EFFECTS OF DECONVOLUTION PROCEDURES ON SIZE ESTIMATES IN THE
BORN INVERSION ALGORITHM

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INTRODUCTION

A great deal of research aimed at the development of quantitative ultrasonic flaw characterization methods has been pursued under Department of Defense sponsorship over the past several years. Since some of these methods are being considered for eventual application, we have undertaken an assessment of one aspect of these methods, concentrating our efforts in an area which has not been subject to much study.

In this paper we report the results of an investigation of the effects of different types of deconvolution procedures on the one-dimensional Born inversion algorithm. In addition, we will show the effect of errors generated in the deconvolution process on the calculated characteristic function which provides the size information in this algorithm.

DECONVOLUTION METHODS

The deconvolution technique incorporated in the Born algorithm assumes that the measured signal from the flaw, \( y(t) \) is a convolution of the overall system response, \( h(t) \), and the flaw response, \( s(t) \), or

\[
y(t) = h(t) * s(t),
\]

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where h(t) is obtained by recording a reference waveform from a planar reflector. The measured signals y(t) and h(t) are transformed into the frequency domain and the flaw spectral response is calculated from

$$S(\omega) = \frac{Y(\omega)H^*(\omega)}{|H(\omega)|^2},$$

(2)

where $H^*(\omega)$ is the complex conjugate of $H(\omega)$. In order to avoid computation of $S(\omega)$ when $H(\omega)$ is zero or both $Y(\omega)$ and $H(\omega)$ are small, $S(\omega)$ is set to zero when $|H(\omega)|$ is less than a predetermined amount (typically 10%) of its maximum amplitude. This type of processing is known as constrained deconvolution or Wiener filtering.³

Alternative deconvolution methods have also been investigated. The first is also a frequency domain method known as cepstral deconvolution.⁴ The details are reported in an earlier paper in these proceedings.⁵ The second method is a time domain deconvolution method which fits both the flaw and reference waveforms with spline functions and then solves the convolution equation directly for the flaw response.⁶ These two additional methods have special features which might make them equal to or superior to Wiener deconvolution for sizing purposes. The cepstral deconvolution technique is known to produce its most accurate reconstruction of the flaw response in the absence of noise when the flaw response and system response occupy different regions of the cepstral domain. Many flaws will produce responses which meet these conditions. The time-domain deconvolution method was considered because it provides a test to determine the optimum trade-off between resolution and sensitivity to noise.⁷

DECONVOLUTION RESULTS USING SYNTHETIC DATA

In order to begin with a fairly realistic case, the simulated impulse response from a void-like scatterer was convolved with an actual transducer response to produce the synthetic flaw data. The three signals are shown in Figure 1. Note that the amplitude of the back surface (creep wave) signal was set to 60% of the front surface amplitude in order to approximate an actual void.

The results of the deconvolution in the no-noise case using the three methods are presented in Figure 2. From the figure one can observe that the Wiener and cepstral deconvolutions reproduce the amplitudes of the two impulses rather accurately, while the spline method yields a second peak with an amplitude of 50% of the front surface signal. Only the cepstral method comes close to reproducing the negative plateau region between the two impulses. This is due to the bandwidth-limiting features of the other
We then added coherent noise signals having mean RMS amplitude 10dB, 6dB and 3dB down to the flaw signal. The resulting waveforms and their deconvolutions are shown in Figure 3 for the 3dB case. We found that the sidelobes grew progressively worse with increasing noise level and the accuracy of the relative amplitude varied erratically. Table 1 summarizes the results obtained using the three deconvolution methods for the relative amplitude of the second peak compared to that of the first peak as a percentage difference from the actual ratio. Note that the amplitude recovery is rather erratic for the good signals and degrades rapidly as the noise level increases. In all cases, accuracy of the time difference recovery is primarily determined by the sampling and degree of smoothing. Exact recovery was obtained with the cepstral processing since the input impulses were exactly 12 sample intervals apart and the method does no smoothing. The spline and the Wiener processing results yielded intervals which were 1 and 3 sample intervals larger, respectively than the input data in 3 out of 4 cases and 1 additional interval larger in the fourth case. This is due to the smoothing and the ±1 sample uncertainty in peak location.
Table I  Percentage difference between recovered ratio and input amplitude ratios

<table>
<thead>
<tr>
<th>DECONVOLUTION METHOD</th>
<th>S/N Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>NO NOISE</td>
<td></td>
</tr>
<tr>
<td>10dB</td>
<td></td>
</tr>
<tr>
<td>6dB</td>
<td></td>
</tr>
<tr>
<td>3dB</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>NO</th>
<th>10dB</th>
<th>6dB</th>
<th>3dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>spline</td>
<td>-15</td>
<td>0</td>
<td>+48</td>
<td>+18</td>
</tr>
<tr>
<td>Wiener</td>
<td>+7</td>
<td>+10</td>
<td>-17</td>
<td>+27</td>
</tr>
<tr>
<td>cepstral</td>
<td>-3</td>
<td>-3</td>
<td>-22</td>
<td>-30</td>
</tr>
</tbody>
</table>

BORN INVERSION CHARACTERISTIC FUNCTIONS - SYNTHETIC DATA

Figures 4 and 5 show typical results for the Born inversion characteristic function, (CF). For the no-noise case, Figure 4, the CF using the synthetic impulse response shows the expected rectangular shape with small ripples on it due to the truncation of high frequencies. The convolution of the synthetic response with the transducer response narrows the effective bandwidth, rounding the CF. This effect can be seen for the cepstral deconvolution which does no smoothing. Thus, the CF obtained in the cepstral case is closest to the ideal and the resulting size estimate agrees with the input data. Both the Wiener and spline methods smooth the data considerably, reducing the effective bandwidth and also rounding the CF accordingly. This results in estimates low by 10% and 13%, respectively.

As the noise level increases, the amplitude accuracy of the recovered impulse response varies, as does the size and distribution of artifacts in the response. Figure 5 shows the CF for 3dB input signal-to-noise ratio. The fact that both the amplitude and sidelobes associated with the impulse response are varying make it difficult to isolate the cause of the variation in the accuracy of the size estimate. However, the overall effect is to decrease its accuracy. The resulting estimates are shown in Figure 6, where the percentage error is plotted as a function of signal-to-noise ratio. The cepstral processing produces the best CF for high signal-to-noise ratios, but it is very susceptible to noise. In addition, for the 3dB case, it is very difficult to decide which of the apparent impulses in the deconvolved response are genuine and should be used for sizing. We note here that size estimates based on the time separation of the impulses are accurate for all noise levels in the cepstral case when the impulses are identified correctly. For the spline and Wiener cases, the size estimate would be larger by 8 and 25% respectively.
Fig. 3. Deconvolution results: 3dB S/N ratio; W, Wiener; T, spline; C, cepstral

Fig. 4. Characteristic functions for the impulse response shown in Figures 1 and 2

Fig. 5. Characteristic functions for the impulse responses shown in Figure 5

Fig. 6. Size estimates obtained from the synthetic data relative to the actual (R₀) as a function of S/N ratio
RESULTS FROM AN 800um VOID IN Ti

In order to complement the synthetic data results, we also looked at an 800um spherical void embedded in a titanium specimen. Two different beam angles were used, and the relative location of the flaw with respect to the axis of the ultrasonic beam was also varied. Figures 7 and 8 show the data and the results using the spline deconvolution. The first two signals and the resulting deconvolutions are also similar. The principal difference is that the first one has a single artifact between the front surface impulse and the creeping wave due to the bond line, which was not totally eliminated during production of the specimen. The second shows two artifacts, again probably due to the bond line. The third signal is rather different since the creep wave signal was maximized. The resulting deconvolution shows the correct time difference between the two impulses, but the amplitudes are very different.

The characteristic functions obtained from the data in Figure 7 are given in Figure 9. Only the result from the second signal bears any resemblance to the ideal. The CF generated from the first signal begins below zero instead of at 1 as it would in the ideal case, perhaps due to the bond line signal. The third signal yields a grossly different CF as can be seen in the Figure. The size estimates obtained from the characteristic function deviate by +20%, +23% and -47% from the actual flaw size. We may contrast these results with an estimate obtained directly from the time separation of the deconvolved impulse train using the a priori information that there is a bond line artifact which can be identified and ignored. In that case a creep-wave model of the flaw signal gives an estimate 7% below the actual radius, where the uncertainty due to the sampling is ±4%. We have found this estimate to be independent of the type of deconvolution procedure.

CONCLUSIONS

Our results suggest that one way to preserve both the amplitude and time interval accuracy during deconvolution is by using the noise-sensitive cepstral processing. Both the Wiener filter and spline methods limit signal bandwidth to suppress out-of-band noise and therefore do not preserve relative amplitudes of the time-domain impulse train and produce systematic errors in the time interval. Ambiguity in identifying the impulse train was present in the noisiest signals, particularly when processed by cepstral deconvolution.

The bandlimiting tends to produce systematic errors which should diminish in severity as the flaw size increases for constant sampling intervals and processing parameters.
Fig. 7. Signals from an 800μm void in Ti for two different beam angles (signals 1 and 2) and a lateral shift of the ultrasonic beam (Signal 3).

Fig. 8. Time-Domain impulse responses obtained from the signals in Figure 7. f, front surface; c, creep wave.

Fig. 9. Characteristic functions for the three signals shown in Figure 7.
Unfortunately, the sensitivity to artifacts can lead to substantial errors both in the case of the Born inversion algorithm and the time-domain interval determination. For the 800μm flaw, we had adequate a priori information to correctly identify the impulses. For real internal defects, this would not be the case. For single beam angle analytical flaw sizing methods considered here, the difficulty in identifying flaw indications in a cluttered environment is the primary impediment to their successful application. It may be possible to overcome this difficulty by the use of multiple beam angles and modes of propagation for those cases permitted by the part geometry.

REFERENCES

5. P.K. Bhagat and K.D. Shimmin, Homomorphic Processing in Ultrasonic NDE, These Proceedings.

DISCUSSION

D.O. Thompson (Ames Laboratory): In looking at some of these inclusions in lucite blocks and other materials, Dave Hsu reported a rather extensive amount of ringing, internal resonance, that emanated from the inclusion itself; it would get excited and ring out.

T.J. Moran: Well, that's a standard property conclusion.

D.O. Thompson: That's right, but they seem to radiate in different directions consistent with your finding that if you look at different directions, you get different amounts of radiation coming back from this ring-out.
T.J. Moran: The point I was trying to make is you get this spreading of the so-called impulse responses of these things--this is before there's a ring-out. The reverberation comes afterwards. You get a lot of reverberation. I windowed those things so that I only saw, say, the first couple rings coming out.

D.O. Thompson: Can you say you are not in the ring-down mode there?

T.J. Moran: There's ring-down through the transducer but nominally, you are taking that out.

D.O. Thompson: But I meant from the inclusion itself ringing?

T.J. Moran: Well, a ring-down has to come from multi-bad inclusion, right? By knowing exactly what I was looking at, I could get the right size of that impulse response.

D.K. Hsu (Colorado State University): Yes, I'd like to comment on that. I think the difference here is the inclusions I put in are spherical so you get S to the zero mode and so on, and those are highly interrupted. Now the inclusions you have are much more irregularly shaped, so I don't really think that that sort of thing will appear very strongly.

T.J. Moran: Yes, I don't think so, either.

J.H. Rose (Ames Laboratory): I'd like to comment on the use of the 50 percent point for the estimate. Bruce Thompson and I have looked at using that to estimate the areas, the integrated area divided by the max, a program that we had a couple of years ago. And I solved the case where I can do it entirely analytically except for a simple function and estimated the accuracy both to the 50 percent and for the area function and for that simple case, the 50 percent point seemed to be almost an order of magnitude of less error. The 50 percent point was the right thing.

From the Floor: Can you comment on the type of the noise you used, Gaussian or whatever?

P.K. Bhagat: Coherent noise.

T.J. Moran: That coherent noise also can be produced by the flaw itself, as I was showing in that last slide, because you really expect just a single signal coming off that front surface, and we are getting more than one delayed in time because of irregularities, unless you are picking up additional signals, which could be looked at in terms of noise if you are just trying to pick out the extreme signals.