AN EMAT ARRAY FOR THE RAPID INSPECTION OF LARGE STRUCTURES USING GUIDED WAVES

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ABSTRACT. A novel EMAT array system for the rapid inspection of steel plate-like structures using guided acoustic waves is described. Issues considered include the choice of guided wave mode, the design of suitable array elements, the layout of elements in the array and the instrumentation required. Results are presented from a variety of plate specimens that illustrate the sensitivity of the system to artificial defects, the effect of generalized corrosion on the test piece and the effect of plate thickness.

INTRODUCTION

The use of guided waves in NDE applications is widespread [1] and can be grouped into three categories according to the propagation distances involved. In short range applications, guided waves are used to obtain localized data about a specimen in situations where conventional ultrasonic techniques cannot be applied such as, for example, air-coupled inspection of composites [2]. In medium and long-range applications, the goal of using guided waves is to increase the amount of a structure that can be inspected from one location, hence reducing inspection costs and sometimes enabling inaccessible regions in a structure to be tested. Long-range applications typically involve one-dimensional waveguide structures such as pipes [3] and rails [4] where the propagation distances are in the order of tens or even hundreds of metres. Plate inspection, where the propagation distance is a few metres, falls into the category of medium-range applications. Guided wave plate inspection in the form of continuous line scanning between two transducers is ideally suited to continuous monitoring of large areas of for example steel plate in rolling mills [5]. However, there has been very little commercial exploitation of guided waves for inspecting large areas of plate-like structures from a single location in a manner analogous to that employed in pipe and rail inspection.

This may be because much of the research effort into guided waves in plates has developed from the classical Rayleigh-Lamb model [6] of guided wave propagation in a cross section through a plate in plane strain, hence forcing the plate to behave as a one-dimensional waveguide. Much work has been published on guided wave transducers [7] and modal selectivity [8] in this simplified system, but the practical development of medium range plate inspection systems is limited by the fact that real plates are two-dimensional waveguides. Hence the issue of guided wave transducer directionality is at
least as important as the issue of modal selectivity. For example, a defect free rectangular plate contains four major reflectors due to the edges (and, depending on the guided wave mode, a further four due to the corners). If the directionality of a guided wave transduction device is not understood, then spurious side-lobe reflections from any of these large reflectors can easily be mistaken for reflections from real defects.

This paper describes a novel electromagnetic acoustic transducer (EMAT) array system for inspecting large areas of a thick (5-25 mm) metallic plate structure from a single test position using guided acoustic waves. The target application for this device is testing the floors and walls of steel plate structures in the petrochemical industry, such as storage tanks and pressure vessels. The layout of the elements in the array is in a two-dimensional circular pattern and this enables a synthesized guided wave beam to be steered in any direction with well-controlled directionality. The first part of this paper deals with the development of the prototype system, results from which are presented in the second part. Finally, the limitations of the technique and the present prototype are discussed and the direction of future research is indicated.

THE EMAT ARRAY SYSTEM

Overview

A photograph of the complete prototype system in operation is shown in Figure 1(a). The most important part of the system is the EMAT array. This is placed on the plate to be inspected and the test sequence is initiated from the controlling laptop PC. The signal processing applied to the data obtained from the array provides beam steering and wavelength selectivity. The overall effect is to mimic the operation of a monolithic, wavelength selective guided wave transducer operating in pulse-echo mode placed at the test location and rotated through 360°. The result is an omni-directional B-scan of the surrounding area of the plate under test, an example of which is shown in Figure 1(b). The greyscale on this B-scan represents the amplitude (in dB) of the reflected signal envelope as a function of spatial position around the array. The signals visible in the B-scan indicate the amplitude and position of reflectors in the plate and include signals from both features (such as edges) and defects.

FIGURE 1. (a) The complete prototype system and (b) an example of the output display.
The array comprises multiple layers of flexible printed circuit board material (PCB) on which the EMAT coil patterns are printed and a bank of permanent magnets to provide the necessary magnetic field. The housing for the array is approximately 250 mm in diameter and contains a simple mechanism to lower the EMAT array onto the plate under test when the device is deployed and to lift it off again when a test is completed.

**Mode Selection**

For simplicity and to minimize the amount of modal selectivity required, it was decided relatively early in the development of this device to use either one of the fundamental Lamb wave modes, \(A_0\) and \(S_0\), or the fundamental shear-horizontal mode \(S_{Ho}\). The problem with the \(A_0\) mode is that the large out-of-plane surface displacement means that its attenuation is very high in cases where a plate is liquid loaded. This makes it unsuitable for some of the proposed applications. Both the \(S_0\) mode at low frequencies and the \(S_{Ho}\) mode have very little out-of-plane surface displacement and hence are not significantly attenuated by liquid loading. The use of both of these modes was therefore considered. However, both need to be excited and detected with transducers that are sensitive to in-plane surface displacement.

**EMAT Elements**

It is thought that for an array to have omni-directional sensitivity, the individual elements within it must also have omni-directional sensitivity. For an array using the \(A_0\) mode this is readily achieved with piezoelectric point transducers that are sensitive to out-of-plane surface displacement and results from arrays of such devices have been presented [9, 10]. The problem with the \(S_0\) and \(S_{Ho}\) modes is to make an omni-directional array element that couples to in-plane surface displacement. For example, consider the case of a transmitting transducer that applies in-plane surface traction. If the device acts at a single point, then the force must be applied in a specific direction and hence the device cannot have omni-directional sensitivity. Instead the device must apply a pattern of axi-symmetric surface tractions to a finite area of the surface of the plate. For \(S_{Ho}\) waves, the forces need to be in the tangential direction about the center of the transducer (i.e. the transducer applies a twisting surface traction about an axis normal to the surface of the plate) and for \(S_0\), the forces need to be in the radial direction. Applying uniformly distributed surface tractions in this manner could in theory be realized by using specially polarized piezoelectric crystals, but practical problems were foreseen in achieving the required uniformity of coupling of such devices onto real plates.

Pancake coil EMATs can produce the necessary surface traction distribution to excite the \(S_0\) Lamb wave and a schematic diagram is shown in Figure 2(a). The magnetic field provided by the permanent magnet is in the direction normal to the plate surface and the current in the coil, and therefore the eddy currents in the plate, flow in a circular pattern. The interaction of the circular eddy currents with the magnetic field causes a radial pattern of surface tractions that are capable of exciting the \(S_0\) mode uniformly in all directions. The EMAT sensitivity to both the \(S_0\) and \(A_0\) Lamb wave modes has been studied as a function of frequency for a variety of coil geometries and plate thicknesses. A typical response graph showing the performance of a 25 mm diameter coil operating on a 5 mm thick steel plate is shown in Figure 2(b). Using the \(S_0\) dispersion relationship, the equivalent \(S_0\) wavelength for each frequency can be calculated. In common with other measurements that have been made, this graph shows a clear peak in response to the \(S_0\) mode at a point where the wavelength is approximately twice the diameter of the coil. This presents a problem when attempting to incorporate these devices into an array, since parallel studies on array signal processing indicated that the maximum spacing between elements should be no more than half of the smallest wavelength of guided waves.
In order for discrete elements to fit together, this implies that the EMAT coil diameter also cannot exceed one third of the wavelength. At the equivalent frequency on the S₀ response graph in Figure 2(b), it can be seen that at this point the sensitivity to S₀ is poor. In order to achieve the required inter-element spacing and the desired efficiency, it was necessary for adjacent element positions to overlap. Initially, schemes for physically moving the elements in the array were considered, but these were rejected in favor of using flexible PCB technology to overlap the coils of adjacent elements. A notionally monolithic permanent magnet is used to provide the necessary magnetic fields for all the EMAT elements, as shown schematically in Figure 2(c). Experiments indicated that there was negligible degradation either of EMAT performance in such a layered configuration. For cost reasons, the prototype array uses a bank of commercially available 25 mm diameter permanent magnets rather than a custom-made monolithic one. This causes a small lack uniformity in the magnetic field which limits the signal to coherent noise level that can currently be obtained.

**Array Layout**

The array comprises 48 pancake coil EMATs arranged in two concentric circles. The 16 EMATs in the inner circle are transmitters and the 32 EMATs in the outer circle are receivers. The coil patterns for the complete array were printed on 4 layers of flexible, 100 μm thick polyamide PCB material in order to achieve the necessary inter-element spacing. The layout is shown in Figure 3.
Operation and Instrumentation

The operation of the array can be considered in three stages, raw data acquisition, data processing and output data presentation. In the acquisition stage, the array is positioned on the structure under test and time-domain signals are obtained from every combination of transmitter and receiver elements in the array, hence yielding 512 time-traces. A suitable signal for transmission such as a Hanning windowed toneburst is generated and amplified using a bespoke high current amplifier and then routed to each of the transmitting EMATs in the array in turn using an automatically controlled relay switch. The transmitting EMATs must be fired individually in this manner so that time-domain signals associated with each transmitter can be obtained independently. So that the acquisition is as rapid as possible, the signals from all 32 receiving EMATs are amplified in parallel and digitized simultaneously, and this is repeated for each transmitting EMAT. The digitized data is uploaded to a controlling laptop PC where the processing is performed. The processing uses a phased addition algorithm with angular deconvolution that is described in more detail elsewhere in these proceedings [12]. The complete time taken to perform a test, including acquisition, processing and data transfer is less than a minute.

RESULTS

The prototype EMAT array has been tested on a variety of steel and aluminium plate samples. Some salient results that demonstrate the potential and limitations of the system are presented here.

6 mm Thick Steel Plate with Artificial Defects

This 2 m x 3 m x 6 mm thick steel plate sample was designed as a test specimen for a variety of plate testing techniques and contained 44 documented artificial defects with a variety of morphologies. The condition of the plate (apart from the defects) was as-new, unpainted and with a good surface finish and square cut edges. The layout of the features in the plate is shown in Figure 4(a) and results obtained from the EMAT array at a center frequency of 170 kHz are shown in Figure 4(b).

FIGURE 4. (a) Layout of artificial defects in 6 mm thick steel plate with defect dimensions indicated in mm and (b) results obtained from the EMAT array at 170 kHz.
The dynamic range in Figure 4(b) is 32 dB. Large signals corresponding to the specular reflection from the four plate edges are clearly visible. Over most of the rest of the plate area, a signal to coherent noise ratio of at least 32 dB has been achieved. This sample was not specifically designed for testing with guided waves and many of the features are too small to be visible and too close together to be resolved. The key features that are visible are the 3 deepest flat bottom holes in the upper right quadrant of the plate, the deeper slots in the upper left quadrant and larger diameter through holes in the lower left. The type of feature in this plate that is most representative of an isolated corrosion path is arguably a flat bottom hole. The shallowest flat bottom hole that is visible on this 32 dB scale is 3 mm (i.e. half the plate thickness) deep and 20 mm (i.e. just over 3 times the plate thickness) in diameter. This gives an indication of the typical sensitivity of the EMAT array in its current form, although the precise relationship between the reflected signal amplitude and the defect shape, distance and size is the subject of ongoing research [11].

**Generally Corroded 8 mm Thick Steel Tank Floor Sample**

The plate in the previous example was in perfect condition. This example shows the results obtained from the EMAT array on a heavily corroded plate. The plate in question was nominally 8 mm thick and had been roughly flame cut from the floor of an oil storage tank. The results obtained from the EMAT array at a center frequency of 170 kHz are shown in Figure 5(a). The thickness of the entire area of this plate had also been previously measured using a semi-automated conventional ultrasonic technique, and the results from these measurements are shown in Figure 5(b).

From the ultrasonic thickness measurements, it can be seen that the plate is in very poor condition with many deep corrosion pits extending through more than half the plate thickness. The EMAT array clearly cannot resolve each pit separately and at best can only give a very approximate estimate of individual defect severity. On the other hand it does provide a rapid method of gaining an indication of the general condition of the plate. It should also be noted that the poor surface condition of the plate does not prevent the EMAT array from being used to obtain data.

**FIGURE 5.** (a) EMAT array results obtained at 170 kHz and (b) ultrasonic thickness measurements for 8 mm thick steel tank floor sample.
10 and 20 mm Thick Steel Plates

The operation of any array is always constrained by the size of the array and the spacing of the elements to a limited range of wavelengths, and hence operating frequencies. The long wavelength (low frequency) limit is when the radial and angular resolution becomes unacceptably poor and the short wavelength (high frequency) limit is when wavelength aliasing begins to take place and causes grating lobe effects.

The current EMAT prototype is also constrained in the frequency domain by severe mechanical resonances within the array preventing operation below around 150 kHz. For a guided wave array such as this, the long wavelength (low frequency) limit is arguably the most important, as this limits the maximum plate thickness on which the array can be used with a particular guided wave mode. This is because the frequency axis of the dispersion curves for a given plate material compresses as the plate thickness increases. The useful part of the $S_0$ mode for this application is the low attenuation region below the $A_1$ cut-off frequency. In order for the 150 kHz low frequency limit of the current EMAT array to remain on this part of the $S_0$ mode, the plate thickness needs to be less than around 10 mm. Results obtained on a defect-free 10 mm thick steel test plate are shown in Figure 6(a). This is close to the low frequency limit of the current prototype, and coherent noise reduces the usable dynamic range to 26 dB as shown in the figure.

In order to increase the maximum thickness of plate that can be inspected, there are two possibilities. Firstly, the dimensions of the array could all be scaled up. This allows the array to operate up to the same point on the $S_0$ dispersion curve, which occurs at a decreasing absolute frequency as the thickness increases. The problems with this approach are the increased size of the array and the worsening resolution in the radial direction due to the decreasing operating frequency. The second approach is to use a suitable higher order mode on thicker plates. The $S_1$ mode for instance also has low attenuation close to its maximum in group velocity. In a 20 mm thick steel plate, this occurs at around 220 kHz, which is within the operating range of the current EMAT array.

**FIGURE 6.** (a) EMAT array results obtained at 150 kHz on a 10 mm thick steel plate and (b) at 220 kHz using the $S_1$ mode on a 20 mm thick steel plate. Note the reduced dynamic range in both figures.
The results from a test performed using the current EMAT array at this frequency on a 20 mm thick steel plate are shown in Figure 6(b). The current array was not designed for use with higher order modes. Even on the 26 dB scale used in the figure, coherent noise signals are still visible. It is thought that these are due to the presence of unwanted modes, the suppression of which is a major problem when using a higher order mode. On the other hand, the angular resolution is actually better than in the other results presented due to the higher operating frequency and shorter wavelength. Other problems associated with using a higher order mode include highly constrained operating frequencies and more complicated interaction with structural features and defects.

CONCLUSION

The feasibility of using a guided wave EMAT array for rapidly inspecting large areas of steel plate structures has been demonstrated. The current prototype can achieve a dynamic range of between 26 and 32 dB depending on the operating frequency. It should be noted that the lower limit of dynamic range is determined by coherent noise signals that are artifacts of signals from the largest real reflectors (typically the plate edges). If a plate is welded into a structure, then the absolute amplitude of the largest reflectors (now the welds) and the associated coherent noise becomes smaller; hence the absolute sensitivity of the array will be increased. Using a monolithic permanent magnet to improve the uniformity of the magnetic field could reduce the coherent noise level obtained from the current prototype further.

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REFERENCES

12. Wilcox, P., Guided Wave Beam Steering from Omni-directional Transducer Arrays, in these proceedings.