SIGNAL PROCESSING OF LEAKY LAMB WAVE DATA FOR DEFECT IMAGING IN COMPOSITE LAMINATES

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INTRODUCTION

Inspection of composite laminates with Leaky Lamb waves (LLW) has been shown to hold promise of improved reliability and increased sensitivity to important defects [1]. Conventional scanning with the LLW has the possible disadvantage that the method is sensitive not only to internal structure, but also to small variations in plate thickness, which are indistinguishable from elastic property changes. To circumvent this potentially irrelevant sensitivity, a technique has been developed [2] whereby such variations can be selectively ignored, while retaining sensitivity to important defects or material property variations. The method consists of applying frequency modulation to the usual tone burst RF signal and exploiting detailed knowledge of the Lamb wave spectrum of composites [3] to discriminate between significant defects or property changes and small thickness variations in the plate. The current work extends and expands this analog signal processing scheme by performing the analysis on digitized data, permitting a much more general and flexible approach which will be described.

LEAKY LAMB WAVE GENERATION

In Fig. 1, a beam of ultrasound propagates to the sample and strikes the plate at an incident angle, generating plate waves satisfying the condition $k_f \cdot \hat{p} = k_p$, where $\hat{p}$ is a unit vector in the plane of the plate. 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. Most of the energy is then contained in the two shaded regions. "N" denotes null zone, and "LW" indicates leaky wave. The transmitted wave below the plate is omitted for clarity.

Exploiting the fact that in certain regions of incident angle the LLW spectrum is quite regular [3], we frequency modulate the RF tone burst with a triangular waveform at low audio rates, about 5 to 20 Hz. At the output of the gated integrating amplifier we then have a time-varying signal whose power is contained principally in the fundamental and whose frequency equals twice the product of the modulation frequency with the number of plate modes subtended by the modulation bandwidth. This signal can then be further processed digitally to extract information about how the sample under study
behaves elastically. The simplest method consists of filtering this signal and integrating the result with respect to time. If the time constant is chosen to be suitably short, the method can be employed in a C-scan type arrangement, where both transducers are scanned raster fashion across the sample. The result of this signal coding and analysis technique permits discrimination between small elastic property or plate thickness variations and larger excursions indicative of defects [2]. A more sophisticated version of this method is the spectral processing method to be described in this paper.

DATA ACQUISITION SYSTEM

In Fig. 2, a sweep generator B sets the repetition rate for the system by triggering both RF generator A and the digitizer. The sweep generator generates a 56 ms ramp causing the RF generator A to sweep from 1.3 to 4.0 MHz. Pulse generator A determines the period (425 microseconds) and the duration of the tone bursts (10-30 microseconds) by controlling a diode switch. Therefore, 132 tone bursts are generated during the 56 ms sweep period. The received signal is amplified, gated and integrated. The resulting signal of Lamb wave modes is then bandpass filtered at 400 Hz on the high frequency end for anti-aliasing and at 25 Hz on the low frequency end to remove effects of the 56 ms sweep period and D.C. components. The low frequency cutoff is required to remove D.C. and low frequency (<20 Hz) components from the reflected signal which degrade the resolution of the spectra calculations described in later paragraphs. The Lamb 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. All data points are then sent to a LSI 11/23 microcomputer for data processing and image generation.

TEST SAMPLE

The characterized samples used in this study are unidirectional graphite/epoxy laminates. One is a 32-ply, AS4/3501-6 panel and the second is a 24-ply, T300/C0914 panel. They have simulated defects embedded at layers 8, 16, and 24 or 6, 12, and 18, respectively. Delaminations are simulated with circular teflon wafers and porosity with 40 micron diameter microballoons.
LAMB WAVE DATA SPECTRAL PROCESSING

Data processing software first scales the 128 digitized Lamb wave mode data points, buffers the data with zeros, and then calculates a 256 point FFT. In this case, only the 0-200 Hz frequency range of the 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. Figs. 3a and 4a are plots of digitized Lamb wave modes, while Figs. 3b and 4b are plots of the resulting FFT spectra of these modes. The modes of Fig. 3a occur in a defect-free area of the panel. This type of plot can be interpreted two ways. First, as a spectral plot of the reflected signal from the panel, it identifies the swept ultrasonic frequencies of the Lamb wave modes as indicated by the frequency scale of the RF frequencies ($\omega/2\pi$). However, Fig. 3a depicts only the relatively low frequency detected envelope (modulation) of the RF frequencies and not the RF cycles themselves. Secondly, it is a plot of the time-dependent digitized signal over the 56 ms sweep period (top scale) representing the modulated, low frequency components of the reflected ultrasonic signal. The FFT of this time-dependent signal is shown in Fig. 3b with a predominant peak at around 140 Hz on the FFT frequency scale ($\omega/2\pi$). In contrast, Fig. 4a is a plot of the Lamb wave modes measured over a delamination located at layer 18 of the 24-ply panel and has fewer minima than did the plot from the defect-free area. Because it has fewer modes, the predominant frequency of the layer-18 defect is lower than that of the defect-free material, as shown in the FFT plot of Fig. 4b. The number of modes is fewer with the beam over the delamination because of the mechanical decoupling effect of this defect. The Lamb wave therefore samples an effectively thinner panel than in the defect-free area where the sound energy propagates through the entire thickness of the panel. Defects located closer to the surface produce correspondingly fewer modes and therefore have lower peak frequencies, shifting the entire frequency band toward the low end of the FFT spectrum.

To present the data in a C-scan image format, each FFT spectrum must be reduced to a single value and located on an x-y position grid. Of the many ways to represent the FFT data, the peak frequency and median frequency...
methods were considered to be the best. On Figs. 3b and 4b the peak frequency method works well, but in the general case it does not. This is because the presence of multiple defects, porosity or changes in the fiber/resin ratio can all cause multiple peaks in the FFT spectrum which may be of nearly equal amplitude. However, we found that even in the presence of multiple peaks, a corresponding shift in the center of the FFT spectrum still occurred. This observation led us to examine the defect discrimination possibilities of the median frequency representation.

To make the analysis slightly more concrete, we introduce the following definitions. Let $Q(\omega, x)$ be the position-dependent Lamb wave spectrum function, as in Figs. 3a or 4a, where $\omega$ is the angular radio frequency and $x$ is a vector position on the sample surface. If the RF tone burst is frequency modulated, the function $Q(\omega, x)$ will be time dependent and have the periodicity of the modulating function. Considering $Q(\omega(t), x)$ as a function of time, we may perform a Fourier transform on it to obtain a pseudo-frequency spectrum of this implicit time-dependent function,

$$\hat{Q}(\nu, x) = |\int Q(\omega(t), x) e^{-2\pi i \nu t} dt|,$$

(1)
where $v$ is the pseudo frequency, generally in the audio range. With this result we may now consider several methods to represent the data. The peak frequency $v_{\text{Peak}}$ is simply the value of pseudo frequency at which $\hat{Q}(v, x)$ is a maximum. This representation presents the problems indicated above with regard to multiple defects. Band limiting, discussed below, consists of summing the spectral components within a specified pseudo-frequency band,

$$\int_{0}^{v_{\text{max}}} F(v_0, \delta v) \hat{Q}(v, x) \, dv,$$

where $F(v_0, \delta v)$ is a unit window function centered at $v_0$ and having width $\delta v$, and $v_{\text{max}}$ is the aliasing frequency of the FFT. In the median frequency representation, the pseudo frequency is sought which bisects the area under the FFT spectrum, such that one half the area lies above and one half below that frequency. That is,

$$\int_{0}^{v_{1/2}} \hat{Q}(v, x) \, dv = \frac{1}{2} \int_{0}^{v_{\text{max}}} \hat{Q}(v, x) \, dv,$$

where $v_{1/2}$ is the median pseudo frequency.

The median frequency gives the best representation of frequency shifts in the FFT spectra and therefore relative defect depth and response when the mode structure varies across the panel. An important advantage of median frequency processing is that no previous knowledge of the location and type of defects in the panel, nor the resulting mode spectra it produces are required to obtain a high quality image with accurate relative depth information. The depth information is retained so long as the frequency difference representing defects close to the same depth is greater than the resolution of the FFT. In the case presented, the FFT resolution is 8 Hz, but it could be improved to 4 Hz by doubling the digitizing rate, recording 256 data points, and performing a 512 point FFT. This would double the depth resolution and also retain defect depth information near the plate boundaries. An important advantage of spectral processing of Lamb wave data in general lies in the ability of this scheme to permit a very wide dynamic range of defect response while preserving sensitivity to small or weak flaws.

**TEST RESULTS**

Fig. 5 is the result of a swept frequency tone burst scan with median frequency processing on the 24-ply test panel. The top row of defects is located between layers 6 and 7 and consists of (from left to right) 1, 1/2 and 1/4-inch diameter delaminations, porosity (middle), and a ply cut (right). The middle row consists of the same defects as the first row except that all defects are located between layers 12 and 13 within the panel. The bottom row of defects, located between layers 18 and 19, consists of porosity (near the middle) and three delaminations on the right side of 1/4, 1/2 and 1-inch diameter, respectively. In this image, increasing median frequency is proportional to increasingly darker shades of gray proportional to defect depth. Black represents the highest median frequency (130 Hz) and occurred in defect-free areas of the panel. Layer-18 defects (bottom row) appear dark gray and represent a median frequency of 90 Hz. Layer-12 defects (middle row) appear medium gray and represent a median frequency of 75 Hz, while layer-6 defects (top row) appear light gray to white and represent a median frequency of 48 Hz. Note that objects in the same row (same depth) appear the same shade except for some of the less concentrated porosity areas down the middle which appear dark gray. Also appearing dark gray are long horizontal streaks which probably represents small changes in the fiber/resin ratio in those areas. Fig. 6 is presented as a comparison to Fig. 5 to show the results of a normal incident C-scan.
Fig. 5. C-scan image utilizing median frequency processing of the Lamb wave mode spectrum. Increasing median frequency is proportional to increasingly darker shades of gray level. Frequency is proportional to defect depth. Black represents defect-free areas while progressively lighter shades of gray indicate defects progressively closer to the surface.

Fig. 6. Normal incidence C-scan image of same panel as in Fig. 5 utilizing an unfocused 2.2 MHz transducer gated on the back surface.
image of the same sample. The C-scan was produced using a 2.2 MHz unfocused transducer and was gated on the back surface. Most of the delaminations were clearly shown, but the porosity and ply cuts are not as sharp and of course no depth information is available.

Since defects of different depths are represented by different frequencies, processing software was also developed to selectively image defects at a particular depth. First, a frequency band is selected which is believed to best represent defects at the desired depth. Then that band in the FFT is integrated (digital bandpass filtered) and used as the value for the C-scan image. Fig. 7 is an image produced by integrating the frequency band that represents defect-free material. This produces an image where defect-free material will appear dark. The frequency band selected was 100-160 Hz and was determined by selecting a band around the frequency of the large peak in Fig. 3b. Fig. 8 was produced by selecting a frequency band around the large peak in Fig. 4b and bandpass filtering (81-120 Hz), thus producing an image representing defects at layer 18. The defects appear dark in Fig. 8 and very good discrimination was achieved in selectively imaging only defects at that particular depth.

To demonstrate the discrimination capabilities of our method, spectral processing was applied to a 32-ply test panel whose thickness was not constant. For comparison purposes, the image of Fig. 9 was generated by measuring the depth of a single null in a 4-MHz constant frequency tone burst. Many of the defects are obscured due to small thickness changes in the plate. Then, the image of Fig. 10 was generated by swept frequency tone burst and spectral processing techniques. The spectral processing technique utilized here was selective imaging of the frequency band which includes defects at all depths. The defects appear dark and all other panel material a lighter shade of gray. Digital bandpass filtering of the 24-137 Hz frequency band of the FFT was selected. Defects shown in the 32-ply panel are similar to those in the 24-ply panel. Each row of defects is at a different depth and includes (from left to right) delaminations, ply cuts, and porosity. All defects were imaged in Fig. 10. Porosity (on the right side) and a ply drop, running across the middle of the panel, are clearly imaged in Fig. 10, but not visible in the non-modulated LLW image in Fig. 9.

Fig. 7. Image formed by digital bandpass filtering of the 110-160 Hz band of the Lamb wave mode spectrum. An example spectrum is shown in Fig. 3b. Defect-free areas of the panel appear darkest while all defect areas appear lighter in shade.
Fig. 8. Selective depth image formed by digital bandpass filtering of the 81-120 Hz band of the Lamb wave mode spectrum. An example spectrum is shown in Fig. 4b. Defect areas of the panel at layer 18 appear darkest while all other areas appear lighter in shade.

Fig. 9. Lamb wave image of a 32-ply panel generated by measuring the depth of a single null in a 4 MHz, constant frequency tone burst.
CONCLUSIONS

Swept frequency Lamb wave techniques have been shown to provide reliable detection of simulated delaminations, porosity and ply cuts in unidirectional laminates. Also, spectral processing techniques avoid the problems associated with tracking the amplitude of a specific null because the entire signal from several modes 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 proportional to depth. Finally, LLW techniques allow the use of low frequency unfocused transducers while providing good resolution and complete depth penetration.

Fig. 10. Image generated using swept frequency tone burst and spectral processing techniques to selectively image the frequency band which would include defects at all depths (24-137 Hz). Defects all appear dark and all other panel material a lighter shade of gray.

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