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An Approach to Determine the Experimental Transmitter–Receiver Geometry for the Reception of Leaky Lamb Waves

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Abstract

Often, either the swept frequency technique or a combination of swept frequency and geometric analysis is used to produce the experimental Lamb wave dispersion data. This paper describes an approach for constructing dispersion curves in solid plates using Fourier analysis of received leaky Lamb wave signals. The Lamb waves are produced by pulsed ultrasound generated using two broad band transducers positioned in a pitch-catch orientation. The relative distances among the plate and the two transducers are set to specific values as per geometric calculations based on beam diffraction. The transducer defocus is used in conjunction with geometric calculation to determine the phase velocity of the Lamb wave mode being monitored. Subsequent to appropriate positioning of the transducers, the plate wave signals are Fourier transformed to obtain a magnitude versus frequency spectrum. Peaks in the spectrum indicate the presence of a Lamb wave root. The feasibility of this method, tested by successfully constructing dispersion curves for a steel plate, is compared with the "null zone" monitoring method of generation of the dispersion curves. The geometric positioning method is further applied to a metal matrix composite sample wherein the sensitivity of various experimentally generated Lamb wave modes is assessed to detect many types of preprogrammed defects in different layers of the composite plate.

Keywords: composite materials, defects, Lamb waves, nondestructive evaluation, stainless steel, steel, ultrasonic testing.

Introduction

Leaky Lamb waves are generated by ultrasonic waves that are obliquely incident on an immersed plate at frequencies that excite plate wave modes. The generation of the leaky Lamb waves leads to distortion of the reflected beam in the specular reflection region. A phase cancellation occurs when the leaky Lamb wave and the geometrically (specularly) reflected beam interfere, generating a null zone. The null zone is monitored in a swept frequency mode to generate dispersion curves in the traditional method. The sensitivity of the leaky Lamb waves to variations in elastic properties, thickness, and boundary conditions provides valuable information about the material. Theoretical studies by Kundu and Blodgett (1993), Yang (1994), and Yang and Kundu (1994a and 1994b) have shown that different Lamb wave modes produce different levels of excitation in various layers in a multilayered solid plate.

The conventional tone burst swept frequency technique is commonly used to experimentally generate Lamb wave roots. Previous efforts of using leaky waves to inspect defects in composite and metal plates include the works of Bar-Cohen and Chimenti (1985, 1986), Chimenti and Bar-Cohen (1986), Chimenti and Fiedler (1987), Chimenti and Martin (1991), Chimenti and Nayfeh (1985), Ditri and Rajana (in press), Ditri and Rose (1994), Mal and Bar-Cohen (1988), Martin and Chimenti (1987), Nagy et al. (1986), Nayfeh (1986), Pearson and Murri (1986), Rajana et al. (in press), and Rose et al. (1986), among others. In this technique, two broad band transducers are positioned in the pitch-catch orientation. The transmitter is excited by a signal function generator, which produces continuous wave forms (tone burst) and varies the signal frequency continuously between two limits (frequency sweeping). An oscilloscope screen displays the reflected signal amplitude (vertical axis) versus the frequency (horizontal axis). If a Lamb wave mode is generated for a particular angle, energy leaks through the fluid-solid interface in the form of leaky Lamb waves (Kundu and Maxfield, 1993). Destructive interference of the leaky Lamb waves with the back-surface reflection produces a null zone that is discernible as a dip (local minimum) in the amplitude-frequency plot of the reflected signal as shown in Figure 1. The corresponding phase velocity can be obtained using

$$C_{ph} = C_w / \sin \Theta \tag{1}$$

where C_{ph} = phase velocity, C_w = longitudinal wave speed in water (1,490 m/s [4,890 ft/s]), and Θ = angle of incidence.

The null zone position changes in presence of an internal defect. Hence, when a defect is encountered, the receiver voltage amplitude is altered and the image of the defect is generated. The major problem with this arrangement is that the null zone position is very sensitive to the plate thickness. Therefore, a few percent change in the plate thickness alters the receiver voltage amplitude significantly. To avoid this problem one needs to filter the *L*-scan generated

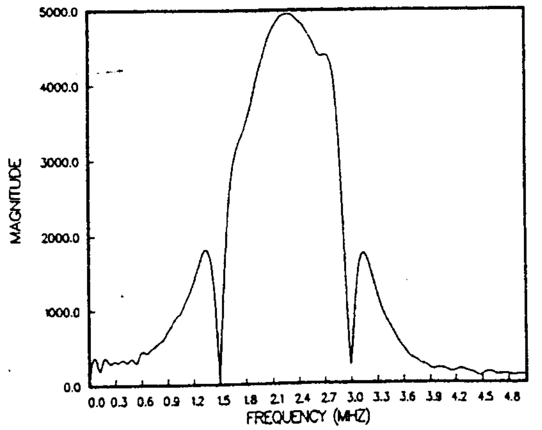

Figure 1 — Spectral nulls produced in the swept frequency "null zone monitoring" method.

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data through a special filter, called MFq filter (Chimenti and Martin, 1991). This signal processing helps to minimize the effect of the plate thickness variation on the null zone, but retains the sensitivity to the defects of interest. An additional problem in the null monitoring technique is that the technique is very sensitive to the relative position among the plate, the transmitter, and the receiver. However, this problem can be avoided/reduced by placing the receiver beyond the null zone as well as the specularly reflected zone of the ultrasonic beam.

This paper provides expressions to numerically calculate the positions of the transmitter and the receiver relative to the plate. Thus only propagating leaky Lamb waves are received by the receiver (similar approach with a single transducer has been reported in the literature by Nagy et al., 1986). Also, dispersion curves are experimentally generated here for a stainless steel plate and compared with the analytical curves as well as curves obtained by traditional "null monitoring" method. Further, the method is used to assess the sensitivity and selectivity of different modes to detect various preprogrammed defects in different layers of a metal matrix composite sample.

PULSE ECHO TECHNIQUE OF LEAKY LAMB WAVE GENERATION

In this technique, Lamb waves are produced by pulsed ultrasound generated using two broad band transducers positioned in a pitch catch orientation as shown in Figure 2. The relative distances among the plate and the two transducers are set to specific values as per geometric calculations based on beam diffraction (Figure 3).

The near field distance, i.e., the distance from the transducer where the axial pressure fluctuations cease and begin to monotonically reduce, is defined by

$$N = (D^2 - \lambda^2)/4\lambda \qquad (2)$$

where λ is the ultrasonic wavelength in water given by $\lambda = c/f$, c is the longitudinal velocity of sound in water (1,490 m/s [4,890 ft/s]), f is the frequency of the transducer, and D is the diameter of the transducer.

Further, half angle of the transducer is given by $\gamma = \sin^{-1}(1.2\lambda/D)$. These equations were first used to calculate the wavelength, near-field distance, and half-angle of the transducers used in this study as shown in Table 1.

Table 1 Transducer specifications (1 mm = 0.04 in)

Frequency (MHz)	Wavelength (mm)	Near-field Distance (mm)	Half-angle (degrees)
2.25	0.658	61.214	3.56
3.5	0.424	214.122	1.53

Once the values in Table 1 are calculated, the "range of validity" for positioning the receivers can be calculated using geometric considerations (Figure 3). Since the objective here is to avoid the geometric reflection completely and receive only the leaky Lamb waves, it is essential to calculate the separation distance, W, between the transmitter and the receiver given the angle of incidence, Θ, and the nearfield, N, of the transducers ($W = 2N \sin \Theta$). Initially, the plate being evaluated needs to be positioned such that the plate is at a distance of N (measured along the axis of the obliquely positioned transmitter) from the transmitter-receiver pair. In this position, the receiver will be aligned to receive only the specular reflection from the surface. The transmitter-receiver pair will now have to be moved ("defocused") towards the plate by a specific distance, Z, such that the receiver is avoiding the specularly reflected beam which is diffracting with a half angle of γ. Thus, from geometrical considerations, the defocus distance is given by

$$Z = N^*\{\cos E - [\sin \Theta/\tan (\Theta + \gamma)]\} \qquad (3)$$

The defocus, Z, will now position the receiver such that it is just beyond the specular reflection region, thus avoiding the null zone completely. Hence, in this defocus configuration, W will be the minimum required distance between the transmitter and the receiver to receive only the leaky Lamb waves (Figure 4). Any position of the receiver beyond W will be suitable (Figure 5); however, increasing the distance of separation between the transmitter and the receiver will result in increased attenuation due to leakage. Thus, the positions of the transmitter, receiver, and the test sample as described in this paragraph will enable the positioning of the receiver as close to the transmitter as possible without entering the "geometric reflection zone." This will avoid the ambiguities that will occur if the receiver is improperly positioned so that the edge of the receiver is slightly encroaching on the "geometric reflection zone" (Figure 6).

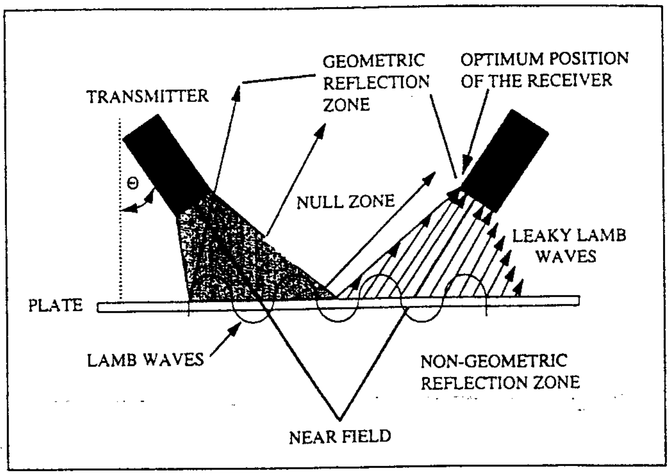

Figure 2 — Schematic of the optimum geometry for the Fourier analysis technique.

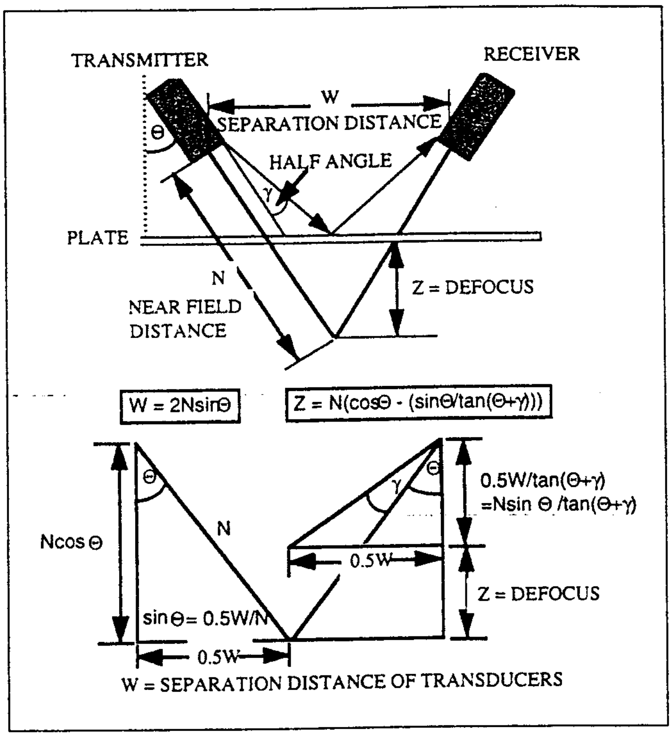

Figure 3 — Geometric considerations based on beam diffraction and nearfield calculations.

EXPERIMENTAL GENERATION OF LAMB WAVES

Conventional Swept Frequency Technique

Theoretical dispersion curves produced by Kundu and Maxfield (1993) was used (Figure 7) as the basis for these experiments. Experimental dispersion curves were constructed for a 1.6 mm (0.063

in.) thick stainless steel plate using the conventional method. One set of broad band transducers was used to generate the curves. The transducers used for the experiments were 19 mm (0.75 in.) diameter transducers of 3.5 MHz center frequency. The frequency sweeping was carried out using programmable wave form synthesizer in the interval from 1 to 5 MHz. The incident angle of the waves was changed from 10 to 22 degrees at an interval of one degree. The experimental data were plotted against theoretical data (Figure 7).

Pulse Echo Fourier Analysis Technique

Two pairs (one pair of 3.5 MHz, 19 mm [0.75 in.] diameter, and the other pair of 2.25 MHz, 12.7 mm [0.5 in.] diameter) of broad band transducers were used to generate the dispersion curves for the 1.6 mm (0.063 in.) stainless steel plate. The transducers were suitably positioned and defocused as described earlier to produce a characteristic leaky Lamb wave signal similar to the one shown in Figure 4a. The plate wave signals in the nonspecular region are subsequently Fourier transformed to obtain a magnitude versus frequency spectrum (Figure 4b). In contrast to the conventional tone burst method wherein spectral nulls are produced (Figure 1), leaky Lamb wave signals are monitored here in the nonspecular region wherein frequency peaks are produced(Figure 4b). Peaks present in the spectrum indicate the presence of a Lamb wave. The phase velocity of the Lamb wave mode is calculated using geometric considerations (Figure 3). The information obtained from the transformations and calculations was then used to construct dispersion curves (Figure 7).

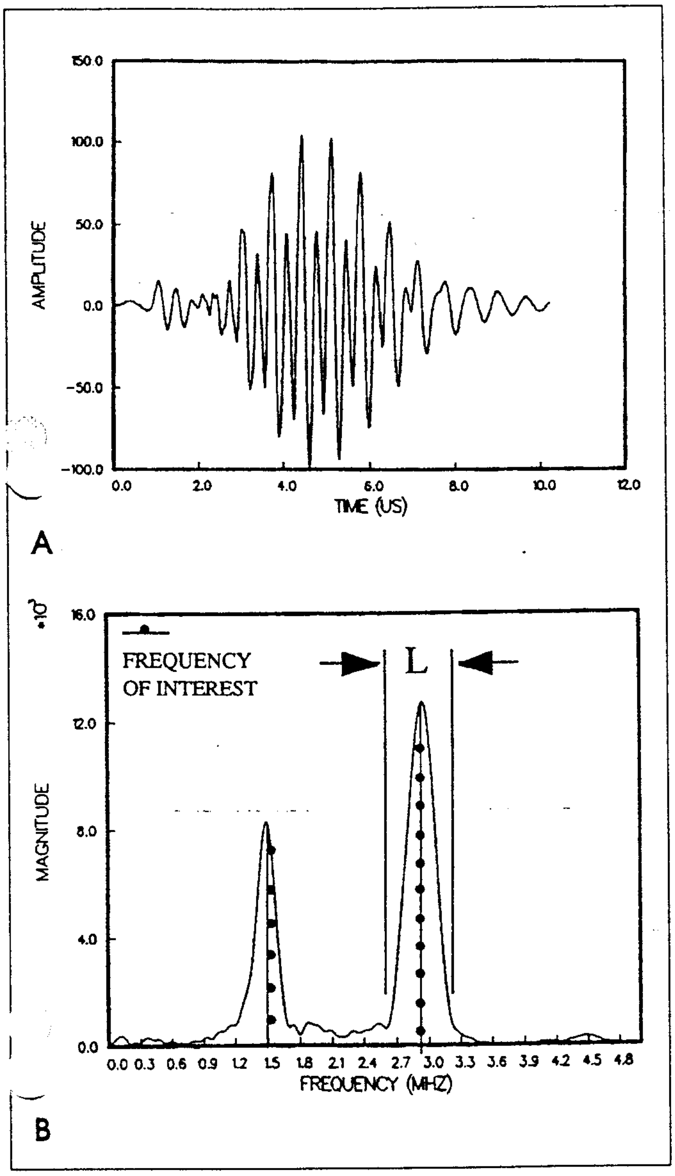

Figure 4 — (a) Received signal when the transducers are properly positioned as per the calculations shown in Figure 3. (b) Fourier analysis of the reflected (leaky) signal in the optimum position.

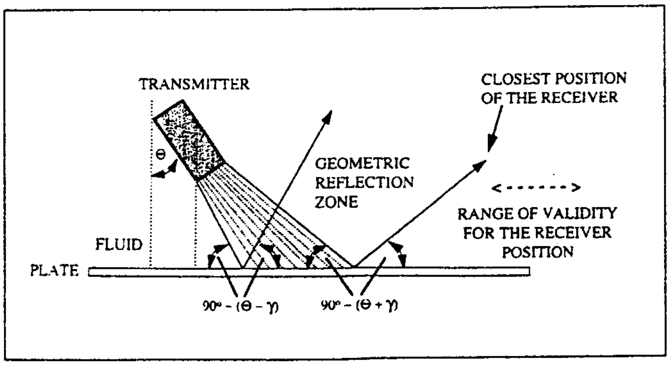

Figure 5 — Valid range of the position of the receiver for the pulse-echo Fourier technique.

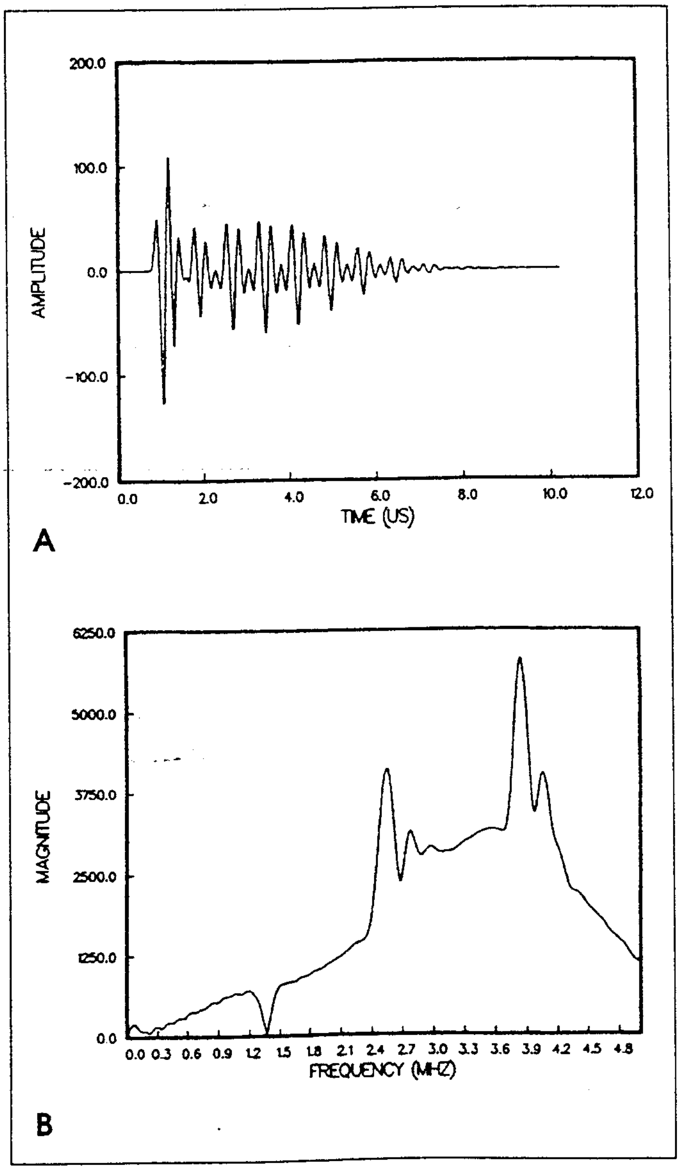

Figure 6 — (a) Received signals when the transducers are in an undesirable location bounded by both the geometric and non-geometric reflection zones. (b) Fourier analysis of the reflected (combination of specular and leaky signal shown in (a).

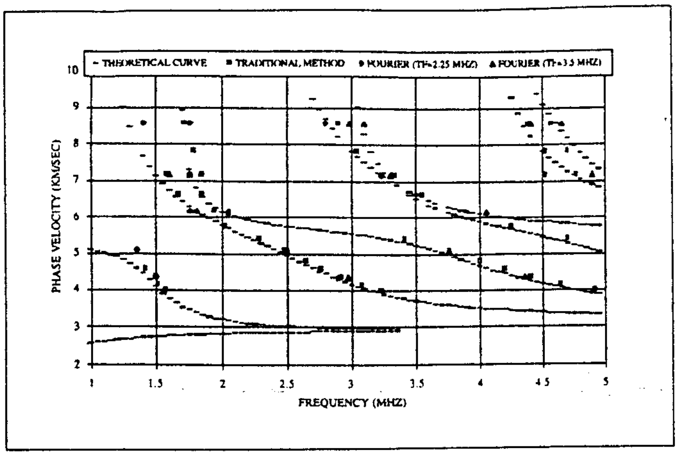

Figure 7 — Theoretical dispersion curves superimposed by experimental data generated by the two methods (frequency and pulsed Fourier techniques).

Metal Matrix Composite with Preprogrammed Defects

The sample used for this study was made (Kundu et al., 1995 and in press) with 5 layers of SCS-6 fibers in (0, 90, 0, 90, 0) lay-up configuration. The matrix material was Ti-6A1-4V. The composite was made by the foil-fiber-foil technique. The first and the fifth layers of fibers were undamaged. A part of the second layer of fibers (90 degrees) were coated with boron nitride to impede the formation of good bonding between the fibers and the matrix as schematically shown in Figure 8a. The fibers in the third layer (0 degrees) were intentionally broken as shown in the photograph in Figure 8b. The fourth layer (90 degrees) had two areas of missing fibers as shown in the photograph in Figure 8c.

The geometric positioning of the transducers was done as per the approach discussed earlier in the paper to avoid both the null zone and the specular reflection region. Frequency magnitude spectrum was used to determine the various modes propagating at each incidence (and reception) angle. Selected modes were monitored while scanning the sample and Lamb wave scans were produced as shown in Figures 9a–c.

RESULTS AND DISCUSSION

The dispersion curves generated using the conventional swept frequency and pulse-echo Fourier analysis techniques are shown in Figure 7. These experimental curves agree quite well with the theoretical dispersion curves generated by Kundu (1995 and in press). Any Lamb wave roots below 1 MHz were undetectable due to the limitations of the experimental equipment.

The pulse-echo Fourier analysis technique requires no frequency sweeping; therefore, additional equipment such as programmable waveform synthesizers, gated amplifiers, and boxcar averagers are not required, unlike the conventional method. In addition, slight changes in the vertical position of the transducers in the Fourier analysis technique does not affect the position of the peak as long as the transducer angle and experimental geometry are properly calculated. On the other hand, the minima in the reflected spectra of the null zone monitoring method are sensitive to the relative positions of the transducers and reflecting surface. Assuming a constant incident angle, slight changes in the vertical position of the transducers can cause the minima to shift on the frequency axis.

Figures 9a–c indicate selective sensitivity of different Lamb wave modes to defects in various layers. Figure 9a shows the lack of interface bonding in the second layer. The mode used for this scan was generated using 1.556 MHz at 18 degrees angle of incidence. Figure 9b shows a mode of 2.620 MHz frequency at 16 degrees angle of incidence which is sensitive to the fiber breaks in the third layer of fibers. Another mode of frequency 2.310 MHz, incident at 18 degrees angle shows sensitivity to a host of features in the plate in addition to the two areas of missing fibers in the fourth layer of the composite. Additional information on this selective detection of this composite specimen can be found in literature (Kundu et al., 1995 and in press).

SUMMARY AND CONCLUSIONS

A method for constructing dispersion curves in solid plates using Fourier analysis of received leaky Lamb wave signals was developed and tested. In addition, Lamb wave dispersion curves were experimentally constructed using a conventional tone burst frequency swept technique. The experimental curves agreed quite well with the theoretical dispersion curves generated by Kundu and Maxfield (1993). A new method for constructing dispersion curves in solid plates using Fourier analysis of received leaky Lamb wave signals has been successfully verified by constructing a dispersion curve for a stainless steel plate. An advantage of this technique is its simplicity. No special type of transducer is required. In addition, the arrangement of the experimental components is based on simple geometric calculations and beam diffraction. The data repeatability and accuracy makes this method easy to standardize for practical applications such as the identification and classification of defects and material properties.

The application of the geometric positioning of the transducer-receiver pair has been demonstrated for the evaluation

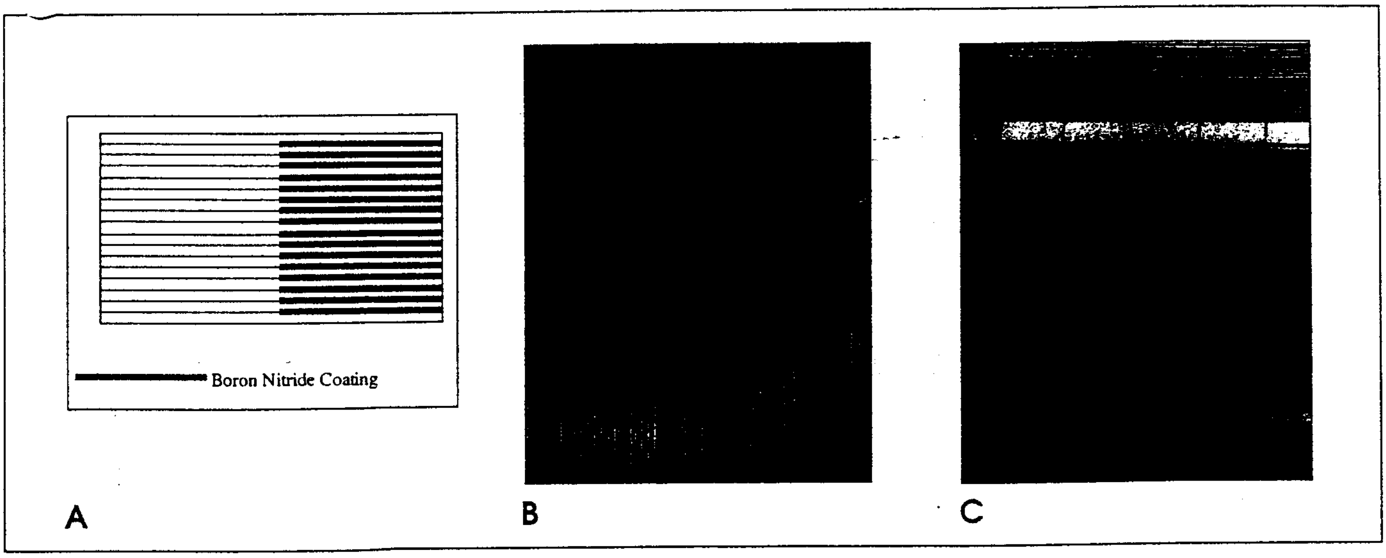

Figure 8 — (a) Schematic of the boron nitride coating of the fiber mat to induced lack of bonding at the fiber-matrix interface; (b) photograph of the fiber mat from the third layer showing the broken fibers, the distance between the neighboring cross waves is 5 mm (0.2 in.); (c) photograph of the fiber mat from the second layer showing the two areas of missing fibers.

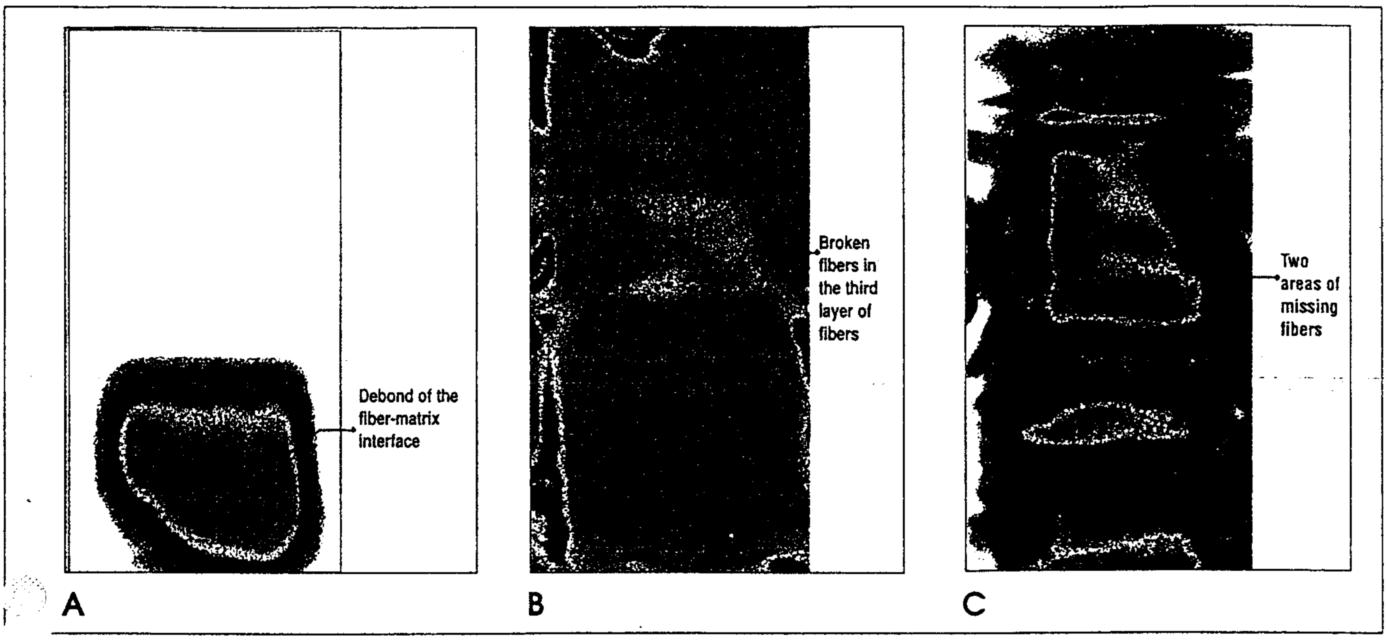

Figure 9 — (a) Lack of interface bonding in the second layer. The mode used for this scan was generated using 1.556 MHz at 18 degrees angle of incidence; (b) Lamb wave scan shows a mode of 2.62 MHz frequency at 16 degrees angle of incidence which is sensitive to the fiber breaks in the third layer of fibers; (c) a mode of frequency 2.31 MHz, incident at an 18 degree angle, shows sensitivity to a host of features in the plate in addition to the two areas of missing fibers in the second layer of the composite.

of selective sensitivity of Lamb wave modes to defects in various layers of a metal matrix composite.

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