INTRODUCTION

The utilization of leaky plate waves in a scanning arrangement has exhibited improved reliability and increased sensitivity to important defects in unidirectional material \cite{1,2,3}. The application of frequency modulation to the usual tone burst signal used to generate plate waves has also been shown to enhance defect discrimination \cite{2,3}. In the current work, leaky plate wave techniques have been applied to the inspection of biaxially laminated graphite-epoxy composites. Test samples having 8, 16, and 24 plies, respectively, are studied. Test specimens contain several types of defects - simulated delaminations, porosity, and ply cuts. In addition, a series of impact-damaged samples are examined to study the method's sensitivity to this type of delamination. All simulated defects were detected, and comparisons with conventional normal-incidence C-scan measurements have shown that the plate wave technique is more sensitive to both porosity and ply cuts, consistent with our observations on uniaxial composites \cite{3}. Novel gating methods have been applied to the plate wave spectra to improve defect detection in biaxial composites.

LEAKY PLATE WAVE GENERATION

Leaky plate waves are generated by a beam of ultrasound propagating to the sample and striking the plate at an incident angle. If conditions of beam width and frequency are favorable, the reradiated field appears distorted and displaced in the direction of propagation of the plate wave. In our application transmitter excitation is provided by a swept frequency tone burst which is generated by frequency modulating the RF tone burst with a triangular waveform at audio rates in the range of 5-20 Hz. Previous publications describe modulated tone-burst leaky wave generation in greater detail \cite{1,2,3}.
DATA ACQUISITION SYSTEM DESCRIPTION

The incident ultrasonic beam consists of a series of swept frequency tone bursts through the range of 0.8 to 4.5 MHz [3]. The received signal is amplified, video-detected, and sampled with a gated integrating amplifier. The experimental output is then a time-varying signal, most of whose power is concentrated at an audio frequency equal to twice the product of the modulation frequency with the number of plate modes subtended by the modulation bandwidth. The resulting signal of plate wave modes is then bandpass filtered at 700 Hz on the high frequency end for anti-aliasing and at 25 Hz on the low frequency end to remove the fundamental of the 56 ms sweep period and D.C. components from the signal. Removal of the D.C. and low frequency (<20Hz) components from the received signal is required to prevent degradation of the resolution of the spectral calculations described in later paragraphs. The plate wave signals are digitized over the entire 56 ms sweep period at a rate of 2064 samples per second with a total of 128 points recorded. Data are then sent to a microcomputer for processing and image generation [3,4].

TEST SAMPLES

The characterized samples utilized in this study are 6 biaxial graphite/epoxy laminates of 8, 16, and 24 plies in thickness constructed from AS4/3501 type material. The stacking sequences are [0/90]_2, [0_2 /90_2]_2, and [0_2 /90_2]_3, respectively. The size of each sample is 3 inches wide by 4 inches in length. Simulated defects are embedded in samples of three different thicknesses. Delaminations are simulated with 0.5 and 0.25 inch diameter teflon wafers (0.5 mil thick) and porosity is simulated with a very light scattering of 40 micron diameter microballoons. There are also single-layer ply cuts. Three samples of different thicknesses have also been subjected to low velocity impacts with a 12.7 mm diameter stainless steel ball on a pendulum impacter to produce true delaminations.

PLATE WAVE DATA SPECTRAL PROCESSING

While the detected RF envelope of the received signal shows minima at various frequencies, some characteristic of this signal is needed to distinguish between defects and defect-free material. Our method is to utilize spectral processing. Data processing software first calculates a 256 point Fast Fourier Transform (FFT) on the filtered low frequency detected RF envelope of the received signal. In this case only the 0-500 Hz frequency range of the FFT spectrum is of interest. In the general case, the spectral frequency range of interest depends upon the modulation frequency introduced by the sweep, the RF frequency range and the thickness of the panel under test. The median frequency of the area under the Fourier amplitude spectrum is computed for each sampling point on the panel using integration techniques. This median frequency measures the overall frequency shifts in the mode data as mode structure changes when passing over defects in the panel. High median frequencies are generated in defect-free material as the plate wave propagates through the entire thickness of the panel (many modes), while lower median frequencies are generated over a defect area of the panel because the panel thickness is effectively decreased and produces fewer modes. Median frequency thus provides a measure of relative defect depth. Figures 1, 2 and 3 depict these stages in signal processing. In each figure, the (a) plots are of the detected RF envelope which can be viewed as either amplitude versus frequency or amplitude versus time data. The (b) plots are the result of applying a 25-700 Hz bandpass filter plus a Hamming window to the signal.
in (a), while (c) is the FFT of waveform (b). Note the shift toward lower frequencies in the FFT spectra (c) progressing from Figure 1 to Figure 3 (effectively thicker to thinner material). The median frequency at each measured point (x,y) on the sample is stored as one data value in a C-scan image. An advantage of using the median frequency technique is that no prior knowledge of defects or their resulting frequency responses is required to produce a high quality image. Also, median frequency spectral processing provides a wide dynamic range of response to defects while preserving sensitivity to small or weak flaws. The depth information is accurate as long as the frequency difference representing defects close to the same depth is equal to or greater than the resolution of the FFT. In the case presented, the FFT resolution is 8.9 Hz, but it could be improved by utilizing any of several methods. A previous publication describes leaky plate wave spectral processing in greater detail [3].

TEST RESULTS

Figure 4a shows a C-scan image of a 24-ply test panel with simulated defects. Data for the image was generated by applying the median frequency signal processing technique to the leaky plate wave data acquired from the panel. The column of defects on the left is located between layers 8 and 9 in the panel while the column of defects on the right is between layers 16 and 17. In each column, the top defect is a 0.5 inch diameter delamination, the second from top is a 0.25 inch diameter delamination, the third is a 0.5 inch diameter area of porosity, while the bottom defect is a 0.5 inch wide ply cut with a 0.125 inch gap.

A pair of 2.5 MHz unfocused transducers with 0.375 inch diameter elements are utilized to acquire data. The incident angle of the beam to the panel is 15 degrees from surface normal, and the swept frequency tone burst covers the range of 0.8-4.4 MHz in a 56 ms sweep time (17.9 Hz modulation). In the image of Fig. 4a, increasing median frequency is proportional to defect depth. Progressively darker shades of gray in the image represent greater defect depth. Thus, the two simulated delaminations on the left are shown as white because they are closer to the entry surface of the panel while the deeper delaminations on the right appear as darker shades of gray. The porosity and ply cuts do not conform to the same gray scale because only partial signal reflections are possible from these structures due to the width of the beam. Defect-free areas of the panel are black because they represent the maximum panel thickness, and thus the highest median frequency.

Figure 4b shows a C-scan image of the same panel utilized for comparison purposes. Data for this image was acquired with a 10 MHz, 4-inch focused transducer with a 0.25 inch diameter element at normal incidence to the panel. Software gating and front surface tracking were used to acquire the image data [5]. Not all defects are shown (especially porosity and ply cuts) and of course no depth information is indicated.

Figs. 1, 2 and 3 depict representative waveforms recorded to generate the median frequency image of Fig. 4a. The median frequency for the defect-free FFT of Fig. 1c is 128 Hz, while median frequency for the layer 8 delamination of Fig. 2c is 112 Hz and for the layer 16 delamination of Fig. 3c is 73 Hz. The most notable difference between these waveforms and the previously reported waveforms obtained with unidirectional material [3] is the increased waveform complexity; however, the median frequency algorithm still correctly encodes depth information. Another finding of this investigation is that the beam direction should be parallel to the orientation of the top surface plies to optimize mode structure and therefore the defect contrast potential. Incident beam angles between 10
Fig. 1. (a) Plot of plate wave modes of a defect-free area showing envelope of detected ultrasonic signal. (b) Bandpass filtered and windowed version of signal in (a). (c) FFT spectrum of the signal shown in (b).

Fig. 2. (a) Plot of plate wave modes of a lower level defect showing envelope of detected ultrasonic signal. (b) Bandpass filtered and windowed version of signal in (a). (c) FFT spectrum of the signal shown in (b).

Fig. 3. (a) Plot of plate wave modes of an upper level defect showing envelope of detected ultrasonic signal. (b) Bandpass filtered and windowed version of signal in (a). (c) FFT spectrum of the signal shown in (b).
Fig. 4. (a) C-scan image of 24-ply panel utilizing median frequency, proportional to defect depth. Dark areas are defect-free; gray scale correlates with distance of defect from surface. (b) Normal incidence C-scan of same panel gated on back surface.

and 30 degrees have been investigated. Acceptable mode structure was generated only at angles close to 15 degrees.

Figures 5a and 5b are also images of the 24-layer panel but have been acquired by measuring the depth of specific nulls in the detected swept-frequency RF envelope waveform. Two software gates, each of which detects the minimum data value within the gate, have been utilized. Their location and typical amplitudes at two specific panel areas are indicated by the position and heights of the rectangular gates shown in Fig. 6. Minimum values detected in gate #1 result in low amplitudes that selectively image the deeper delaminations (white areas) in Fig. 5a, while minimum values detected in gate #2 (Fig. 6) result in high amplitudes (dark areas) for all defect areas and low amplitudes for defect-free material (Fig. 5b). The null in gate #2 is at a frequency characteristic of defect-free material. The contrast and definition of defect areas in Figs. 5a and 5b are superior to those in the median frequency image of Fig. 4a, but the resulting signal has no depth information encoded.

A median-frequency processed image of an 8-ply thick panel which has been impacted with an energy of 1 joule is shown in Figure 7a. The RF sweep frequency range is 1.2 to 4.0 MHz in a 56 ms time period. Delaminations from an impact generally are small in plies near the impact surface, but grow in area outward and downward from the impact and overlap each other in successively deeper plies. This morphology is verified by performing a software gated normal incidence C-scan with gates set at the depth of each ply interface within the material. Figure 7b is taken from such a scan and is an image from a gate on the back surface of the sample.
Fig. 5. (a) Image formed by measuring minima in gate #1. Deeper delaminations are selectively imaged in white. (b) Image formed by measuring minima in gate #2. All defects are imaged in darker shades of gray.

Fig. 6. Positions and amplitudes of two minimum value software gates on the leaky plate wave mode spectrum. (a) lower level defect. (b) upper level defect.

showing the cumulative damage of all levels of delaminations. A 10 MHz focused transducer has been utilized. Figure 7a shows two areas of damage near the top surface (white areas), and then larger areas of damage at greater depths within the material, shown by increasingly darker shades of gray. Black indicates undamaged material. Figure 7b verifies the damaged area, but encodes no depth information. The wide acoustic beam and larger x,y step size of Figure 7a result in lower spatial resolution than the image in Figure 7b. Note that the leaky plate wave median-frequency processing of a real delamination (Fig. 7a) is much better than that of the simulated delamination in Figure 4a. The improvement is apparently due to a greater acoustic impedance mismatch in the real delamination.
An energy of 6 joules has been utilized to impact a 24-ply thick panel. A normal incidence 10 MHz C-scan is performed with a software gate at every ply interface and at the back surface to verify delamination damaged areas. The back surface gated image is shown in Figure 8a. Delaminations are generated in both the 0 and 90 degree ply directions and they enlarge in area outward and downward from the impact site. A leaky plate wave scan is performed utilizing a frequency sweep range of 0.8-4.4 MHz in a 56 ms period. A very wide software gate is then placed on the received RF envelope of the leaky plate waves. This gate will detect the minimum amplitude value that falls within the time interval of the gate. The gate covers the sweep over the time of about 10ms (1.4 MHz) to 44ms (3.6MHz). The resulting image is shown in Figure 8b and has the interesting effect of outlining the edges of the many levels of delaminations. The effect might be caused by a very deep null being created when the acoustic beam is on the edge of a delamination and partially covering both delaminations. Although this technique does not provide depth information, relative depth of the delamination areas can be easily inferred by prior knowledge of the manner in which impact delaminations are formed. The width and location of the wide gate is not critical, but experimentation has shown that the best images are produced with a gate width of 0.5 to 0.75 of the sweep time and nearly centered in the sweep band.

CONCLUSIONS

Swept frequency leaky plate wave techniques have been shown to provide reliable detection of simulated delaminations, porosity, and ply cuts in biaxial laminates. Also, the extent and relative depth of delaminations due to impact damage can be determined. Spectral processing techniques avoid the problems associated with tracking the amplitude of a specific null because the entire mode signal is utilized. Median frequency processing of the mode spectra provides a good general purpose processing technique for defect detection and relative depth determination, since median frequency is related to depth. Specific minimum value gating techniques have also been shown to provide important information and defect detection capabilities.
Fig. 8. (a) Normal incidence C-scan of same panel gated on the back surface. (b) C-scan image of 24-ply impact damaged panel utilizing a wide minimum value software gate on the leaky plate wave modes.

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