Digital Measurements of Scattering from Spheroids and Flat Bottom Holes

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Abstract
I would like to discuss some of the problems and successes related to using computerized signal processing to characterize internal flaws in materials. The work reported on will be limited to the flawed specimens provided by Rockwell International which consist of flat bottom holes and spheroidal voids.

In this presentation I will first discuss the signal processing system that was prepared to perform this study and will identify some of the measurements that can be rather routinely made with the system. Also, I will describe our attempts to obtain rf and frequency spectral signatures of the various flaws that we have analyzed, and finally, I will discuss a data format that is more convenient for comparison with theoretical calculations.

Disciplines
Materials Science and Engineering | Structures and Materials
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Figure 1 shows the equipment that was prepared for this work. Either of two digital computers may be used. One is a PDP 11/45 with a 20K memory and the other is a HP 2100 with a 16K memory. These computers control a complete signal processing system so that under computer control (1) it is possible to position and scan the transducer over a specimen containing a flaw and to digitize the reflected rf signal; (2) it is possible to gate any portion of the rf signal and analyze the gated portion for display on the spectrum analyzer; and (3) it is also possible to display the rf signal on a Tektronix scope and then, by viewing it in the delay mode, select the portion of interest, display that on a scanning scope, expand the time scale and then digitize the selected portion.

The computer is used to generate a digital number, convert it to an analog voltage which drives the x input to where we wish to measure the signal amplitude. Then, through an analog to digital converter, the signal amplitude is stored in the computer memory for digital analysis. Using the HP 2100 system we are able to digitize a waveform in 256 discrete positions that are equally spaced in time. (On the PDP 11/45 we can record up to 1024 digital points.) Once the data are read into the computer, there are several tricks that can be used to process the data and then display the output either on a digital plotter, an x-y display unit, or a Tektronix display scope. A hard copy of the data displayed can be made.

Figure 2 is an example of the kind of data that we can obtain under computer control with the scanning system. We used four satellite transducers located around the main pulser receiver transducer, and balanced the arrival time of the transmitted signal in order to keep the transmitting transducer normal to the surface. An alternate approach is to keep the transducer normal to the surface to adjust for the maximum echo amplitude received in the transmitting transducer. Figure 3 gives examples of C-scans of some of the specimens provided by Rockwell. They contain flat bottom holes. The size resolution of the flat bottom holes is limited by the size of the transmitting transducer. To obtain a C-scan where the pattern size would relate to the size of the hole, one would have to collimate the transmitting transducer.

* Research sponsored by ARPA/AFHIL Center for Advanced IDE
Fig. 1. Equipment Used for RISC Signal Processing
Fig. 2. Computer Controlled Scans of RISC Blank Specimens
Fig. 3. Isometric Projection of Pulse Echo from a .08 cm diameter Flat Bottomed Hole in Aluminum Specimen E(1-8-24/19)
As the transducer is scanned across the specimen, it is possible to gate between the front surface reflection and the back surface reflection. Any amplitude that appears within that gate can be stored on a disk pack for later analysis, if desired. We can automatically scan a specimen. In Fig. 3 we show three passes over the area where echoes were received from the flat bottom hole. The computer can display an isometric projection of these transverses. (These profiles are the kind of indicia that Dr. Packman discussed in his paper). In Fig. 3 we have shown maximum amplitude echoes. It is possible to return to some position where we observed a signal of interest and then digitize the rf wave form into the computer and actually signal process it, say by Fourier spectrum analysis techniques. When a signal is displayed on the Tektronix oscilloscope, it may look something like that shown in Fig. 4. Operating in the delay mode the computer can position the transducer over to some area of interest, display any rf portion on the Hewlett Packard scanning scope, increase the gain of the signal, and then Fourier transform the signal portion.

We prepared a computer software algorithm to analytically solve the Fourier integral shown in Fig. 4: (1) the value of the integral from minus infinity up to the beginning of the rf wave form was set equal to 0; (2) the integral was integrated stepwise to the end of the rf signal; and (3) the integral was set equal to 0 from the end of the rf signal to positive infinity. By this procedure, we’re not bothered by generating the transform of information that is repeated in an interval. Such sampling interval noise is sometimes present in fast Fourier transforms. Our method for evaluating the Fourier integral is to curve fit the RF with some functional interpolation fit that can be substituted into the Fourier integral and integrated in closed form over each sampling interval. So, it’s just a stepwise procedure to accumulate the Fourier integral.

Figure 5 is an example of a gated portion of an rf signal that is Fourier transformed with a spectrum analyzer as well as by the stepwise procedure described above. The frequency spectrum is shown in Fig. 5 along with the power spectrum obtained with the software program. The frequency range is from 0 to 17 MHz. One can see that all of the dominant features of the spectrum analyzer transform are present in the analytic transform. The advantage of the analytic transform is that one can expand any frequency range of interest and look at the shape of a resonance in great detail. Figure 6 shows another example of a transform of an rf signal. The rf is a pulse echo from a 5 mil thick oil filled gap in aluminum. Figure 6 also shows the spectrum analyzer transform. The analytic Fourier transform is computed from 0 out to 30 MHz. A 5 MHz transducer was used. One can see the same dominant features in both transforms but much more detailed is present in the analytic transform.

A little trick for displaying the data gets a lot more information in a smaller space. If one computes the Fourier transform of the square wave, you notice that 1/2 appears in the transform. If you multiply each computer power by \( \omega \) the procedure flattens out the power spectra and makes it possible to compress the vertical scale over fewer log cycles.

Another special capability that we built into the signal processor is that of gating the gain. For example, Fig. 7 shows the top surface reflection
COMPUTE: \[ P(\omega) = \frac{1}{2\pi} \left| \int_{-\infty}^{\infty} F(t) e^{-i\omega t} \, dt \right|^2 \]

**Fig. 4.** RF Display and Segment Isolation for Fourier Power Transforms
Fig. 5. Waveform, RF Power Spectrum, and Analytic Transform
Fig. 6. Second Example of RF Waveform, Power Spectrum Obtained with Spectrum Analyzer and Analytic Power Transformer to 30 MHz
Fig. 7. Examples are given of Information Enhancement by introducing an Artificial Gain to Overcome Attenuation
from a specimen that has a flaw located somewhere inside. The medium is very
atenuating, as can be seen by the reduced amplitude of the flaw and the back
surface echoes. If the rf signal is Fourier transformed, the transform appears
as shown in Fig. 7. The spectra in Fig. 7 are normalized transforms. Normalizing
transforms will be discussed later. The spacing between the resonance dips
in the right hand spectra, corresponds to the depth of the flaw under the top
surface. If we're interested in the thickness of the specimen, we have to
gate out the flaw echo signal and increase the gain of the back surface
reflection. The spacing between the resonance dips is related to the thickness
of the specimen by the relationship that the velocity of sound divided by twice
the thickness of the specimen is equal to the frequency spacing.

Since the rf signal is stored in the computer, it can be analyzed in many
ways. We can isolate the flaw signal, expand it, and Fourier transform it,
obtaining the power transform shown on the bottom right hand side of Fig. 7.
That transform should contain information on the flaw that reflected the signal
if we can find a means of extracting such information from it. This signal
processing system provides a means to examine several transmitter transducers
and select a suitable transducer for the Rockwell International Science Center
study.

The top two curves in Fig. 8 show the rf output from a 5 MHz transducer
critically damped, and the frequency spectra that we obtained from it. The
maximum intensity is somewhere around 5 MHz and drops off with quite a bit of
noise in the region above 10 MHz. The middle curves in Fig. 8 show rf output
from a 10 MHz transducer as well as the resulting power spectrum. The power
spectrum is shifted toward the 10 MHz region, but extends a little bit
beyond. The bottom curves in Fig. 8 show the output from a panametics 15 MHz
transducer. This 15 MHz transducer provides a broadband source that is useful
for spectral analysis work, 2 MHz up to nearly 30 MHz.

Figure 9 shows one of the parameters that we are concerned with in
characterizing internal flaws. It is the water path effect. Figure 9 shows
rf and power spectra for three different water path distances of 0.7 cm, 2.2 cm
and 4.4 cm. These data show that when a transducer is close to the reflecting
surface, the frequency spectrum is in general broader than when it is moved away.
If the transducer is moved away to roughly 4 cm from the top surface of the
specimen, the frequency band width is narrowed.

Another important factor is the surface roughness effect. We obtained
some surface roughness standards and studied the effects of RMS roughness
upon the reflected source spectra. When reflected from a smooth surface
(Fig. 10), the frequency spectrum is broad out to nearly 30 MHz, but as the
surface roughness is increased the reflected wave form gets more and more
disturbed in shape until we observe interference patterns in the frequency
spectra, which would be very hard to analyze.

A very useful computational procedure that can be performed on the computer
is source normalization. If one has a source spectrum like the one shown
in Fig. 11c and is interested in making a thickness measurement, then the rf
Fig. 8. A Comparison of RF and Power Spectrum of Candidate Transducers for Use in the RISC Study
Fig. 9. These examples show how an increase in water path can perturb the bandwidth of a transducer.
Fig. 10. These examples demonstrate how surface roughness of a material (or included flaw) can perturb the reflected source spectrum.
Fig. 11. This example shows how source normalization can remove the Frequency Spectral Features of the source and thereby improve resolution of useful spectral details.
signal containing the top surface reflection and back surface reflection must be Fourier transformed to produce a frequency spectrum as shown in Fig. 10d. If we divide the frequency spectrum in Fig. 10d by the frequency spectrum in Fig. 11c, we flatten out the resulting power spectrum (see Fig. 11e). This procedure produces the normalized power spectrum mentioned before. The frequency range from 0 to roughly 3 MHz contains quite a bit of noise, but the interference dips are well defined to nearly 30 MHz.

We received 4 blank specimens from Rockwell and used them to measure sound velocity. Figure 12 shows the rf and Fourier transforms of the top surface and back surface echoes from the aluminum specimens. The frequency range from 4 to 6 MHz is shown in each case. By measuring the frequency space between resonance dips and knowing the thickness of a specimen, we can compute the sound velocity. Figure 13 shows that the attenuation is more pronounced in the titanium specimens and the resulting normalized interference dips are less pronounced. Again, we can make a measurement of the spacing between resonance dips and obtain the velocity of sound in the medium if we know the thickness.

One of the problems associated with the time of travel calculation of sound velocity is that of determining reference points on the top surface reflection and the back surface reflection that actually indicate the time differential. The accuracy of the measurement is accordingly limited. If the material is thin or if the echo comes from a very shallow flaw, top surface and echo signals overlap. In this case, it's virtually impossible to find a common reference point. Overlapping signals don't cause a problem when one is operating in the frequency domain because the spacing between the resonance dips is inversely proportional to specimen thickness.

Table I shows the velocities that were measured in the blank specimens both by the time of travel method and by using ultrasonic spectroscopy. Results are in good agreement. Time of flight velocities are probably accurate out to a couple of significant digits but the velocities determined by ultrasonic spectroscopy are probably accurate to three significant digits.

Figure 14 shows rf and Fourier transform spectra of the Rockwell specimens. Shown are a prolate spheroid, spheroidal void, a sphere, a thick oblate, a thin oblate, and a flat bottom hole. These have approximately the same coaxial radius. Fourier transforms of only three rf wave forms are shown in Fig. 14. You can see that there is a definite difference between the rf wave forms and you also can see that there is a definite difference between the frequency spectra. Empirical techniques based on pattern recognition methods might classify a reflecting surface according to its surface shape—whether its prolate, spherical, oblate, or flat.

Figure 15 shows some coaxial rf reflections from flat bottom holes, 400, 800, and 1200 microns in diameter along with the corresponding Fourier transforms of those signals. When the data is in this form, it can be compared with theoretical calculations. Accordingly, Fig. 16 shows three repeated measurements of the frequency spectrum for an 800 micron diameter flat bottom hole compared with Cohen's theoretical predictions. Since the flat bottom hole
Fig. 12. Power Spectra of Front Surface and Back Surface Echoes from RISC Aluminum Blank Standards
Fig. 13. Power Spectra of Front Surface and Back Surface Echoes from RISC Titanium Blank Standards.
Table I. Velocities of Sound in RISC Specimens (cm/sec).

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Travel Time Measurement</th>
<th>Interference Spectroscopy Measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>A (1100 Al)</td>
<td>6.4x10^5</td>
<td>6.34x10^5</td>
</tr>
<tr>
<td>C (2024 Al)</td>
<td>6.3x10^5</td>
<td>6.24x10^5</td>
</tr>
<tr>
<td>F (Ti)</td>
<td>5.9x10^5</td>
<td>5.91x10^5</td>
</tr>
<tr>
<td>I (64 Ti)</td>
<td>5.9x10^5</td>
<td>5.83x10^5</td>
</tr>
</tbody>
</table>
Fig. 14. Co-Axial Pulse Echo and Power Spectra from Varying Flaw Shapes that have the same Co-Axial Areas.
Fig. 15. Co-Axial Pulse Echoes and Power Spectra from Flat Bottom Holes.
Fig. 16. Power Spectra of 800μ diameter FBH taken for comparison to the Ermolov Predictions as presented by Tittmann.
radius is 0.08 cm, it's power spectrum should fall in somewhere between the curves labelled 0.05 and 0.10. The trend is rather encouraging at this point.

I thought it might be of interest to compute the power transforms in a dimensionless parameter format where more direct comparisons could be made with the theory. One of the problems encountered is that the first 3 MHz of noise and the noise in the high frequency end of the source spectrum restricted meaningful data to frequencies between the broken lines drawn in Figs. 17 and 18. Within this useful frequency range, the signatures are definitely different for the flat bottom holes and the spherical reflectors. The spectra in Fig. 17 were obtained with a quarter inch diameter transducer and the spectra in Fig. 18 were obtained with a half inch diameter transducer.

In follow-on work, I think the appropriate thing to do in computing power spectrum in terms of dimensionless parameters would be to compute Cohen's theoretical power spectrum in the computer and divide it by the power spectrum computed from the Fourier transform of a flaw echo and plot out the ratio. Then an operator could quickly vary experimental parameters until he found a fairly constant ratio.
Fig. 17. Co-Axial Power Spectra of Spheres and FBHs in Titanium in Dimensionless Parameter Representation (1/4" diameter transducer).
Fig. 18. Co-Axial Power Spectra of Spheres and FBHs in Titanium in Dimensionless Parameter Representation (1/2" diameter transducer).
DISCUSSION

DR. JOHN SIMMONS (National Bureau of Standards): One thing you did I don't understand. You seem to have taken a gated time section of your signal and it looks like you multiplied that signal by a Heavyside function. Your transform is convoluted with the transform of the square wave and you never mentioned about how this is going to affect the accuracy of both the low frequency end and the high frequency end. Why do you use a square wave? Why not a Gaussian where the transform...

DR. COUCHMAN: We have an analytic transform so we can simply transform any rf signal. Unless we zero the beginning and the end of the rf signal, we do obtain a superimposed transform of the square wave ramp. There are many windowing techniques, but the technique we used is to zero the point in time where the wave form first begins by subtracting the initial value from each of the tabulated values. If the last value is different from zero, we correct for it by subtracting a saw tooth having the end point amplitude. We wind up, then, with a wave form that is zero on both ends. We know the transform of the modulating saw tooth very precisely--it contains several noise oscillations at the low frequency end which damp out as frequency increases.

DR. JIM SEYDEL (University of Michigan): You can avoid the whole Heavyside problem just by subtracting off the DC value of your signal. You won't have to worry about that and it will give you a true Fourier transform of your signal. You will not get into modulation.

DR. COUCHMAN: We have an alternate computational mode where we can subtract off the DC value but we still have some noise that appears because of discontinuities at the beginning and the end of the rf. To remove the transform of these non-zero discontinuities on the extremities, we need some windowing procedure. There are several techniques that can be used for windowing. We've looked at several of them.

PROF. KINO (Stanford University): What are the tradeoffs of doing it this way as opposed to using just a swept frequency input gate when you can get a generator that goes over this frequency range?

DR. COUCHMAN: We tried some swept frequency work and we found that to avoid burning up transducers, we had to pulse the transducers. One of the problems is gaining enough cw power to penetrate attenuating media like Lucite. We've done quite a bit of work in Lucite with pulsed sources.

DR. LARRY KESSLER (Sonoscan, Inc.): You showed some rather drastic changes in the received pulse length as a function of surface roughness.

DR. COUCHMAN: Right.
DR. KESSLER: Would you comment on the roughness of the surface compared to the wave length for those particular experiments and whether the surface was in both cases or all cases normal to the transmitter?

DR. COUCHMAN: In all cases the average surface was normal to the transducer. With regard to the wavelength versus the depth of the flaw, I would guess that they are of comparable size.

DR. KESSLER: You showed perhaps a three-fold increase in return pulse length above what one would expect from the surface roughness of that dimension; is that correct?

DR. COUCHMAN: Yes. So, that would indicate that they were of comparable lengths.