This paper presents an overview of the ARPA/AFML Program for Quantitative Ultrasonic Flaw Characterization which will serve as a framework to interrelate the papers which follow. Work supported by the ARPA/AFML program will be primarily discussed. However, it should be noted that other work has also played an important role in the development of this body of knowledge and will be cited in a more comprehensive review paper to be published elsewhere.

Figure 1 summarizes the basic NDE Decision Process, as has been presented in previous papers by Rau and Evans. Therein are indicated the three types of information which are needed to estimate the expected lifetime, or probability of failure, of a part. (It is assumed that the part design and service conditions are known and fixed parameters.) First, the naturally occurring flaw distribution should be known. This is then conditioned by the results of non-destructive measurements to produce a sharpened, more accurate estimate of the flaw sizes likely to be present. Finally, failure models must be used to predict the range of lifetimes which are consistent with the estimated flaw distribution. This information must then be combined with economic data to define the Accept/Reject criteria which minimizes the total costs of the system. The role of Quantitative NDE is to provide the most accurate data possible regarding the flaw size "a". This sharpens the functions $P(a|m)$, $P(n)$, and $\delta$ shown in Fig. 1, and thereby reduces system costs.

![Fig. 1. Quantitative analysis of NDE decision process](image)

This paper reviews ultrasonic techniques which have been developed for application to interior flaws and which are described in the papers immediately following. Similar work directed towards the ultrasonic and electromagnetic characterization of surface flaws is described elsewhere in these Proceedings.

One of the reasons why it is difficult to develop measurement techniques which sharpen the distribution $P(a|m)$ is illustrated in Fig. 2. A pulse-echo ultrasonic measurement is shown for two cases. The upper sketch shows a planar flaw oriented parallel to the surface which will produce a large backscattered signal. For the in-plane loading shown, this flaw will have a size "a" of essentially zero. The lower sketch shows a similar flaw rotated 90° which produces a much weaker ultrasonic reflection. For the in-plane loading, this flaw will be much more likely to fail as "a" is equal to the full flaw radius. If the amplitude of the ultrasonic echo is used as the indicator, one finds that it is inversely related to flaw severity. It is thus necessary to derive more information from the ultrasonic signal so that the flaw severity can be more precisely determined.

![Fig. 2. Inverse relationship between ultrasonic pulse-echo data and flaw severity](image)

Figure 3 illustrates the methodology used to develop techniques which can deduce this information from the ultrasonic signals. It is first necessary to establish an understanding of the interaction of the ultrasonic energy with the flaw. This is done in a classical manner by comparing theory and experiment. Once sufficiently accurate models are available, they can be used as the basis for solution of the inverse problem. This addresses the problem of the greatest practical importance: How does one identify the properties...
of an unknown flaw from measurements of the scattered ultrasonic fields? The solutions of the inverse problem take the form of predictors which convert experimental data into numerical flaw parameters to be used in fracture mechanics models. The final step is the verification of these results on controlled samples. When this has been completed, the techniques are available for more extensive verification evaluation on a statistically significant set of samples.

**VIII. EXPERIMENTAL MEASUREMENTS ON CONTROLLED SAMPLES**

Fig. 3. Methodology for developing quantitative NDE techniques.

The remainder of the paper will amplify these concepts and discuss the specific approaches that have been adopted within the individual building blocks. Turning first to the theoretical studies, there are two basic objectives. The theory not only provides insight into the flaw-ultrasound interaction, but also serves as the "kernel" for the inversion procedure.

Figure 4 illustrates the former use. Here orthographic projections of angular contours of equal scattering intensity are shown for a spherical flaw and an oblate spheroid (pancake) flaw. These calculations were performed by the Cornell group, led by Prof. J. Krumhansl and are based upon the Born approximation. The different shadings indicate varying strengths of ultrasonic scattering. For the case of an incident longitudinal wave, it is seen that the sphere produces symmetric scattering patterns with longitudinal scattering strongest near the backscattered direction and mode converted transverse wave scattering strongest at angles approaching 90°. For the case of the oblate spheroid whose normal is inclined at 45° with respect to the direction of incidence, the results are similar to those which would be expected on the basis of specular reflection. The longitudinal wave is most strongly scattered near, though not exactly at, the specularly predicted downward direction. The mode scattered signal is also greatest in this direction.

The fact that these are approximate results should be reemphasized. An important part of the program philosophy has been to pursue approximate techniques, which can be applied to fairly general flaw shapes, rather than to seek exact solutions which are tractable for a much smaller set of flaws. It is recognized, however, that the latter are quite important for both the detailed information which they contain and for calibrating the approximations.

Approximations have been developed during the ARPA/AFML Program which may be mathematically described by a sum of selected elements of this series. As will be discussed later, these solutions provide both insight into the flaw-ultrasound interaction and serve as a basis for simplification of the inversion process.

The first approximation developed was the Born approximation. The basic assumption is that the change in properties is small, so that the resulting expression is equivalent to including only those terms of the double series which are linear in \( \Delta c/c \). Inspection of the closed form expressions for this sum show that it can be directly related to the spatial Fourier transform of the object shape function. Within this regime, the obvious strategy for inversion is to gather enough data to be able to evaluate the inverse Fourier transform.

Though of broad utility, the Born approximation breaks down for strongly scattering flaws. As a remedy, the Quasi-Static approximation was developed, which is correct at long wavelengths...
The theoretical developments were supported, and often guided by experiments on controlled samples. These were fabricated using the diffusion bonding procedure developed by Paton and illustrated in Fig. 7. This has enabled us to place cavities, or inclusion, at the center of an otherwise homogeneous piece of material. The sample initially is made of two halves with mating flaw sections. After bonding, grain growth across the boundary essentially returns the material to a homogeneous condition with only the flaw remaining.

Fig. 6. Summary of theoretical approaches and their uses in inverting data.

The final approximation illustrated in Fig. 5 is the extended quasi-static approximation. This is an ad hoc combination of the former two which is rigorously correct in both the long wavelength limit for all perturbations and in the weak scattering limit for all frequencies. In addition to the specific terms associated with the two previously discussed models, the quasi-static approximation contains selected higher order terms from the double power series which quantitatively appear to improve its accuracy. The inversion work of Rose is based on this model as will be discussed in a subsequent paper.

Initial work was focused on ellipsoidal shaped cavities, selected because of the ease with which they could be theoretically modeled coupled with the fact that they approach, as a limiting case, a crack. More recently, this crack limit has been actively explored by constructing thinner and thinner discs by a variety of techniques. Very promising results have recently been obtained by placing ythia powder at a diffusion bonded interface. It has long been known that this contamination would inhibit bonding. It was not clear, however, whether the deformation occurring during bonding would place the treated region in compression and thereby cause it to behave as a ythia inclusion rather than a crack. Fortunately, ultrasonic measurements indicate that the flaw does, in fact, act like a crack, and this looks like a very useful way to model this important class of flaws.

Experimental measurements by Adler and Tittmann and Elsley have been performed on these controlled samples with a variety of objectives. First, the data have been used as a guide for the theoretical development and a check of the accuracy of the resulting approximations. This has been particularly important since exact theoretical solutions have only been available for "calibration" of approximate models in a few special cases. A further role of experiment has been to provide test
Fig. 7. Summary of defect shapes produced by diffusion bonding. data to be used as input to evaluate the inversion procedures. Finally, the experience gained in developing precise measurement techniques for these purposes will lead to improved measurement procedures for field use.

Figure 8 illustrates the use of experiment to check and guide the theory. Here the angular dependence of the backscattered signal from a 400 x 800 μm oblate spheroidal cavity is plotted as a function of angle.19 The theory is the Born approximation, averaged over the frequency content of the pulse. This both simulates the pulse response from the monochromatic theory, and also suppresses some of the detailed frequency response known to be inaccurate in this model. The agreement is quite good, which is somewhat surprising in view of the large change in properties presented by the cavity which place it outside the expected range of convergence of the Born approximation. Such agreements have demonstrated the utility of relatively simple models and have allowed an early consideration of the inverse problem.

The inversion techniques under consideration are summarized in Fig. 9. These have been classified in terms of their domain of application as measured in ka values. As a reference, the sketch at the bottom superimposes these regions on a plot of the frequency variation of the signal backscattered from a sphere. At high frequencies, ka > 6.3, an image will resolve the gross structure of the flaw since the diffraction limited spot size is less than the flaw's radius. Under such conditions, the high information content and ease of interpretation make this the preferred mode of data processing and presentation. When the flaw size and/or material attenuation make it impossible to reach this high frequency limit, it is necessary to make use of specific knowledge of the flaw-ultrasound interaction. For ka > 3, it is still possible to reconstruct the flaw shape by incorporating a physical model into the data processing to increase resolution. At longer wavelengths, there is not sufficient information to fully reconstruct a flaw. However, adaptive learning networks have proven successful in the difficult regime of ka ~ 1 in which the flaw-ultrasound interaction is quite rich in structure, as shown in the sketch at the bottom.

Even at long wavelengths, ka < 0.5, it has been possible to measure a number of quite important flaw parameters, including in certain cases the stress intensity factor. The results go against intuition, and appear to have considerable potential for practical application.

Figure 10 summarizes the two approaches to imaging under consideration. Kino16 is developing a synthetic aperture system in which a single transducer is scanned over the surface of the part. At each location, pulse-echo data is stored and subsequently combined to form the image. This recombination is accomplished by the superposition of the waveforms with appropriate time delays. Lakin17 is considering a slightly different approach. His system uses a tone burst rather than impulsive excitation and images are constructed by a phased superposition of the signals received at a transducer array in a fashion equivalent to holography. Both techniques have the advantageous features that a) the image of any plane can be reconstructed once the data has been collected and b) modern advances in integrated
circuitry are being incorporated to make practical advanced signal processing procedures.

<table>
<thead>
<tr>
<th>TYPE</th>
<th>REGIME</th>
<th>ADVANTAGES</th>
</tr>
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<tbody>
<tr>
<td>IMAGING</td>
<td>$k_a &gt; 6.3$</td>
<td>HIGH INFORMATION CONTENT</td>
</tr>
<tr>
<td></td>
<td>$k_a &lt; 3$</td>
<td>EASILY INTERPRETED DISPLAY RESOLVES MULTIPLE FLAWS</td>
</tr>
<tr>
<td>MODEL BASED RECONSTRUCTION</td>
<td>$k_a &gt; 3$</td>
<td>PHYSICAL PRINCIPLES USED TO IMPROVE RESOLUTION AND TREAT MODE CONVERSION</td>
</tr>
<tr>
<td>MODEL BASED ADAPTIVE LEARNING NETWORKS</td>
<td>$0.4 &lt; k_a &lt; 3$</td>
<td>MULTIPLE SCATTERING TAKEN INTO ACCOUNT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>GAIN MORE INFORMATION IN DIFFICULT REGIME</td>
</tr>
<tr>
<td>LONG WAVE SCATTERING</td>
<td>$k_a &lt; 0.5$</td>
<td>FRACUTRE RELATED PARAMETERS DEDUCED FROM A FEW MEASUREMENTS MAY BE USEFUL IN AUTOMATION</td>
</tr>
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</table>

Bliestein and Cohen⁸ and Rose⁶ have developed model based reconstruction algorithms based on a careful analysis of a forward scattering model. In each case, they consider the processing of backscattered data. Bleistein and Cohen base their results on a physical optics model and do their processing in the time domain. Rose bases his work on the extended quasi-static model and does his processing in the transform domain. In each case a reconstruction of the flaw shape results with somewhat improved resolution over that of a simple image.

Figure 11 shows an example of the reconstruction of a spherical cavity using the procedure of Rose. The dashed line indicates the actual result and the solid lines shown the output of the algorithm. For this measurement, $k_a \sim 5$, and it can be seen that the sharpness of the edge was equivalent to a considerable better resolution.

When $k_a \sim 1$, the flaw-ultrasound interaction is quite complex, and analytical solution of the inverse problem has not yet been possible. Here, adaptive learning procedures have proven fruitful, as illustrated in Fig. 12. Whalen and Mucciardi¹⁹ have used theoretical waveforms as a basis for training their networks and have then tested the result on experimental data. This approach has the advantage that expensive sets of samples with a wide variety of flaws are replaced by theoretical expressions in the training process. Early results based on the Born approximation were quite encouraging and the results obtained with other improved models are presented in this volume.¹⁹

One of the newest, and most exciting inversion procedures is the long wavelength technique developed during the last year. This has been the result of the efforts of many contributors. The early theoretical work was performed at the ARPA Materials Research Council by J. Rice, B. Budianski and W. Kohn. This is summarized by Rice⁶ in this volume. Richardson²⁰ and Khuri-Yakub and Kino²² further discuss the theory and present experimental verifications for the cases of bulk and surface flaws respectively.

Fig. 9. Summary of inversion techniques.

KINO, CORL, GRANT - SYNTHETIC APERTURE IMAGING SYSTEM

Fig. 10. Summary of imaging techniques.

Fig. 11. Comparison of calculated and exact characteristic function for a spherical cavity based on Born inversion.

In each case:
- IMAGE IN ANY PLANE CAN BE ELECTRONICALLY RECONSTRUCTED FROM BASIC DATA.
- MODERN ADVANCES IN INTEGRATED CIRCUITRY ARE INCORPORATED.
Fig. 12. Adaptive learning approach to inversion.

Figure 13 presents the basic principles. At a particular angle, the parameter \( A \) is defined as the coefficient of the leading quadratic term of a frequency power series expansion of the scattered fields. From values of this parameter measured at a set of angles, it is possible to estimate fracture critical parameters including, in certain conditions, the stress intensity factor. Advantages include high leverage on the experimental data and insensitivity to minor shape perturbations.

Figure 14 presents the results of the use of this technique to measure the size of an ellipsoidal cavity in a diffusion bonded titanium sample. Not only is the 400 \( \mu \)m value accurately determined, but the standard deviation of the estimate is extremely small due to the previously cited high leverage on the data.

As the research advances in these areas, the need for practical demonstrations under practical constraints presents itself. This is being addressed by Addison in the Test Bed Program, which is coupled to the Quantitative Flaw Definition Program as shown in Fig. 15. This will lead to the demonstration of the utility of the techniques in sizing flaws and prediction lifetimes for a number of practical geometries and conditions. Other applications to the inspection of ceramic components are also developing rapidly.

Finally, the same conceptual framework is being applied to the problem of quantitative characterization of surface flaws using both electromagnetic and ultrasonic techniques. Results are presented in Session IV, Lddy Current Techniques, and Session XIII, Surfase Measurements, of the Proceedings.
Fig. 15. Roadmap of Test Bed Program showing coupling to Program for Quantitative Flaw Definition.

REFERENCES


4. J. E. Gubernatis, informal presentation at the 1976 ARPA Materials Research Council Summer Session, La Jolla, California.


9. V. V. Varadan and V. K. Varadan, "Scattering of Elastic Waves by Oblate Spheroids and Cracks," these proceedings.


13. L. Adler and K. Lewis, "Frequency Dependence of Ultrasonic Wave Scattering from Cracks," these proceedings.


16. G. S. Kino, P. M. Grant, and P. D. Carl, "Digital Synthetic Aperture Acoustic Imaging for NDE," these proceedings.

17. K. Lakin, "Acoustic Imaging and Image Processing by Wavefront Reconstruction Techniques," these proceedings.


DISCUSSION

George Wiley (unidentified): In the Born approximation, what was the frequency compared to the size of the defect?

Bruce Thompson (Science Center): I believe that it was 5 megahertz data. Kα was probably about somewhere between 1 and 3.

Bernard Tittmann (Science Center): The defect, that we are talking about, was an ellipsoid with an aspect ratio of 2 to 1 ellipsoid, 800 by 400μm major-minus axis and the frequency, indeed, was 5 megahertz.