APPLICATION OF HIGH RESOLUTION INVERSION OF ULTRASONIC DATA
TO THE IMAGING OF MULTI-LAYERED COMPOSITE STRUCTURES

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INTRODUCTION

Ultrasonic imaging has evolved from its early application which utilized only amplitude C-scans to more complex techniques which make extensive use of digital signal processing. Techniques, such as one- and two-dimensional deconvolution processing and synthetic aperture focussing techniques (SAFT), are becoming more widely accepted for conventional applications. In general, each of these techniques aims to improve the interpretability of the ultrasonic image by increasing the resolution in one or more dimensions.

Resolution losses in the time dimension of ultrasonic images result from the superimposition of the transducer impulse response onto the true acoustic impulse response of the layered material.[1] The occurrence of multiple reflections further complicates the interpretation of an ultrasonic image. Several one-dimensional deconvolution algorithms have already been developed and applied to the problem of removing the transducer impulse response from the ultrasonic data.[1-3] These techniques have been shown to be useful for the interpretation of two-dimensional B- and C-scan images.[4] Deconvolution techniques provide only a partial solution, however, to the general inversion problem for discretely layered media, i.e. the formation of a structural model based on ultrasonic data. A complete inversion solution would estimate some material parameter, such as the acoustic impedance of each layer (or, equivalently, the reflection coefficient of each interface) as a function of pulse travel time.

This inversion problem has already been studied extensively for application to seismic signal processing and several possible inversion schemes have been proposed.[5-10] The current inversion techniques may be generally divided into two categories; "exact" methods[5,6] and "estimation" methods.[7-10] The "exact" methods provide the analytically exact solution, but require that the input data be totally broadband and noise free.[11] Neither of these two criteria are ever met in practical NDE applications, which encounter several noise sources and a bandlimited wavelet. Therefore, exact inversion techniques are seldom directly applicable to these problems. The so-called "estimation" techniques can be further classified into three categories:

(1) thresholding techniques;[7]
(2) maximum likelihood methods;[8]
(3) optimization methods.[9-10]

Each of the estimation techniques has some practical value, although all suffer from some practical limitations imposed by the nature of NDE ultrasonic data. For example, some are unable to accommodate the arbitrary wavelets generated during pulse-echo ultrasonic imaging,[11] while others are very sensitive to the amount of noise prevalent in most NDE ultrasonic data.

The first criterion for a practical inversion technique, therefore, is the ability to accommodate the mixed phase, band-limited wavelets that are generated by most ultrasonic transducers. Also, in order to be useful, an inversion algorithm should possess several other characteristics:

- the algorithm must be able to tolerate errors in the wavelet estimate and to withstand alterations in wavelet shape caused by propagation losses;
- the inversion result should be sufficiently accurate for imaging purposes;
- in the case of composite materials, the occurrence of near-surface defects produces overlapping echoes. Therefore, the algorithm should possess the ability to resolve closely spaced reflectors;
- the algorithm should be sufficiently fast to allow real time signal processing, i.e. to operate concurrently with the scanning operation, or, at least, with a minimum of computing time subsequent to data acquisition.

In order to meet the criteria listed above, the algorithm should make use of prior knowledge concerning the structure and the expected response for discretely layered media.[11,12] Recently, a high resolution inversion algorithm which employs an optimization approach has been proposed by Zala.[12,13] This algorithm also makes use of several features that have been used in other algorithms which are less successful for NDE applications, such as:

(1) layer stripping, used in exact surface calculation procedures;[5]
(2) stable estimation of reflection coefficients by deconvolution[13] and
(3) thresholding techniques used in other estimation techniques.[7]

This paper will first briefly describe this inversion algorithm and its application to the problem of impedance profile estimation using a titanium - graphite/epoxy specimen. Finally, the utility of high resolution inversion applied to the formation of C-scan images will be demonstrated.

![Figure 1](image_url)

Figure 1. (a) Calculated A-scan corresponding to Ti - Gr/Ep stepped lap joint.
(b) Detected A-scan corresponding to Figure 1(a).
FORWARD MODELLING OF NDE DATA

Prior to any further consideration of the inverse problem, it is first necessary to develop an adequate forward model for the 1-dimensional propagation of a normally incident plane wave through a layered medium. A derivation of the general problem of a plane wave at an arbitrary angle of incidence has been given by Brekhovskikh[14] and a particular solution for normal incidence has already been developed by Bube and Burridge.[6] This continuous model may be discretized using the convention of Goupillaud[15] which assumes a series of internal layers which are equally spaced in travel time and that the two-way travel time is equal to the discretization time step of the sampled data. The up- and down-going wave components may be given in terms of linear combinations of the reflection and transmission coefficients at each interface:

\[
\begin{align*}
    u^i_j &= R^i_d^j + T^i_j u_{j+1}^{i+1} \\
    d_{j+1}^{i+1} &= T^i_j d^i_j + R^i_j u_{j+1}^{i+1}
\end{align*}
\]

The forward model may be solved in a recursive manner using an even time-layer grid.[6]

In this study, a three-layer stepped lap joint consisting of a layer of Gr/Ep, a layer of titanium followed by a third layer of Gr/Ep was modelled. Figure 1(a) shows the detected reflection response (A-scan) obtained from a three layer specimen composed of a 0.443 cm thick plate of Ti-6Al-4V, bonded to two outer layers of AS-4/3601-6 Gr/Ep, each 0.471 cm thick. By direct application of this forward model and assuming the absence of attenuation in the material, it was observed that, as expected, the reflection amplitudes were consistently overestimated. Although some differences still occur, a reasonable correlation between the calculated (Figure 1(b)) and measured reflection responses was obtained by allowing for an attenuation coefficient of 1.9 Nepers/cm (the previously measured estimate of the attenuation coefficient at 5 MHz) in the Gr/Ep layers.

HIGH RESOLUTION INVERSION ALGORITHM

The high resolution inversion algorithm to be applied here combines components of three methods, any one of which is incapable of satisfying all of the criteria for a useful inversion technique.[13] The algorithm is fundamentally a layer stripping approach in which an estimate of the inverted trace is obtained by sequentially estimating each layer followed by the calculation of a residual trace. The effects of each layer are removed from the residual trace and the next layer is then estimated. This algorithm estimates the reflection coefficients by applying an L2 norm deconvolution within a limited region of the residual trace. In this way, potential interfaces are identified and may then be either accepted or rejected by thresholding. In the current model, potential reflection coefficients must pass two tests prior to acceptance. First, they must exceed a threshold level, as calculated in the technique given by Koltracht and Lancaster.[7] Also, the decrease in the sum of squares obtained by adding the new reflection coefficient to the model must exceed a second threshold. The first threshold has the effect of rejecting small reflections caused by noise or misfit. The second threshold suppresses the estimation of layers which do not significantly increase the fit to the trace.

In principle, any method for the identification of interface positions
and the measurement of the reflection amplitude could be applied, to the inversion algorithm given above. A particularly fast and accurate deconvolution algorithm has recently been described by Zala[13], based on the work of Powell.[16] This algorithm minimizes the following objective function by either addition, deletion, shifting or merging of spikes:

$$||t - Ws||_2^2 + Tol \times \text{ (number of nonzero spikes of } s)$$

where $W$ is a convolution matrix containing the wavelet such that:

$$W_{i,j} = w_{i-j+1}, \quad 1 < i-j+1 < k;$$
$$W_{i,j} = 0, \quad \text{otherwise.}$$

The algorithm is iterative and alters the spike series according to the following scheme:

1. Try to delete a spike from the current set; if successful, go to 1; otherwise,
2. Try to add a spike to the current set; if successful, go to 1; otherwise,
3. Try to shift a spike provided that one spike does not pass through the position of an existing spike; if successful, go to 1; otherwise,
4. Try to merge two adjacent spikes; if successful, go to 1; otherwise, exit.

**SPECIMEN AND DATA ACQUISITION SYSTEM**

In order to examine the application of this algorithm to realistic multi-layered bonded structures, pulse-echo ultrasonic data were first acquired from the Ti - Gr/Ep specimen shown in Figure 2. This specimen consists of a double-stepped wedge of Ti-6Al-4V bonded between two layers of AS-4/3501-6 graphite epoxy in a quasi-isotropic layup. In addition, four Teflon inserts (1.27 x 1.27 cm) have been added to the specimen in order to simulate disbonds and delaminations. This figure shows their lateral positions as well as their positions through the depth of the specimen. In order to more closely simulate actual flaws, the inserts were constructed so as to include a thin layer of air (low acoustic impedance).

![Figure 2. Schematic diagram of the stepped lap joint specimen and the positions of the simulated flaws.](image-url)
The data acquisition and signal processing system that was used to acquire all of the ultrasonic data is a slightly modified version of that described previously.\(^4\) A schematic diagram of this system is presented in Figure 3. In brief, all acquisition and processing functions, including the ultrasonic pulser/receiver and a 100 MHz A/D converter, are controlled by an IBM 80386 PC-compatible computer. Both the L2 norm deconvolution and the inversion signal processing may be performed using a TMS 320C30 digital signal processor which is capable of carrying out the complete inversion of ultrasonic traces (256 data elements per trace) at a rate of approximately 60 milliseconds per trace. It is possible, therefore, to perform the inversion processing in real time during the scanning operation. Optionally, all data may be acquired, stored and subsequently transferred to a larger computer for processing and display.

RESULTS OF HIGH RESOLUTION INVERSION

The ultrasonic trace acquired (1024 elements sampled at 100 MHz) from a bonded region of step level 2 is shown in Figure 4. The dotted line shows the calculated impedance profile. Starting at an initial value of relative impedance of 1.0 (relative to water, \(Z = 1.484 \text{ g/cm}^2\text{-sec}\)), the detected reflection indicates a layer with a relative impedance value of 2.70, which corresponds well with respect to the actual value of 2.87 for Gr/Ep. At the next interface, the calculated acoustic impedance rises to a value of 19.77 (actual value 18.78 for titanium) and then falls to a final value of 2.88, once again corresponding to Gr/Ep. In this case, multiple averaging of the data increases the signal-to-noise ratio, thereby allowing the detection of the second Ti-Gr/Ep interface. The back surface of the specimen (Gr/Ep - water interface) was not detected.

Figure 5 shows the result obtained for a simulated disbond (defect \#2, Figure 2). In this case, however, the relative impedance of the Gr/Ep layer is again accurately determined but then falls to near zero at the depth corresponding to the disbond. In this way, the occurrence of a near zero relative impedance can be used for the identification of disbonds.

Individual A-scans may then be used as the basis for the formation of reflection coefficient "C-scan images". First, data representing a three dimensional volume of the specimen is acquired from the region indicated by the shaded region of Figure 2. These data consist of individual A-scans (256 elements per trace sampled at a rate of 25 MHz) which were acquired.

![Figure 3. Schematic diagram of the data acquisition and signal processing system.](image-url)
at each point of a 256 x 256 element raster. Each A-scan was then processed using the inversion algorithm described above and the magnitudes and positions of the detected reflection coefficients were then calculated. A series of C-scan images were then generated by selecting narrow time gates corresponding to a time width of 0.4 microseconds and then increasing the gate delay through the depth of the specimen.

Figures 6(a) to 6(c) show three reflection coefficient C-scan images, each corresponding to specific time delays of 1.2, 1.6 and 2.0 microseconds. Because only the acoustic impedance, but not the velocity, of each layer may be estimated, it is not possible to calculate the depth at which each interface occurs. Figure 6(a) shows the interface of step 2 (Figure 2). As the reflection coefficient values increase from -1 to +1, the image grey scale goes from black to white. Therefore, most of the interface at this step can be interpreted as a reflection from a high impedance interface material (high positive reflection coefficient). The simulated disbond appears as a black region, indicating a reflection coefficient of -1 and, hence, a region of extremely low acoustic impedance. At the next time increment (Figure 6(b)), a portion of the step 2 interface is still visible as a light coloured region, with a
Figure 6. Reflection coefficient C-scans corresponding to mean time delays of:
(a) 1.20 microseconds,
(b) 1.60 microseconds,
(c) 2.00 microseconds.

CONCLUSIONS

This inversion algorithm represents a stable method for the estimation of reflection coefficients at each interface of a planar, layered medium, such as bonded structures. In general, the algorithm meets all of the criteria stated as necessary for successful application to nondestructive imaging. The algorithm is still dependent, however, upon the correct selection of convergence tolerances and thresholds.

The use of a priori information, such as the assumption of a small number of discrete layers in the structure, greatly simplifies the inversion problem to allow a more rapid solution.

An enhanced method for the identification of disbonds has been developed for the situation in which the bonded substrate has a high acoustic impedance. By imaging the estimated reflection coefficients, rather than the amplitude of the reflection, the polarity of each reflection is maintained.

REFERENCES


