparison of the received signals from the unwelded and welded stainless-steel plates. Figure 6 shows the received time-domain A-scan signal recorded using the MC EMAT receiver.

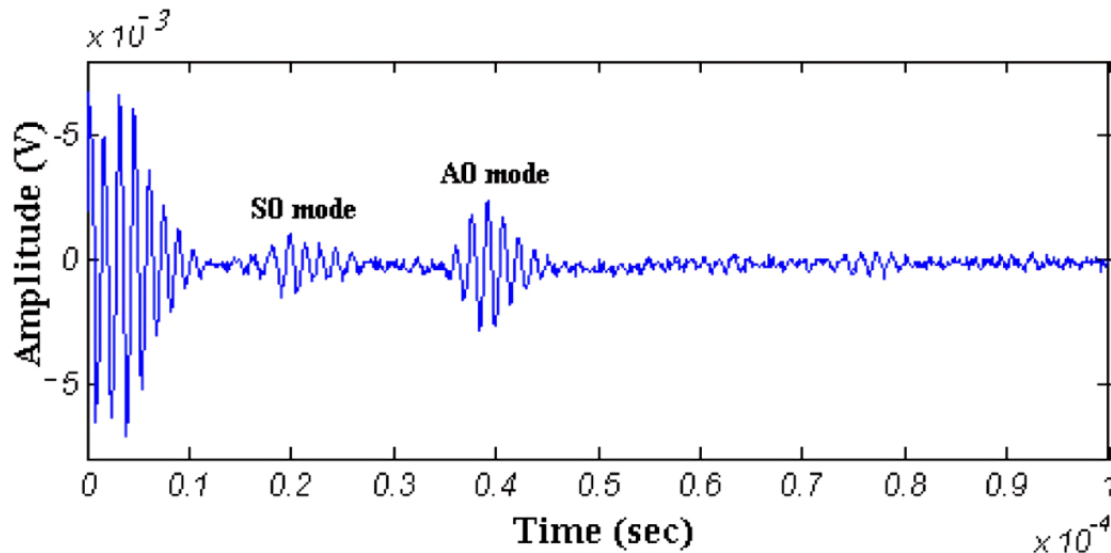


Figure 6. Plate wave modes generated by the MC EMAT in a 2 mm-thick stainless steel plate

In Figure 6, the initial signal represents electromagnetic crosstalk between the transmitting and receiving EMATs. This was followed by a low-amplitude signal arriving at approximately $\sim 19 \mu\text{s}$, which was attributed to the fundamental S0 mode. The subsequent signal, which arrived at $\sim 33 \mu\text{s}$ with considerably higher amplitude, corresponded to the fundamental A0 mode. These wave modes were confirmed by their group velocities in the dispersion curves shown in Figure 4. The higher amplitude of the A0 mode at the selected excitation frequency was attributed to its predominant out-of-plane displacement component, which resulted in greater sensitivity of the EMAT configuration to this mode. In contrast, the S0 mode exhibited predominantly in-plane displacement, resulting in a comparatively lower received signal amplitude under the experimental conditions. These observations confirmed the successful generation and detection of both fundamental guided plate-wave modes using the developed MC EMAT system.

5.2. Defect Detection in Stainless steel weld

The same MC EMAT system was subsequently employed to test the 2-mm-thick stainless-steel welded plate containing two artificial defects, designated as Defect A and Defect B. For the measurement, the MC EMAT transmitter was positioned on one side of the weld region, and the MC EMAT receiver on the opposite side. The transmitter was excited with a tone-burst signal at the same center frequency, 500 kHz, as used in the initial measurements, thereby ensuring consistent excitation conditions. The receiver was positioned 100 mm from the transmitter, with the weld and the designated defect locations within the propagation path of the generated plate waves. The received signals were subsequently analyzed to evaluate the interaction of the propagating wave modes with the weld region and the artificial defects. Figure 7 presents a schematic of the experimental measurement configuration used to test the stainless steel welded plate, showing the relative positions of the transmitting and receiving MC EMATs, the weld region, and the artificial defects.

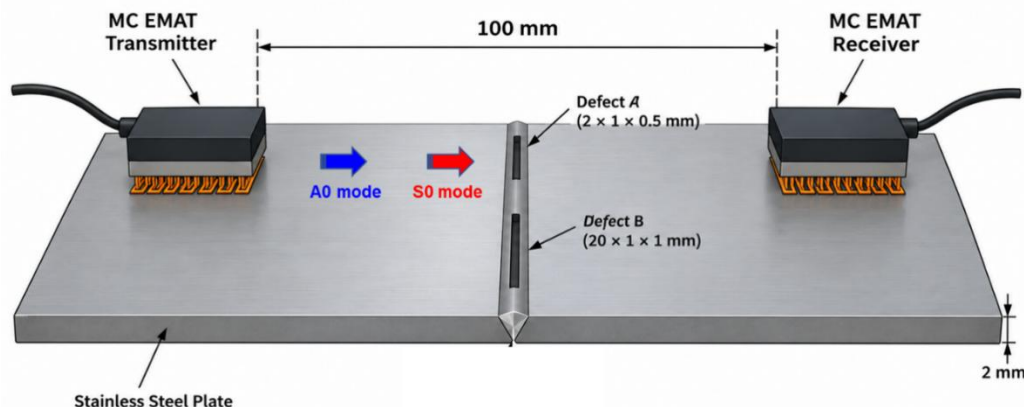


Figure 7. Schematic of measurement set-up used detection of artificial defects in 2 mm thick stainless steel plate

The fundamental S0 and A0 plate wave modes generated by the MC EMAT transmitter propagated through the weld region and interacted with the two artificial defects, Defect A and Defect B. The corresponding time-domain A-scan signals were acquired using the MC EMAT receiver and are presented in Figure 8. The signals following the S0 and A0 modes were identified as reflections from the plate edge. A reduction in the amplitudes of both the S0 and A0 modes was observed as defect depth increased, indicating increased scattering and attenuation of the propagating wave energy. The A0 mode showed a relatively higher amplitude variation due to its larger out-of-plane displacement component, making it more sensitive to thickness variations. A small change in the time of arrival of both modes was also observed during their interaction with the defects, indicating that the primary effect of the defects was on signal amplitude rather than on the propagation time of the plate-wave modes.

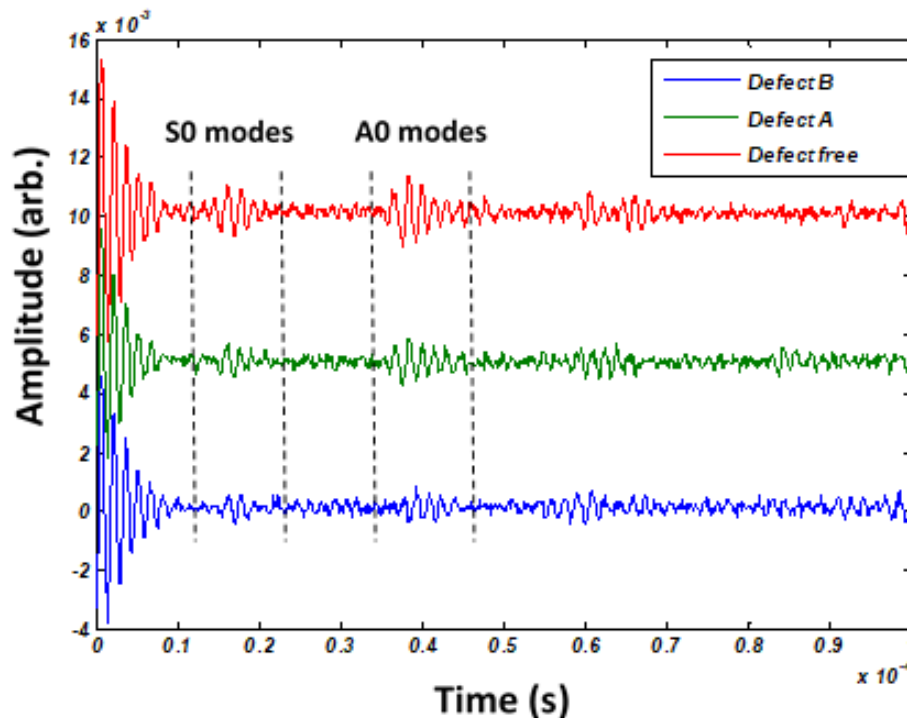


Figure 8. Time-amplitude A-scan signals obtained from the defect free and defective regions in stainless steel weld plate

The time-domain A-scan signals were further analyzed in the frequency domain to obtain additional information on the influence of the defects on the propagation of the S0 and A0 plate-wave modes. Fast Fourier Transform (FFT) was employed to transform the acquired time-domain signals into their corresponding frequency spectra. This analysis enables quantitative evaluation of frequency-dependent changes in the received signals, particularly those associated with defect-induced attenuation and redistribution of the spectral amplitude. For the analysis of the S0 mode, only the time-amplitude information of the corresponding S0 mode was retained, and the remaining portions of the A-scan signals were set to zero (zero-padding/windowing). The resulting time-domain signals were then subjected to an FFT to obtain their frequency-domain representation. The same procedure was subsequently followed for the A0 mode, yielding an FFT. This mode-specific processing minimizes the influence of the other plate wave mode and facilitates a more reliable comparison of the spectral characteristics of the defect-free and defective signals. The FFTs of both S0 and A0 modes were plotted and shown in Figures 9(a) and 9(b). The resulting magnitude-frequency spectra were compared for the defect-free region and for the signals obtained from regions containing defects A and B. The variations in the spectral amplitude and frequency distributions are shown in Figure 9(c) and (d).

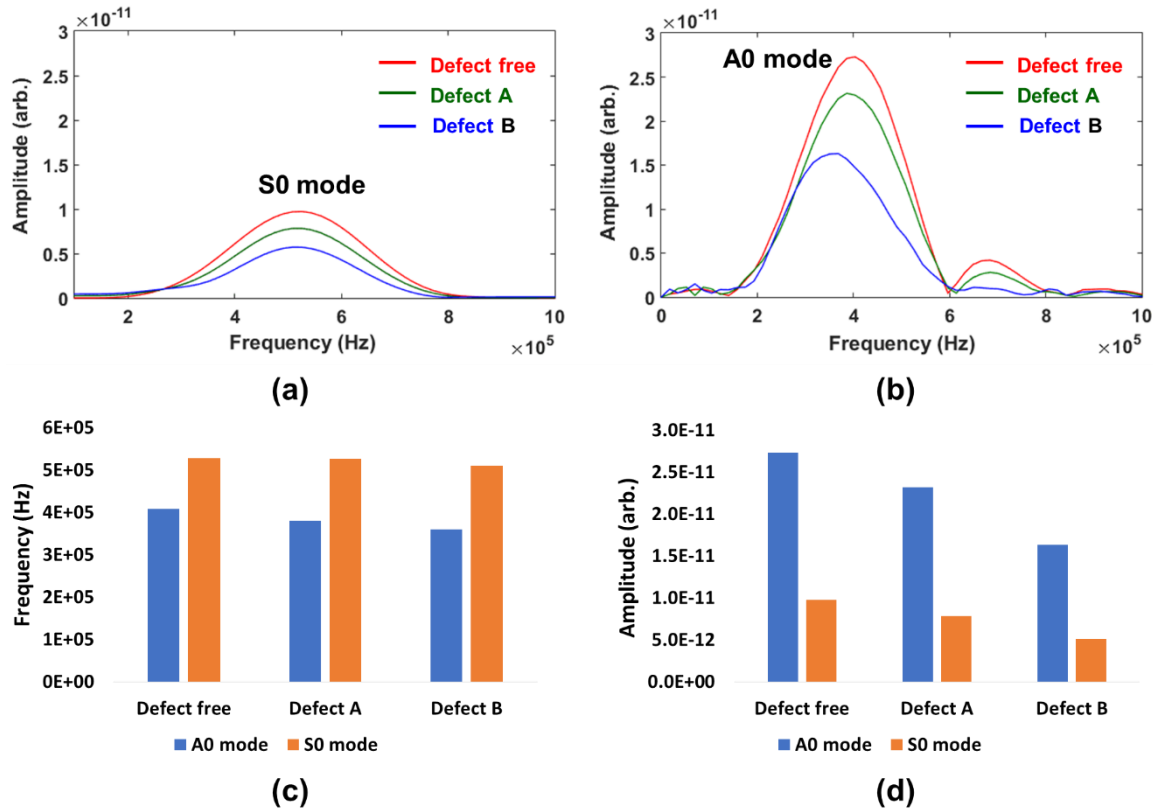


Figure 9. Overlapped FFT's of (a) S0 modes, (b) A0 modes, (c) variation in frequency of S0 and A0 modes, and (d) variation in FFT magnitude of S0 and A0 modes for defect-free, Defect A, and Defect B

Figure 9 shows the frequency spectra of the received S0 and A0 mode signals for the defect-free and defective regions. A clear variation in spectral magnitude was observed for both modes in the presence of defects, confirming their interaction with the defects. In particular, the A0 mode exhibited a noticeable shift in peak frequency towards the lower-frequency region as defect depth increased. The spectral amplitude also decreased by approximately 50% for defect B, indicating increased scattering and energy redistribution due to defect interaction. The relatively small change in the peak frequency of the S0 mode can be attributed to the different displacement characteristics of the two modes. The A0 mode has predominantly out-of-plane displacement and is therefore more sensitive to surface and near-surface defects. In contrast, the S0 mode is predominantly associated with in-plane displacement and is comparatively less sensitive to surface defects. Hence, the shift in peak frequency and the reduction in spectral amplitude of the A0 mode provide more distinct indicators of the presence and depth of the defect. Overall, the systematic changes observed in the spectral characteristics demonstrate the potential of frequency-domain analysis for defect characterization. The results indicate that plate-wave-based EMATs can be effectively used for non-contact detection and assessment of defects in welded joints, with the A0 mode showing greater sensitivity to surface defects.

VI. Conclusion

The MC EMATs were developed to generate and detect the fundamental S0 and A0 plate-wave modes in stainless-steel weld plates. The MC EMATs were designed and fabricated using flexible meander coils based on PCB technology and permanent magnets. The EMATs were optimized to generate the zeroth-order symmetric and asymmetric plate-wave modes at 500 kHz in 2-mm-thick stainless-steel plates. The generated modes were analyzed and identified using dispersion curves. The A0 mode exhibited a higher amplitude than the S0 mode, which was attributed to its predominant out-of-plane displacement. The generated S0 and A0 modes were subsequently used to detect artificial defects in a 2-mm-thick stainless-steel weld plate. Fast Fourier Transform (FFT) was employed to analyze the defect-free and defective signals. Variations in spectral magnitude and peak frequency were observed for both modes in the presence of defects, confirming their interaction with the defects. The A0 mode exhibited greater changes in spectral magnitude and peak frequency due to its predominant out-of-plane displacement.

In contrast, the S0 mode, associated mainly with in-plane displacement, showed comparatively smaller changes. Hence, the spectral amplitude and peak-frequency shift of the S0 and A0 modes can provide useful

indicators of defect presence and depth. The results demonstrate that plate-wave-based EMATs can be effectively used for non-contact detection and assessment of defects in thin stainless-steel weld plates.

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