AN INVERSION APPROACH TO ULTRASONIC IMAGING THROUGH
REFLECTIVE INTERFACES IN MULTI-LAYERED STRUCTURES

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INTRODUCTION

The increased use of composite materials and adhesively bonded joints has resulted in the need for the development of inspection techniques appropriate for multi-layered structures. Normal incidence ultrasonic pulse-echo imaging has been and continues to be a principal technique for the detection of interface condition. Ideally, only a single reflection from each interface in the layered structure would be received and the ultrasonic image would be based upon a single parameter intrinsic to the material, such as the reflection coefficient. The reflection coefficient is, in turn, primarily determined by the relative change in ultrasonic impedance across the interface. In the absence of a complete inversion procedure by which the reflection coefficient may be calculated from pulse echo-data, the reflected signal amplitude is used to form the ultrasonic image. Unfortunately, the reflection amplitude, as indicated in Figure 1(a), often decreases rapidly due to the presence of reflective, overlying interfaces.

If large impedance mismatches occur at the two bounding interfaces of a layer, most of the acoustic energy will tend to remain and reverberate within that layer of the structure (shown schematically in Figure 1(b)). In this event, the ultrasonic image will now be dominated by multiple reflections from the upper interfaces, thus obscuring the reflections from the lower interfaces.

An inspection problem of interest to the Canadian Forces is the development of a technique to detect scratches or grinder marks, should they exist, on the surface of a longeron (aluminum alloy) which has been strengthened by supporting strap (precipitation hardened stainless steel). Each strap is slightly contoured (thickness variation from 0.015" to 0.063") and fastened to the longeron with an intermediate adhesive sealant layer. The adhesive sealant layer thickness is variable and unknown. The required inspection technique should be capable of detecting scratches in the range of 0.005" to 0.010" in depth.
The difficulty of this particular inspection is illustrated schematically in Figure 2(a). Ultrasonic energy that enters the structure is strongly reflected by both the stainless steel - sealant interface and by the stainless steel - water interface, thereby producing a sequence of multiple reflections within the upper steel layer. Due to the reflectivity of the stainless steel - sealant interface, very little energy is transmitted through the sealant and subsequently reflected from the sealant - longeron interface. In addition, the sealant itself is highly attenuating, further reducing the total reflected energy signal from the longeron surface. Figure 2(b) shows a typical pulse-echo A-scan from this structure using a 5 MHz transducer. This A-scan verifies that the data are dominated by the reflection from the steel - sealant interface and subsequent multiples. It was necessary to eliminate the front surface reflection from these data in order to gain sufficient dynamic range for imaging purposes. Reflections from the lower sealant - longeron interface are not readily detectable.

**SPECIMEN AND DATA ACQUISITION**

A specimen was manufactured in order to simulate the structure to be inspected. A series of grooves were machined into the surface of an aluminum plate at depths of 0.005", 0.007" and 0.010", as illustrated in Figure 3(a). For each specific depth, a series of four grooves were machined with widths of 0.009", 0.020", 0.063" and 0.094". In order to simulate the presence of the steel strap, a small piece of 0.060" AISI 316 stainless steel was then bonded to the surface of the aluminum plate with adhesive sealant. No attempt was made to control the thickness of the
Ultrasonic data were obtained by scanning the region noted above using a focused 5 MHz immersion transducer in pulse-echo mode. Individual A-scans were acquired at each point of a 256 x 256 raster. Each A-scan consisted of 256 elements, sampled at a frequency of 100 MHz and with 8-bit resolution. In this way, a three dimensional array of data which corresponds to the three dimensional volume of the specimen is obtained. As shown in Figure 4, B-scan images may be formed by selecting portions of the array corresponding to the X-Z plane. Similarly, a series of C-scan images through the depth of the specimen may be determined by selecting a sequential series of narrow time gates (Z axis) and calculating the maximum absolute value within those gates in the X-Y plane.

Figure 5(a) shows a B-scan image obtained from the raw data, prior to any processing. The image is totally dominated by the multiple reflections that occur within the upper stainless steel layer (strap material). Reflections from the lower sealant-longeron interface are not detected. The corresponding C-scan image (Figure 5(b)) also shows virtually no indication of the simulated "scratches" in this specimen. The feature visible at the bottom of Figure 5(b) corresponds to the edge of the machined plate.

Figure 4. (a) Three dimensional data array showing B-scan generation (b) Generation of C-scan image with narrow time gate
RESIDUAL CALCULATION BY REFERENCE SUBTRACTION

Clearly, it is necessary to eliminate the reflection response of the reverberant upper layer in order to obtain sufficient information to image the lower sealant-longeron interface. One potential method is to simply subtract the pulse-echo ultrasonic response of the reverberant upper layer from the corresponding response of the complete multi-layered system [1,2]. In the case of a constant layer thickness (as in this example), an averaged A-scan obtained from the pulse-echo response of the upper stainless steel layer, backed with sealant, is used as a reference. In principle, the residual A-scan which results from this simple subtraction technique should contain only the reflection from the sealant-longeron interface.

In order to illustrate this method, averaged A-scans were obtained from the stainless steel strap (Figure 6(a)) and from the multi-layered structure (Figure 6(b)). Note that in order to obtain sufficient dynamic range in the residual A-scan, it was necessary to increase the amplifier gain until the back surface reflection filled the entire 8-bit range of the A/D converter. The residual A-scan obtained by simple subtraction of Figure 6(a) from Figure 6(b) is shown in Figure 6(c). It is seen that this residual response has mainly eliminated the reflections from the front and back surface of the upper stainless steel layer. A series of reverberating echoes due to the multiple reflections within the sealant bondline now persists. Reference subtraction is quite unstable, however, due to minor thickness changes in the upper layer and to minor misalignment of the two
Figure 6(c) Residual A-scan remaining after subtraction of Fig. 6(a) from Fig. 6(b)

traces. Note the different amplitude scales for Figures 6(a) and 6(b) and Figure 6(c).

A similar reference A-scan was then obtained and subtracted from the three dimensional data set described above. Following reference subtraction, B- and C-scan images were then formed in an identical manner to that used to obtain Figures 5(a) and 5(b). Although the B-scan (Figure 7(a)) is very noisy due to the unstable subtraction procedure, there also exists a clear indication of a series of reflections within the sealant layer. The corresponding C-scan following reference subtraction (Figure 7(b)) also exhibits very low S/N ratio, but several of the simulated scratches are now clearly visible in this image. The smallest "scratch" which can be detected from this image is 0.007" deep and 0.020" wide. In practice, however, the longeron straps are not a constant thickness; therefore, reference subtraction is not a viable technique for this inspection procedure. It will be necessary to provide some alternative technique for the elimination of the multiple reflections within the upper layer.

MULTIPLE ELIMINATION BY INVERSION

One approach to the problem of elimination of multiple reflections from the ultrasonic image would be to perform a complete inversion of the ultrasonic data, i.e. to calculate either the impedance profile or, equivalently, the reflection coefficients of the individual interfaces. Recently, an efficient inversion algorithm based on the combined application of a layer stripping approach and L2 norm deconvolution has
been developed [3,4]. This algorithm has been described elsewhere [3] and will not be presented in detail here. In brief, however, a residual trace is iteratively computed by first identifying potential reflection coefficients, updating a forward modelled trace and calculating the residual. Potential reflection coefficients are identified by high resolution L2 norm deconvolution applied within limited regions of the data trace and tested against a noise-rejection threshold of the type described by Koltracht and Lancaster [5]. Successful reflection coefficients are used to update the forward model. Iteration continues until the sum of squares of the residual reaches a specified limit or the end of the trace is reached.

A limitation of this algorithm is that it requires all reflections to be included in the A-scan, including the large front surface reflection. Because the data acquisition system is restricted to 8-bit resolution, there is insufficient dynamic range to allow sufficient resolution for the reliable detection of the sealant-longeron interface. Although this algorithm has provided accurate and reliable inversion results for less reflective interfaces, no usable result was obtained from the application of this inversion algorithm.

RESIDUAL CALCULATION BY OPTIMIZATION

Because simple reference subtraction is not feasible in the case of a variable thickness layer and the complete inversion procedure suffers from inadequate dynamic range, the possibility of developing an alternative approach based on forward modelling was investigated. In this approach, a model trace is generated for each trace in the data set. It is assumed that the material may be modelled as a number of layers of approximately known acoustic impedances, attenuations and thicknesses. Using an optimization algorithm [6], the impedances and thicknesses of the layers are then adjusted to give the best least-squares fit of the model trace to the measured trace. This approach has been described by Zala and McRae [7].

The model trace is parametrized in terms of (continuously variable) impedances $z_j$, $j=1,M$ and (discrete) thicknesses $h_j$, $j=1,M-1$, where $M$ is the number of layers. Given an initial estimate for $z$ and $h$, and fixed values for the attenuations in the first $M-1$ layers, the algorithm optimizes the fit to the measured trace, i.e. it optimizes:

$$
\sum_{n=N_1}^{N_2} [d_n - t_n(z,h)]^2
$$

where $d$ is the measured trace, $t$ is the model trace and $N_1$ and $N_2$ define the region of the trace to be used in the computation of the objective function. Upper and lower bounds on the impedances may also be specified for each layer.

Briefly, the algorithm proceeds in a series of stages, as follows. Given the initial estimate for the thicknesses, the impedances of all the layers are optimized subject to the bounds constraints. Then the thicknesses of the individual layers are sequentially incremented and decremented one unit at a time, with an optimization being performed at each set of thicknesses. The cycle of layer thickness adjustment continues until no adjustment can be made which results in a further decrease in the norm of the residuals. By this sequence of events, the optimal thicknesses and impedances of the layers are found.
The time window for the trace was set to begin after the decay of the front surface reflection and included the back surface reflection and four multiple reflections. Traces were acquired using high gain, under which conditions a low frequency artifact was present. Consequently, the traces were high pass filtered before analysis. The wavelet used for the forward modelling was also pre-processed using the same high-pass filter.

Two possible approaches to the application of this strategy to the current imaging application were investigated. In the first, the model was parametrized in terms of three layers: water, steel and epoxy. The modelling procedure was applied to each trace in the data set, and the residual traces were computed and displayed. In the second, a four layer model was used, where the fourth layer was aluminum. In this case, the reflection coefficients corresponding to the optimized model were computed as a function of time; these reflection series constituted the output "trace" to be displayed.

Although the latter approach to the inversion problem proved to be more successful than high resolution inversion described previously, it was still not possible to obtain an accurate estimate of the sealant-longeron reflection coefficient. A typical inversion result using this approach is shown in Figure 8. Attempts to form ultrasonic images from these data were not successful.

![Figure 8](image_url)

(a) Unprocessed A-scan with front surface reflection eliminated (b) Result of inversion using optimization method of parameter estimation.

![Figure 9](image_url)

Figure 9. C-scan obtained from residual data remaining after inversion by optimization using a three-layer model.
In the former case, however, the ultrasonic C-scan image that results from the image formation from the residual data (Figure 9(a)) does show some of the larger machined grooves on the surface of the aluminum plate. The image quality is similar to that obtained by straightforward reference subtraction (Figure 7(b)). Again the smallest groove to be reliably detected is 0.007" deep by 0.020" wide.

CONCLUSIONS

A marked improvement in image quality was obtained if the ultrasonic C-scan image was formed from the residual data remaining after the elimination of the response of the reverberant upper layer. In the case of a constant thickness layer, this residual could be calculated by a simple reference subtraction, for which the reference represented the pulse-echo response of the upper layers. For a variable thickness layer, it was possible to estimate this residual with only limited a priori information using the optimization procedure described above. However, these residual based techniques did not provide truly satisfactory detection of the simulated "scratches" on the surface of the longeron test specimen because of the limited dynamic range of the A/D converter and the resulting low SNR of the residuals. An increase of the dynamic range of the data would be required to improve the success of these techniques.

REFERENCES