A HOMOMORPHIC DECONVOLUTION TECHNIQUE FOR IMPROVED ULTRASONIC IMAGING OF THIN COMPOSITE LAMINATES

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INTRODUCTION

Advanced composites, particularly high modulus laminates, are often susceptible to transverse impact loading. The major damage introduced due to low velocity impact includes matrix cracking, fiber break and delaminations. Such flaws tend to reduce residual strength of the material and may cause structural failure when the material is subjected to higher operating loads [1, 2]. Unfortunately, such a damage cannot be observed on the surface until failure; hence, structural integrity should be assessed by nondestructive evaluation (NDE) methods at the earliest possible stage.

Conventional ultrasonic pulse-echo C-scan methods have been widely used for detecting delaminations in composites. More recently, a three-dimensional imaging technique has been developed for full-volume evaluation of impact and other types of damage [3]. All of these methods use broadband ultrasonic signals analyzed in the time-domain using either gated peak detectors or digitized A-scan waveforms. The major drawback of these methods is that the pulse widths are significantly larger than lamina thickness. The resolution in the thickness direction is therefore inherently poor, resulting in potentially false and confusing B-scan images. It is particularly important to reduce the pulse width for imaging of defects in thin laminates.

ECHO DETECTION SCHEMES

Typically, delaminations in thin composite laminates are detectable by a focused immersion transducer operating in pulse-echo mode. Figure 1 shows a typical ultrasonic scanning system. Due to the mismatch of acoustic impedances, there are multiple signals reflected from the surfaces of the specimen as well as from delaminations in the material, as shown in Fig. 1. Typical waveforms recorded by an oscilloscope are shown in Fig. 2, where Figure 2(a) is an A-scan in an undamaged zone and Figs. 2(b) and 2(c) are the waveforms obtained from impact damaged regions of a graphite/epoxy laminate, respectively.

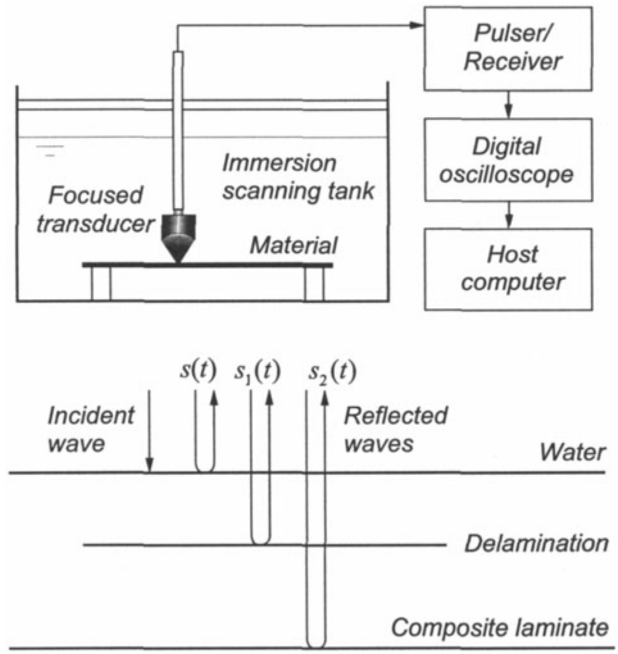

Figure 1. Experimental setup for immersion pulse-echo testing and a schematic of reflected echoes.

Time-Domain Processing

Ultrasonic B-scans are usually constructed from the time-of-flight measurements [4]. The first echo shown in Fig. 2(a) represents the front face reflection and the one that appears in the gate 2-3 is the backface reflection. Figures 2(b) and (c) show echoes reflected off of the delaminations; one located in the middle of the materials and the other that is closer to the front surface. Measuring the time-of-flights from the front surface and knowing the wavespeed of the material, one can determine the location of delamination from the surface in the thickness direction.

A wide variety of digital signal processing techniques are readily available for measuring time-of-flight. A useful echo detection technique is the Hilbert transform [5], which rectifies a signal and produces an envelope of echo trains. This technique is convenient, in that echoes do not have to be treated individually. Due to the bandwidth limitations of the transducer, the echoes often ring several times, resulting in a finite pulse width. As a result, interfaces in an Hilbert-transformed B-scan image generally appear as wide bands, rather than thin hairlines, causing poor image quality.

Wooh and Daniel [4] used digital windows to trace individual echoes for constructing better B-scan and three-dimensional images of impact damage in composites. This technique is, however, somewhat subjective on selecting windows and is sensitive to amplitude thresholds. Figure 3 shows the influence of threshold values on the image quality. Improper selection of threshold may result in faulty images, as shown in the figure.

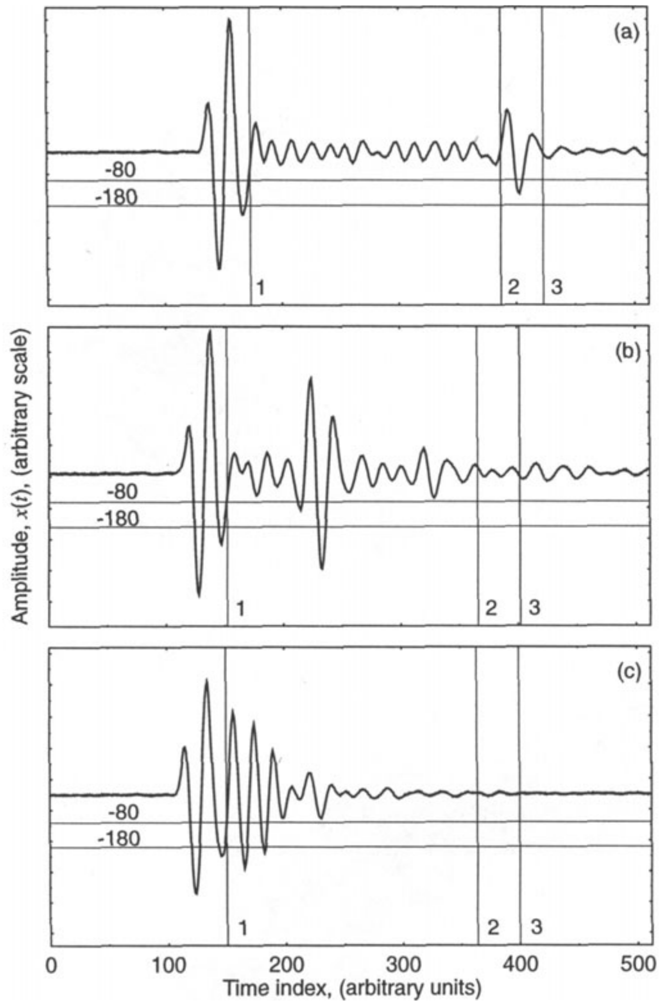

Figure 2. Typical A-scans and gate locations. (a) waveform in undamaged region, (b) and (c) waveforms in damaged region.

Cepstrum Techniques

The time-domain processing techniques can be confusing when the signals are distorted or the echoes are overlapped. Alternatively, the echoes can be detected in the frequency domain. Typical examples of measuring time-of-flight in the frequency domain include cross-correlation [6] and power cepstrum techniques [7]. These techniques can be used for relatively low signal-to-noise ratios and high echo distortion. We will discuss, in this paper, an homomorphic deconvolution technique for detecting echoes in thin laminates. In our approach, the resolution of the A- and B-scans was greatly improved by detecting the reflected echoes in the complex cepstrum domain using homomorphic deconvolution techniques.

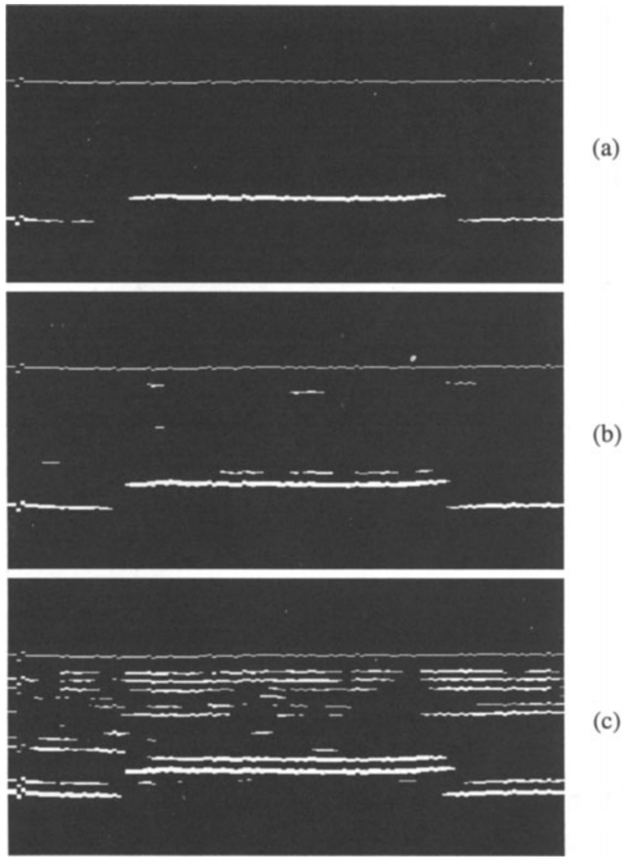

Figure 3. B-scan images of specimen with embedded film patch obtained with different threshold values.

Deconvolution

As discussed before, the return signals $x(t)$, in Fig. 2, show the wave train reflected from the surfaces and delaminations in the material. Assuming that the material is nondispersive, the front face reflection $s(t)$ can be expressed as the incident signal $s_0(t)$ retarded by the travel distance between the transducer and the front surface of the specimen, whose magnitude is multiplied by the reflection coefficient of the front face. The subsequent reflections $s_i(t)$ can be similarly expressed by taking the transmission and reflection coefficients at the interfaces and the time retardations into account. Since we do not know exact expression of the incident wave, these signals can be written in terms of the front surface reflection, i.e.,

$$s_i(t) = a_i s(t - \beta_i) \tag{1}$$

where a_i are the amplitude ratios of the reflected signals with respect to the front-face reflection and β_i is the time delay for the ith reflection measured from the front-face, and $\delta(t)$ is the delta function.

An A-scan can now be considered as a convolution of these echoes with respect to the front face reflection. Using proper amplitudes and phases, it can be written as

$$x(t) = s(t) + \sum_{i=1}^{N} a_i s(t - \beta_i) \tag{2}$$

or in a short form notation

$$x(t) = s(t) * h(t) \tag{3}$$

where $s(t)$ is the front face reflection and N is the number of subsequent reflections appearing in the entire waveform. The index 0 represents the front-face reflection such that $a_0 = 1$ and $\beta_0 = 0$. The response function $h(t)$ contains precise time-of-flight information of the reflected signals, delayed from the front surface, such that

$$h(t) = \sum_{i=0}^{N} a_i \delta(t - \beta_i). \tag{4}$$

This time domain signals can now be expressed in the frequency domain as

$$X(\omega) = S(\omega) H(\omega) \tag{5}$$

where $S(\omega)$ and $H(\omega)$ are the Fourier transforms of the signals $s(t)$ and $h(t)$, respectively. One can immediately deconvolve the signal by simply dividing $X(\omega)$ by $S(\omega)$ in the frequency domain and taking the inverse Fourier transformation. However, it requires an *a priori* knowledge of the input function $S(\omega)$. This approach is therefore not valid particularly when the delaminations are close to the surfaces or the echoes are overlapping.

Homomorphic Deconvolution

The core idea of homomorphic deconvolution is to convert the product $S(\omega)H(\omega)$ into a sum by applying a logarithmic function. The *complex cepstrum* is defined as the inverse Fourier transformation of the log-normalized Fourier transform of the input signal, which is reverted to the time or the *quefrency* domain [8,9]. According to the definition of the complex cepstrum, the return signal can be written in the transform domain as

$$X'(\omega) = S'(\omega) + H'(\omega) \tag{6}$$

where the prime notation is used to denote the log operation of the Fourier transformed signals $S(\omega)$ and $H(\omega)$. The corresponding complex cepstrum is then written as the sum of the cepstra for the front face reflection and the system response, as

$$y_x(q) = y_s(q) + y_h(q) \tag{7}$$

where q is the quefrency, which has the same units as time. The signals $y_s(q)$ and $y_h(q)$ represent the cepstra of the reference signal (i.e., front face reflection) and the system response, respectively. Note here that the front face reflection is oscillating at the frequency of the transducer and the response function contains the periodicity that is equivalent to the time delays between the echoes. In other words, the functions $y_s(q)$ and $y_h(q)$ are clearly separated in the quefrency axis, unless the echoes are very close together. That is, the system response function $y_h(q)$ is separable from the response of the front face reflection $y_s(q)$ in the transform domain by cutting off $y_s(q)$ at any quefrency between the responses. For a given transducer with known frequency response or the estimated layer thickness, it is relatively easy to find the cut-off quefrency.

After the cut-off, the system response $y_h(q)$ becomes equal to the transformation of the entire waveform $y_x(q)$, i.e., $y_h(q) = y_x(q)$. The response function $h(t)$ in eq. (4) can now be reconstructed from an inversion process by taking the Fourier transform of $y_h(q)$, applying an exponential operator to it, and taking inverse transformation of it. It is interesting to note that this scheme does not require an *a priori* information of the front face echo. A raw waveform can be processed straightforwardly by using the aforementioned procedure, followed by the cut-off and inversion processes. The only information that should be known in advance is the transducer response for determining the approximate cut-off quefrency. By comparison, conventional deconvolution requires the front wall information from the same waveform, which may not be possible in some cases.

EXPERIMENTAL RESULTS

The technique was experimentally verified for 8-ply and 16-ply quasi-isotropic graphite/epoxy laminates (AS4/3501-6, Hercules) with embedded Teflon film patches to simulate delaminations. Specimens with actual damage due to low-velocity impact were also investigated. An experimental scanning system shown in Fig. 1 was used for acquiring A-scan data and reconstructing the system responses. The ultrasonic pulse-echo signal $x(t)$ was acquired by a digital oscilloscope using a broadband focused immersion transducer (2.5 MHz center frequency).

The as-obtained waveforms and the deconvolved signals are given in Fig. 4. Figure 4(a) shows the original and reconstructed signals acquired at a position with no flaws, whereas Figures 4(b) and (c) show the signals for the specimens with embedded patches at different thickness locations. The time-of-flight information $h(t)$ was successfully extracted from the as-obtained signal $x(t)$ based on the homomorphic deconvolution algorithms described above.

Note the excellent resolution improvement of the deconvolved signals (signals in the bottom row) reconstructed from the raw A-scans (signals in the top row). The reflected waves in the A-scans appear as sharp peaks in the reconstructed signals. This is an excellent improvement over the other techniques for constructing B-scan images, since the interfaces now appear as sharp hairlines in the image.

Also note that the absolute locations of the peaks in the time axis exactly correspond to the time delays of the echoes measured from the front face. In other words, the algorithm

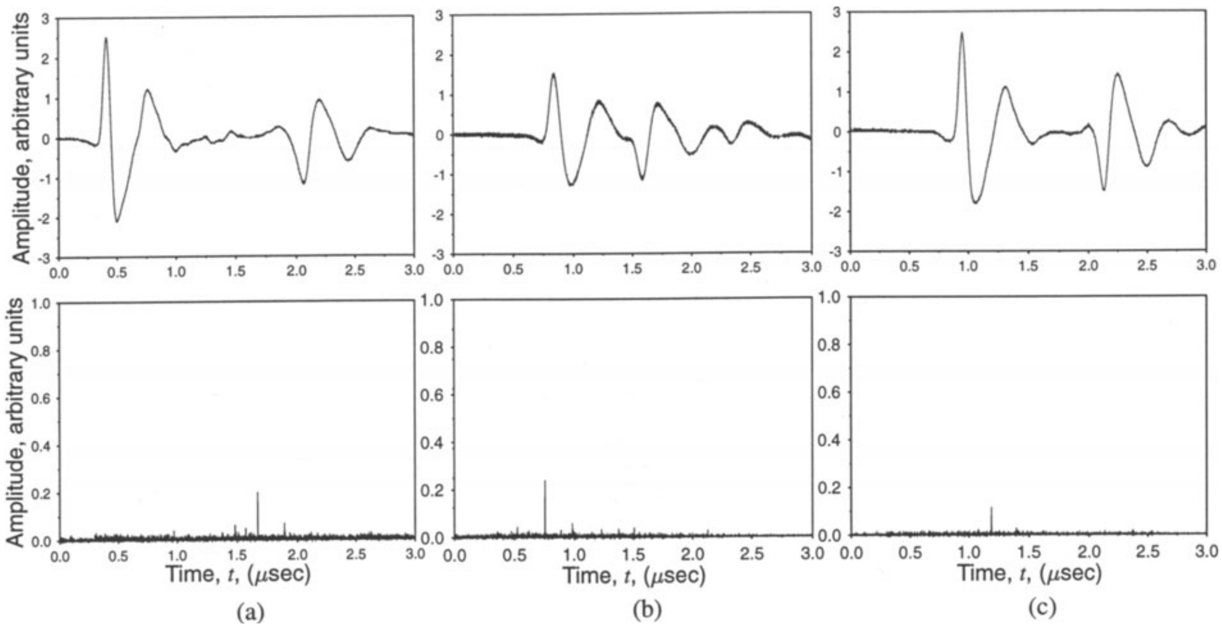

Figure 4. As-obtained waveforms and reconstructed signals after deconvolution for a 16-ply $[0/\pm45/90]_{2s}$ quasi-isotropic graphite/epoxy laminate with embedded Teflon film patches: (a) Area with no embedded patches, (b) Teflon patch embedded between the 6th and 7th layers, (c) Teflon patch embedded between the 12th and 13th layers.

can trace the front surface and map the front face location to the zero time, allowing automatic surface-follower mode. This is an advantage because the simple algorithm is self-adjusted to extract the time-of-flight information accurately even for inspecting slightly curved parts or irregular surfaces.

SUMMARY AND CONCLUSIONS

Detection of delamination in thin laminates is possible by processing the as-obtained signals in the complex cepstrum domain. The logarithmic operation allows the separation of the interface response from the system response in the quefrency domain. The response function is processed by an inverse complex cepstrum process followed by a cut-off of the surface response to obtain time-of-flight information.

The algorithm does not require an *a priori* knowledge of the surface characteristics or the response of the surface. For reasonably well-separated echoes, the cut-off frequency can be easily established from the transducer response, known in advance. The automatic surface-follower mode is another feature of the algorithm so that the technique can be used for measuring velocities in thin laminates as well. The influence of noise and the use of the technique for imaging should be studied in the future.

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