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Applications of Electromagnetic Acoustic Transducers in the NDE of Non-Conducting Composite Materials

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An electromagnetic acoustic transducers (EMAT) can usually generate or detect an ultrasonic wave in an electrically conducting material across a small gap. The transducer is a unique ultrasonic EMAT probe that does not require a couplant or gel. Therefore it can be applied in a noncontact mode with a high degree of reproducibility. Shear waves and Lamb waves can be easily generated with EMATs in single-sided access. However, the application of EMAT has been limited to electrically conducting materials. In this work, EMAT was applied to the inspection of nonconducting composites by adhering a removable aluminum foil tape on the part surface. Ultrasonic waves generated in the aluminum layer by the EMAT readily propagated into the nonconducting composite. The reversed process was used in the reception of ultrasonic waves by EMAT. For composites that contained surface metallizations (e. g., metal foil or mesh) for lightning protection and electromagnetic interference (EMI) purposes, EMAT probes were placed directly on the composite surface. Finally, EMAT-generated, normal-incidence shear waves were used for the inspection of "green" laminates before curing to detect errors in ply orientation and layup sequence.

Key Words : Electromagnetic Acoustic Transducers, SH Waves, Nonconducting Composites, EMAT Probes

1. Introduction

One of the essential characteristics of ultrasonic measurements is the uniform coupling between the transducer and the solid. This coupling is generally achieved in either of two ways. In immersion measurements, energy is coupled between the transducer and the sample by placing them in a tank filled with a couplant, generally water. In contact measurements, the transducer is pressed directly against the sample, and coupling is enhanced by a thin couplant layer between the two. If shear waves are to be transmitted, the couplant with a higher viscosity such as a burnt honey couplant (Thompson, 1990) is generally selected. Electromagnetic Acoustic Transducers (EMAT) act based on totally different physical principles. EMATs derive their name from the fact that they can excite and detect ultrasonic oscillations in metals by an electromagnetic induction process across an air gap (Thompson, 1973 and 1977). Therefore the EMATs can operate well without any couplant such as gel, water, grease etc. EMATs open up a wide variety of applications such as inspections at high speed or at high temperatures, when the conventional piezoelectric transducer techniques can not be applied. It is seldom known that EMATs also can be designed to excite a wider variety of ultrasonic waves (Thompson, 1973 and Vasile and Thompson, 1977) and are much more amenable than the conventional devices to inspections of parts with complex geometries. EMAT is a relatively mature technology and has found a number of nondestructive testing (NDT) applications over the

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years (Thompson, 1973, Beissner, 1976, Alers, et al., 1987 and Clark, et al., 1993). An EMAT probe consists of a coil and one or more permanent magnets. The ultrasonic generation mechanism relies on the Lorentz force exerted by the permanent magnets on the currents induced in a conducting part held adjacent to the coil (Thompson, 1990). EMATs have found wide applications in the inspection of metal components but have not been applied to nonconducting or poorly conducting materials such as ceramic matrix or polymer matrix composites (Fortunko, et al., 1976 and Mohr, et al., 1978). Also, nondestructive characterization of texture was studied mainly for metal sheets with the EMATs (Kawashima, 1990) and the anisotropy characteristics of conducting materials have been evaluated based on the ultrasonic velocity measurements using the EMATs (Ahn, et al., 1997).

In this work, a novel approach for applying EMAT on nonconducting or poorly materials (Im, et al., 1998) was developed and tested on a variety of composite materials. In this approach an aluminum foil tape is applied to the surface of the part, an EMAT probe then generates sound waves in the aluminum layer and the waves then propagate into the bulk of the composite via the adhesive bond between the foil and the composite. When scanning is not involved, the foil tape only needs to be large enough to cover the footprint of the EMAT probe and can be easily removed after the measurements.

Two types of EMAT probes have been used so far on poorly conducting and nonconducting composites: shear horizontal (SH) wave probes (Vasile, et al., 1979) and normal incidence shear wave probes. The SH waves were applied to the inspection of elastic anisotropy of composite plates in a geometry similar to that of "acousto-ultrasonics". SH wave EMATs in this configuration were used for the detection of a skin-to-core disbond of a honeycomb sandwich and for the detection of impact damages in a solid laminate. EMAT-generated normal incidence shear waves and SH waves were propagated through thick composites. The transmission of cross-polarized shear waves, generated by normal incidence EMAT probes, was used for detecting errors in ply orientation and layup sequence of "green" laminates before curing. In addition, EMATs were also applied directly to metallized composites, such as graphite/epoxy containing copper mesh or metal-coated graphite fibers.

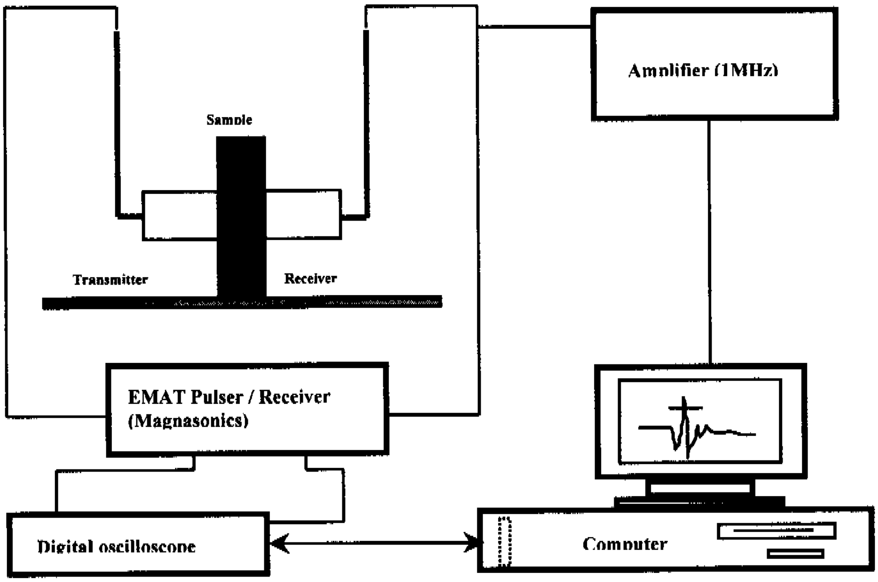


Fig. 1 Schematic diagram of experimental setup for through-transmission scan mode (pitch-catch scan mode also used in this study)

2. EMAT Probes Used in the Study

Schematic diagram of an EMAT system setup is shown in Fig. 1, which is constructed with a through-transmission scan mode. Also pitch-catch scan mode was tested. Figure 2 shows a photo. of an EMAT apparatus that consists of the the permanent-magnet EMAT probes, EMAT pulser/receiver electronic chassis, EMAT amplifier (max. range 1MHZ), PC, etc. The EMAT probes for generating SH waves were of the "periodic permanent magnet" design (Vasile, et al, 1979). It consisted of a flat rectangular coil and 14 pairs of Sm-Co permanent magnets placed over the flat coil. Each of the magnets had a base dimension of 3.3x7 mm. The probe was approximately 12.7 mm wide and 48 mm long. The top view and side view of the SH wave EMAT probe are shown in Fig. 3. The side view diagram also depicts the generation mechanism based on the Lorentz force. As shown, the current flowing in the RF coil is **I**, the induced current density in the metal is **J**, the dc magnetic field produced by the Sm-Co magnet is $\mathbf{B}_0$, and the Lorentz force is

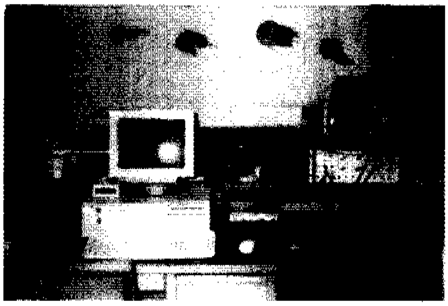
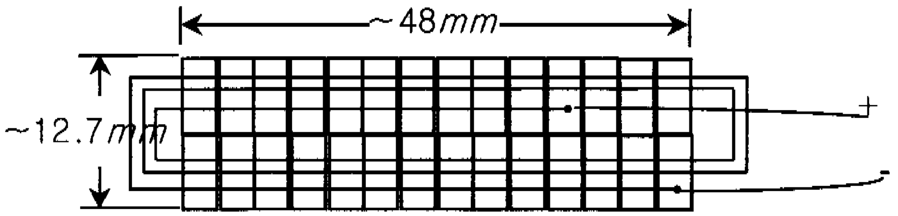
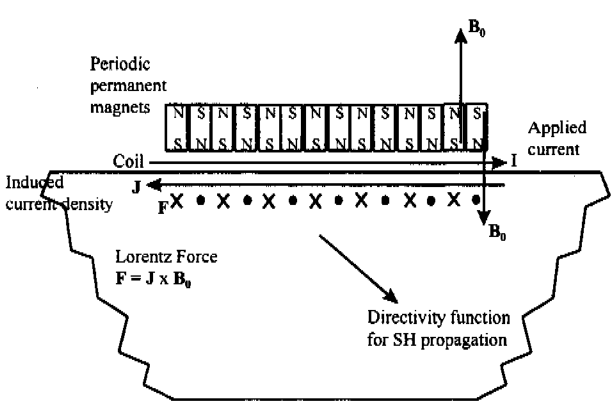


Fig. 2 Photo. showing the permanent-magnet EMAT probes, EMAT pulser/receiver electronic chassis, EMAT amplifier (max. range 1MHZ), PC, etc.



14 pairs of Sm-Co magnets on top of a rectangular coil.
Each magnet has a 3.3 x 7 mm base.
Top View



Side View

Fig. 3 The top view and side view of a SH wave EMAT probe based on the periodic permanent magnet design.

given by $\mathbf{F}=\mathbf{J}\times\mathbf{B}_0$. The probes were originally designed for propagating SH waves in thin metal plates and would launch SH waves that propagate in the forward and backward directions symmetrically with a directivity function that depended on the spatial period of the magnets, the wave velocity and the frequency (Maxfield, et al., 1983). Figure 4 shows assembled apparatus showing the sample and the EMAT probes in holders for a normal-incidence shear waves-incidence shear waves.

The normal incidence shear wave EMAT probe had a flat racetrack-shaped coil that consisted of 16 turns of 26 gauge copper wire and a pair of neodymium-iron-boron permanent magnets with 8x15 mm base dimension each. The top view and side view of the normal incidence shear wave EMAT are shown in Fig. 5.

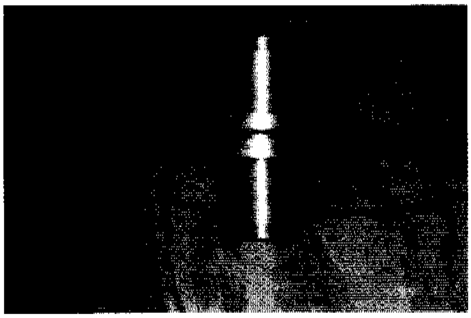


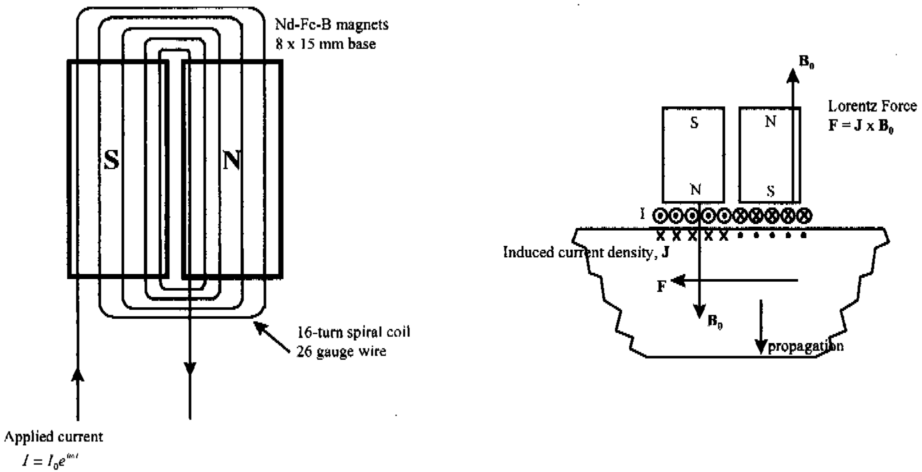
Fig. 4 Photo. of EMAT probes

The aluminum foil tape used for EMAT generation and reception was manufactured by 3M Company (Product #425). The aluminum layer was made of dead soft aluminum and had a thickness of 80 μm. The total thickness including the adhesive layer was 120 μm. The foil tape was easy to apply on flat and certain curved surfaces and can be peeled off cleanly after testing

The generator and receiver for the EMAT probes described above were manufactured by Magnasonics. The excitation pulse consisted of four cycles of square waves of a chosen frequency. Most of the measurements were made in the 400 - 500 kHz range, but a lower frequency was used for propagation through lumber. The electronics of the EMAT system had a dead-time of approximately 22 μs for the receiver to recover from saturation. To move the received signal beyond this dead time, the necessary delay may be provided by separating the SH wave generating and receiving probes on the same side of a composite plate and by using delay blocks for normal incidence shear waves.

3. EMAT-Generated SH Waves in Composite Plates

To generate SH waves in a composite plate, the two SH wave probes were placed in a toe-to-toe



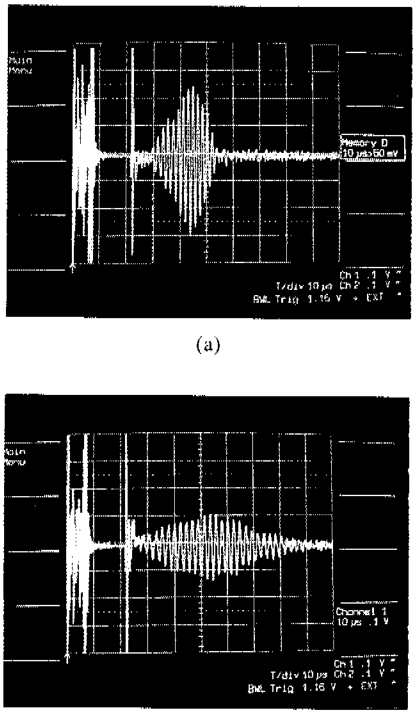
Top View Side View

Fig. 5 The top view and side view of an EMAT probe for generating and receiving normal-incidence shear waves.

fashion, separated by the desired distance, on the same surface of the plate. Figure 6(a) shows the received SH wave signal on a 8 mm thick quasi-isotropic graphite-epoxy plate using the aluminum foil tape. The oscilloscope trace showed that the first 22 μs were gated out and that the SH wave signal started at about 30 μs for a separation distance of 6.5 cm between the EMAT probes. Figure 6(b) shows the SH wave signal on a 4 mm thick carbon/carbon (C/C) composite laminate with a [0/90] layup. The SH wave EMAT probes were again placed on aluminum foil tape attached to the C/C composite surface. In both cases the frequency was 450 kHz and the signal-to-noise ratio was quite adequate for nondestructive inspection. SH waves were also generated on composites containing metallization; the results are to be presented in the following section. In all cases we use the general term "SH waves" for signals generated by the SH wave EMAT probes, regardless of how the waves have interacted with the boundary surfaces of the composite laminates.

4. EMAT-Generated Normal Incidence Shear Waves in Composites

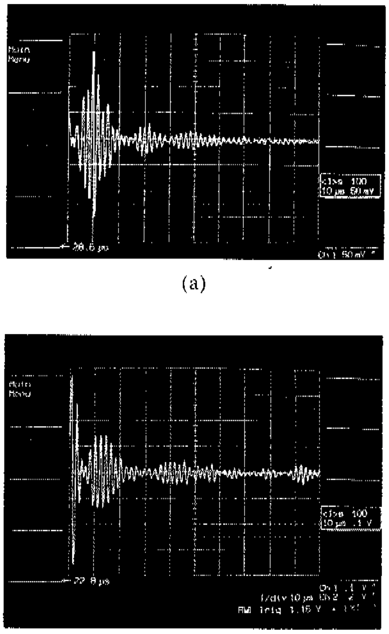
Using the normal incidence EMAT probes described above and the aluminum foil tape, shear mode bulk waves were generated and propagated through thick composites. Figure 7 (a) shows the shear wave signal propagated through a 51 mm thick cross-plied graphite-epoxy laminate. Part of the dead-time was shifted to the left of the picture and not shown here. Figure 7(b) shows the shear wave signal propagated through a carbon/carbon brake disk 17 mm thick. The C/C brake disk contained both fabric and chopped fibers and had considerable



(a)

(b)

Fig. 6 SH wave signals generated and received on (a) 8 mm thick quasi-isotropic graphite-epoxy, and (b) 4 mm thick [0/90] layup carbon/carbon composite plate.



(a)

(b)

Fig. 7 EMAT-generated, normal-incidence shear waves propagated through (a) a 51 mm thick cross-plied graphite-epoxy composites, and (b) a 17 mm thick carbon/carbon brake disk. The transmitter and receiver polarizations were aligned in the through-transmission configuration. The dead-time portion of the RF signal was not shown.

porosity; as a result, it had a high degree of ultrasonic scattering and attenuation. The frequency used for acquiring the signals in Figs. 7 (a) and 7(b) was 450 kHz. The results of Fig. 7 showed that EMAT-generated ultrasonic waves can be used in the inspection of highly attenuative thick composites. Finally, as a test on wood, aluminum foil tapes were attached on a two-by-four lumber; a strong shear wave signal was transmitted through 45 mm of wood at a frequency of 180 kHz.

5. SH Waves Propagated Through Thick Composites

Although the SH wave EMAT probes were designed to launch plate waves in the forward direction of a metal plate, the fringe field of the probe was found to be sufficient for generating and propagating bulk SH waves through a thick composite. By placing two SH EMAT probes described above on the top and bottom surfaces of a 27 mm thick graphite-epoxy laminate, the received signal amplitude showed interesting changes as the receiver EMAT was moved relative to the transmitter EMAT. The amplitude versus position curve is shown in Fig. 8. Also in the figure the experimental configuration is shown. The vibration direction of the SH wave was along the fibers and the propagation direction was normal to the fibers. The amplitude variation showed two main features: the fast oscillations with a period of 3.3 mm near the center of the curve and the two broad maxima located symmetrically at 3.2 cm from the center.

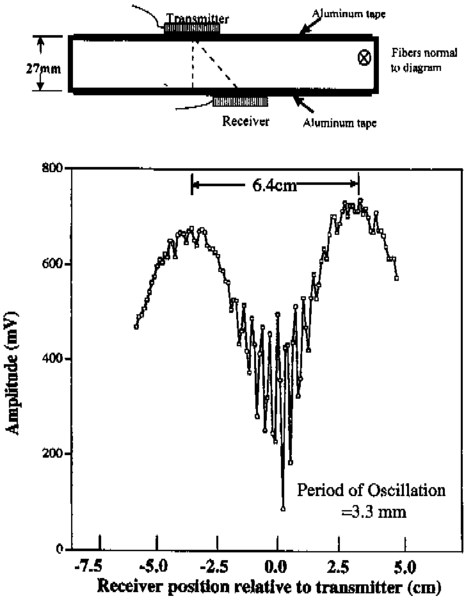


Fig. 8 Propagation of EMAT-generated SH waves in a 27mm thick unidirectional graphite-epoxy laminate. SH-wave EMAT probes containing 14 pairs of magnets were used.

The rapid oscillations near the center of the curve may be explained as a beat pattern caused by the interference of the periodic magnets in the SH wave EMAT probes. As the receiving probe moved across and underneath the transmitting probe, there was alternating reinforcement and cancellation of the signal, leading to the rapid oscillations of the received signal amplitude. Figure 9 shows the sequence in detail. Consider the SH waves generated by one of the magnets (second from left) in the transmitting EMAT, the waves propagated downward and induced currents J_1 and J_2 via the reversed effect of the Lorentz force mechanism. These currents were then sensed by the coil in the receiving EMAT to produce a voltage signal. However, when the magnets in the receiving EMAT were shifted by one half of a magnet width relative to those in the transmitting EMAT, J_1 and J_2 would cancel each other and produce a null signal. In reality the cancellation would not be exact and the resultant signal would be a minimum instead of a null.

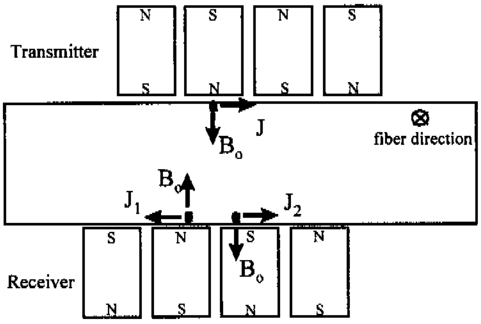


Fig. 9 The interference mechanism that caused the rapid oscillations in Fig. 8. Shown here is the relative position of the transmitting and receiving EMATs that corresponded to a minimum in the received signal amplitude.

When the two sets of magnets were aligned, the induced currents would add and produce a maximum signal. When the two sets of magnets were again shifted by one half of a magnet width, the signal would show another minimum. Therefore, the period of these oscillations should be equal to one magnet width or 3.3 mm.

The two broad shoulders at 3.2cm from the center may be explained in terms of the directivity function of the SH wave EMAT probes. For EMATs with the periodic permanent magnet design, the main lobe of its radiation pattern should be at an angle θ, measured from the normal of the probe, with $\theta=\sin^{-1}\left(\frac{2\pi v}{\omega D}\right)$. Here v is the wave velocity, ω is the angular frequency, and D is the periodicity of the magnets. For a unidirectional graphite- epoxy laminate, shear waves polarized along the fibers and propagating normal to the fibers have a nominal velocity of 2.06 mm/μm. The magnet period is equal to twice the magnet width, or 6.6 mm. Hence, the computed θ is 44°. The experimental curve in Fig. 8 gave a measured value of 49°. Considering the nominal values used in the prediction, the agreement is reasonable.

6. EMAT Signals in Composites Containing Metallization

For aluminum aircraft the "Faraday cage" effect provided by the high electrical conductivity of aluminum has eliminated most of the concern about lightning strike and electromagnetic interference (EMI). With poorly conducting graphite-epoxy structures, some form of metallization must be imposed onto the surface [DeMeis, 1984]. Common practices for metallization included flame-sprayed metal coating, incorporated copper or aluminum mesh and foil [Alumesh, 1998], and the use of graphite fibers coated with nickel [Conductive-, 1991].

On composite structures containing metallization, EMAT may be applied directly without the application of aluminum foil tape. Figure 10 shows the results of EMAT-generated SH waves on a 2 mm thick graphite-epoxy laminate containing copper mesh. The graphite fibers were in the 0 and 90 directions whereas the wires of the copper mesh were oriented at +/- 35°. Two SH wave EMAT probes were placed toe-to-toe on the surface of the plate and the received signal amplitude was recorded as a function of azimuthal angle.

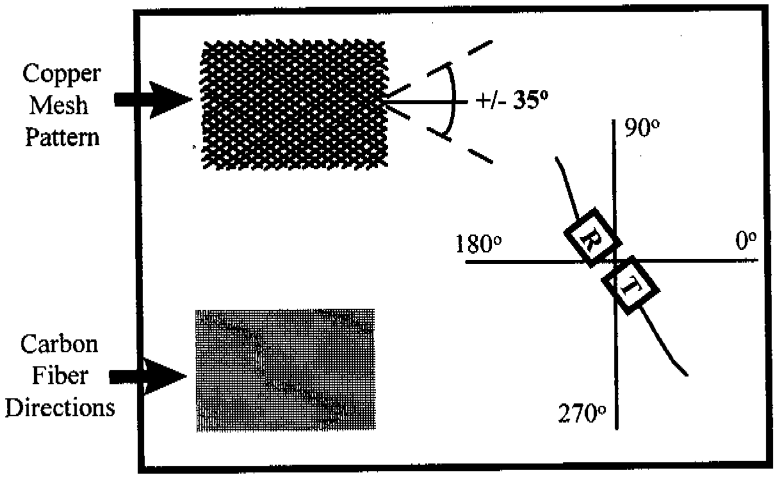
The polar plot in Fig. 10(b) shows the angular dependence of the signal amplitude. It is interesting to note the anisotropy of the four lobes: the lobes at 0° and 180° are greater than those at 90° and 270°. The same plate was studied earlier with acousto-ultrasonic (A-U) scan using a pair of 5 MHz longitudinal wave transducers. The A-U results showed basically no difference between 0°, 180° and 90°, 270° directions, indicating that the mechanical properties were probably dominated by the graphite fibers and were the same in the four directions. The tentative interpretation for the EMAT results was that the anisotropy observed in the signal amplitude could be attributed to the orientation of the copper wires of the mesh. The wires were closer to being parallel to 0° and 180° than being parallel to 90° and 270° and hence enhanced the generation and reception in the 0° and 180° direction.

In addition to graphite-epoxy laminate with copper mesh, EMAT was also applied directly to a graphite-epoxy aircraft skin panel containing a near-surface fabric layer made of nickel-coated graphite fibers. Strong SH wave signals were generated and received with a pair of periodic permanent magnet EMAT probes. The amplitude of the waves was found to be dependent upon the orientation angle of the EMAT pair on the surface of the panel.

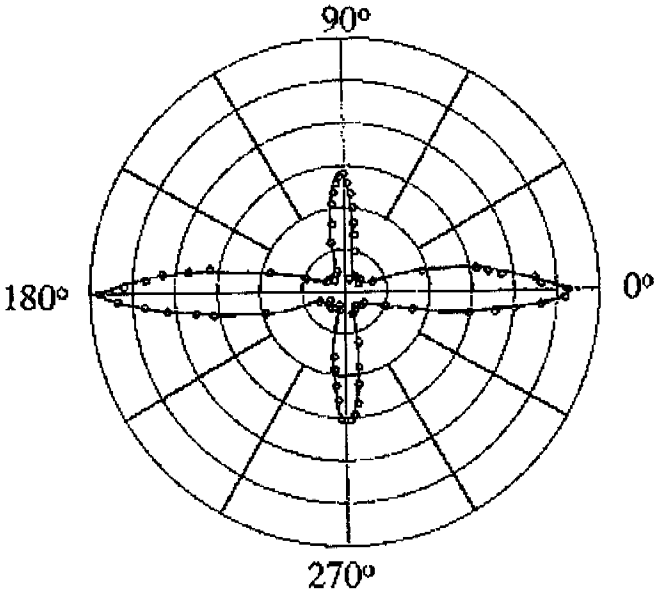
7. Detection of Flaws in Composites using SH Wave EMAT

This work was the first experimental study on applying EMAT to the inspection of poorly conducting and nonconducting composites. Its main emphasis has therefore been on the generation and reception of ultrasonic signals in various composite materials. Flaw detection with EMAT remains one of the main topics to be investigated, however, some preliminary flaw detection experiments have been performed. Single-sided, EMAT-generated SH waves were used for detecting flaws in composite panels. This required that the area of flaw search be covered by aluminum foil tape. In searching for the defects, a pair of SH wave EMAT probes were joined toe-to-toe and moved on the surface of the composite panel as one search unit. Using this arrangement, impact damages in glass-epoxy composite laminates were detected. This setup was also used in the detection of disbonds between a thin graphite-epoxy face-sheet and the Nomex honeycomb core of an aircraft rudder skin panel.

Figure 11 shows the variation of the EMAT-generated SH wave signal amplitude as the pair of probes moved across an impact damage in a direction normal to the length of the EMATs. The



(a)



(b)

Fig. 10 Angular scan of a 2 mm thick graphite-epoxy containing copper mesh using SH- wave EMATs.
(a) Directions of the copper mesh and the carbon fiber and the EMAT configuration.
(b) Amplitude of received signal versus angle.

apparent flaw size agreed well with the maximum damaged area which had a diameter of 25 mm. Repeated tests produced results with excellent reproducibility, as shown in Fig. 11. The "double-dip" shape of the flaw indication was suspected to be associated with the morphology of an impact damage: there was a small region of less severe damage under the impact. However, this has yet to be experimentally verified. Figure 12 shows the test configuration and results for the disbond in a rudder skin panel. Here the pair of SH wave EMATs was moved across the flaw in a direction parallel to the length of the EMATs. As expected, the wave amplitude increased considerably over the disbonded region. The flaw indication was wider than the actual width of the disbonded region because of the large length of the EMAT probes.

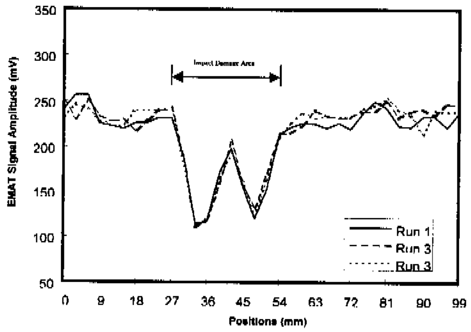
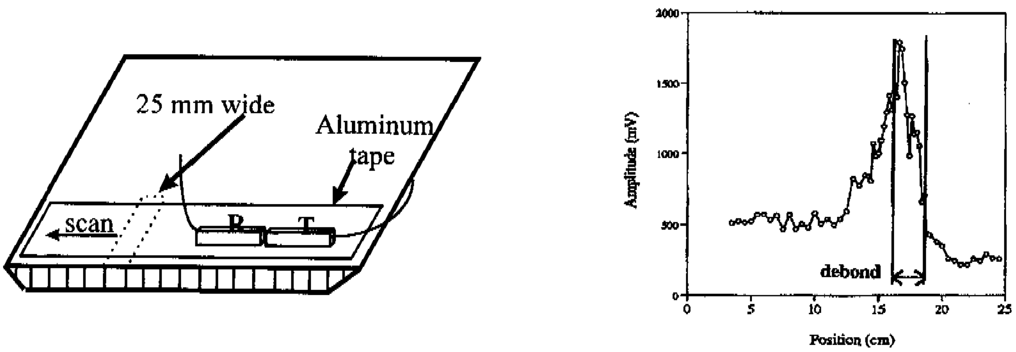


Fig. 11 Variation of SH-wave EMAT signals as the pair of probes, held together toe-to-toe, were scanned perpendicular to the probe length direction over an impact damaged area approximately 25 mm in diameter.

8. NDE of Green Composite using Cross-polarized Shear Waves

In tape-layup composite laminates all the fibers in a ply are oriented in the same direction. Because of this highly directional nature of fiber placement, the laminate plies interact strongly with linearly polarized shear waves propagating through the thickness of the laminate. We have exploited this interaction and developed NDE methods for detecting ply orientation errors and layup sequence errors using cross-polarized shear waves (Hsu, et al., 1993 and Hsu, et al., 1996). The most sensitive technique has been a through-transmission measurement using two linearly polarized shear wave transducers oriented orthogonal to each other. The transmitted shear wave amplitude is measured as a function of azimuthal angle while rotating the two transducers and keeping them orthogonal. The angular dependence of the transmitted signal was found to be sensitive to a number of ply layup errors. For example, a 48-ply laminate with only one misoriented ply produced a transmitted signal significantly different from that of an error-free laminate. For cured laminates the shear wave transducers may be adhered to the surfaces by using highly viscous shear wave couplants, however, this approach is not suitable for inspecting green composites before curing. Since errors in cured



(a)

(b)

Fig. 12 Detection of a disbond between graphite-epoxy skin and Nomex honeycomb core of a rudder skin panel. (a) Experimental configuration, and (b) Received SH-wave amplitude versus probe position.

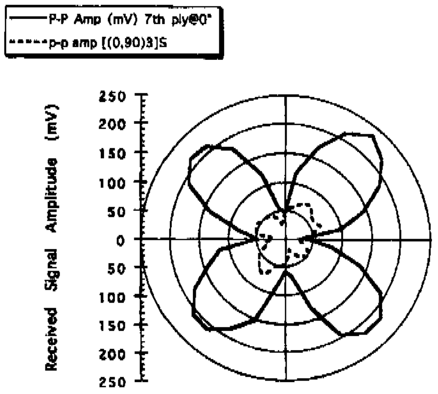


Fig. 13 Angular dependence of EMAT-generated normal incidence shear wave amplitude propagated through a 12-ply green laminate of graphite-epoxy sandwiched between two aluminum delay blocks. Dashed line: $[0/90]_{3S}$ layup. Solid line: same layup but with the7th ply misoriented at 0o instead.

laminates can no longer be corrected, it is desirable to inspect for errors in the green state before curing. To inspect green laminates with cross-polarized shear waves, EMATs can be used to generate shear waves in aluminum delay blocks and the green laminate can be sandwiched between the delay blocks and coupled by pressure (Hsu, et al., 1997). The advantage of this technique is that there is no couplant between the EMAT probes and the aluminum delay blocks; the probes can therefore be rotated freely with precision and reproducibility.

Tests were performed in the laboratory to detect ply layup errors in 12-ply uncured graphite-epoxy laminates. Experimentally the laminates were sandwiched between two 51 mm thick aluminum delay blocks. A pair of normal incidence shear wave EMAT probes were used in a cross-polarized configuration in the transmission mode. Figure 13 shows a comparison of the angular dependence of transmitted signal amplitude for two green laminates: an error-free laminate with $[(0/90)_{3S}]$ layup and the same laminate except with the 7th ply intentionally placed at 0° instead of at 90°. The dashed line shows the result for the error-free laminate and the solid line shows the results for the laminate with the layup error. The difference is quite large and easily detected.

Conclusions

This work has demonstrated that EMATs may be used in the NDE of nonconducting or poorly conducting composites with the aid of aluminum foil tape. Using this approach, SH waves and normal incidence bulk shear waves were generated and received in a variety of composite laminates with thickness up to 51 mm. It was also demonstrated that EMATs may be applied directly on composites that already contain some form of metallization such as mesh, foil, or metal coated graphite fibers. Some preliminary tests were conducted for flaw detection. EMAT generated normal incidence shear waves were used in the detection of ply misorientation and layup sequence errors in uncured laminates. A number of advantages of EMAT were exploited: the probes require no couplant and can be operated in a noncontact mode, the probes are easy to rotate for angular dependence measurements, the EMAT probes may be designed for generating specific modes, and the results obtained by EMATs can complement those obtained with more traditional ultrasonic testing.

Acknowledgments

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