

DEFECT CHARACTERIZATION BY QUANTITATIVE ULTRASONICS

INTRODUCTION

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"Flaw Characterization by Ultrasonic Techniques" is the subject of this morning's session. The ultimate goal is to predetermine the in-service failure probability of a structural component with the best possible confidence. To achieve such a comprehensive goal there are a number of parts that are needed, as is schematically illustrated in Fig. 1. One first needs a measurement system. In this set of talks, ultrasonic techniques are being discussed. One needs a transducer or transducer array to gather ultrasonic information, coupled with techniques for processing this information. In this session, attention will be focused on ultrasonic scattering techniques and the types of signal processing and signature identification operations that can be used to identify the nature of the defect; e.g., its size, shape, and orientation. Imaging techniques will be discussed in later sessions. To achieve the ultimate goal of prediction of failure probability, of course, one must combine this information with fracture mechanics or other failure predictions schemes to develop some sort of an accept/reject criteria that would lead to a go/no-go decision. However, the scope of the ARPA/AFML program has not included fracture mechanics, only those elements on the left-hand side of the figure--the gathering, the processing, and the interpretation of the ultrasonic data in terms of geometric characteristics of the defects--have been considered.

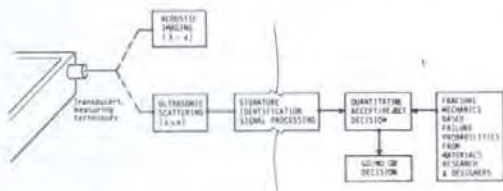


Figure 1. Steps required to incorporate quantitative accept/reject criteria with ultrasonic NDE to make GO/NO-GO decisions.

The papers to be presented in this morning's session were all prepared as a part of Project I of the ARPA/AFML Program for Quantitative NDE. Before presenting a specific overview of the flaw characterization studies, I would like to indicate that there are a number of other related activities that have been a part of the project that will be presented later on in the program. Figure 2 is a summary of this work. These are items that will be needed in a flaw characterization system in addition to the defect characterization results

to be discussed today. For example, improvements in transducers, imaging systems, new ultrasonic standards, and filters for NDE systems are all included. In each area, the advances reported can have immediate impact on today's NDE systems as well as being an integral part of a future defect characterization system. There has also been a new effort recently started dealing with extending the bulk defect work discussed today to the case of surface flaws. Finally, some very successful applications of the scattering techniques to the development of techniques for the inspection of ceramic components will be presented. All of these elements will be needed in the development of a fully integrated defect characterization system.

ELEMENTS OF PROJECT I TO BE PRESENTED IN OTHER SESSIONS

- VIII "NEW TECHNOLOGY ROOTS"
POSTER SESSION, FRIDAY MORNING
 - ELECTROMAGNETIC TRANSDUCERS, OPTIMIZATION & APPLICATION
R. B. THOMPSON, C. M. FORTUNKO, C. F. VASILE, G. ALERS
 - CHARACTERIZATION SYSTEM FOR NDE TRANSDUCERS
K. M. LAKIN
 - PROGRAMMABLE FILTER FOR ULTRASONIC NDE SYSTEMS
R. M. WHITE
 - NEW ULTRASONIC STANDARDS
B. R. TITTMANN AND N. E. PATON
 - ULTRASONIC IMAGING SYSTEMS
G. S. KIND
 - IV "NEW TECHNIQUES AND PHENOMENA"
POSTER SESSION, WEDNESDAY AFTERNOON
 - NEW METHODS OF DETECTION AND CHARACTERIZATION OF SURFACE FLAWS
B. A. AULD
 - VII "RELIABILITY OF STRUCTURAL CERAMICS"
THURSDAY EVENING
 - OVERVIEW OF RELIABILITY IN STRUCTURAL CERAMICS
A. G. EVANS
 - HIGH FREQUENCY ULTRASONICS: A CASE IN POINT
G. S. KIND, P. T. KHURI-YAKUB, B. R. TITTMANN
- Figure 2. Elements of Project I to be presented in other sessions.

Returning to this session on Flaw Characterization, the immediate goal that we have adopted is to develop techniques and procedures to determine the size, shape, and orientation of defects in metal parts. The philosophy of the technical approach adopted to accomplish this goal is shown in Fig. 3. We have wished to establish a set of procedures, whereby a defect characterization capability is built up from fundamental building blocks involving an understanding of the basic interaction of the ultrasound with the flaw. This will not only establish an immediately useful result, but will also illustrate a method that can be generalized in the future as needed for specific cases. The first element is an understanding of the details of the ultrasound defect interaction. This is accomplished by a close interaction between the development of theories and the performance of verifying and/or guiding experiments. These experiments should be performed on controlled samples in which there are defects of predetermined sizes and shapes. In this program, the development of approximate theories has been emphasized because the number of flaw shapes which can be treated by exact techniques is extremely limited. We wish to develop techniques which can be generalized to the complex shapes of real flaws. Even if one has developed a complete understanding of this ultrasound-defect interaction, it does not immediately follow that one can identify a flaw from a set of experimental data. In order to do so, one needs to develop inversion techniques. That's the second half of the procedure, the one that's going to produce the ultimate payoff. We have made use of an analogy to an integral equation. The theory can be viewed as the kernel of this integral equation which relates ultrasonic measurements to physical parameters of the flaw. By solving the equation by whatever means is appropriate, one develops a relationship that predicts the size, shape, and orientation of the defect in terms of certain measurable. In order to verify this relationship, one must put real experimental data into these mathematical expressions and compare the predictions with independent knowledge of the flaw parameters. This completes the loop of the demonstration of the defect characterization capability. The predictive relationship is then available for use coupled with fracture mechanics or other failure predictions disciplines to develop accept-reject criteria.

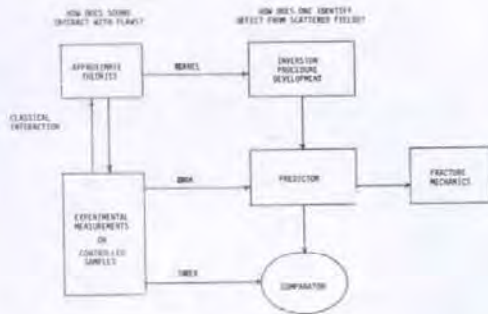


Figure 3. Philosophy of development of quantitative defect characterization techniques.

This is the methodology being followed in Project I. The remainder of this paper briefly describes some of the philosophies that were taken in filling each of these boxes as a preview for the in-depth presentations by the individual investigators.

We have used the diffusion bonding technique to fabricate samples with defects of controlled shapes. Figure 4 illustrates this. One starts out with two cylindrical pieces of titanium. In each is machined half of the desired defect shape. They are then diffusion bonded together. Grain growth takes place across the interface and there is virtually no memory of the bonding plane. One then has a homogeneous piece of material with the desired defect in the center. The choice was dictated by two reasons. Most of the defects had an ellipsoidal shape. This makes it possible to develop theories in a relatively simple manner and hence is a very good place to start to develop our understanding and test the methodology shown in Fig. 3. In addition, you will notice that in the oblate spheroid case as the aspect ratio becomes large the defect shape more and more closely models a planar shape which is an idealization of a crack, a very real defect of great practical concern. The dimensions were chosen to be typical of the sizes of flaws typically sought in aerospace systems. In such cases the ultrasonic measurement frequency is often on the order of 1 to 10 MHz. As a scale factor, we have shown the range of wavelengths of these frequencies as compared to the defect size. As you see we are in a difficult regime in which the wavelength is comparable to the defect size. The very successful results that will be reported in later papers illustrate some of the power of the defect characterization techniques.

As a physical example, Figs. 5 and 6 show pictures of experimental configurations that have been used. Figure 5 shows the experimental apparatus that Tittmann and Elsley have used. In this case, the diffusion bonded samples with the defects at the center have been machined with a spherical exterior surface. It is clear this doesn't represent any practical situations except a ball-bearing with a defect exactly in the center. Nevertheless, it is a very important configuration for experimental measurements as needed in the development of understanding of scattering phenomena. It allows the experimenter to arbitrarily vary the angle of incidence of the ultrasound as well as the angle at which the ultrasound is detected. In one sample, one can simulate all possible orientations, and this flexibility has been used to great advantage as will be discussed in much greater detail during subsequent papers. Since this is a very unrealistic configuration from a practical point of view, a second set of samples have been used as shown in Fig. 6. These have identical defects imbedded on the interior. However, they have a planar surface. The figure shows the immersion measurement configuration which has been used by Adler. It is very similar to an on-line inspection station at many industrial laboratories around the country. By studying the same flaw geometries in the two sample shapes, it has been possible to directly compare the more basic and practical approaches.

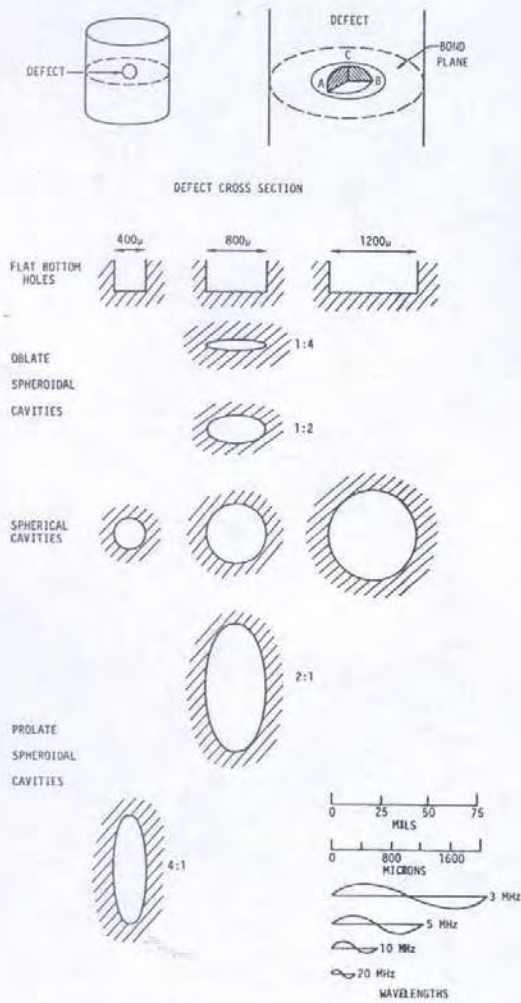


Figure 4. Defect shapes in diffusion bonded samples.



Figure 5. Photograph of sample holder.



Figure 6. Apparatus used for immersion testing of samples with flat faces.

During the first two years of the program primary attention was placed on the development of the experimental and the theoretical building blocks needed for an understanding of the ultrasound-defect interaction. During the third year, the focus has shifted to the inversion problem. The first question one must ask is, "How much information am I going to be able to use?" If one can assume that one can measure the ultrasonic scattering at all frequencies and at all angles, one has a tremendous amount of information about the flaw, but one could never hope to realize this in a real situation. We have therefore restricted ourselves as is schematically illustrated in Fig. 7. We considered the situation in which the defect is on the interior of a part having a geometry such that ultrasonic waves can enter or leave the part at angles no greater than 60° with respect to the surface normal. Although the spherically shaped samples allow full axis from any angle, we have restricted ourselves to use only that information obtainable with transducers in a cone of 60° half-angle. No use is made of large angle scattering information or of any through transmission signals. In terms of the frequencies available, we have taken the natural attenuation of the titanium samples to be the limit. Thus we are considering frequencies in the range of 1-10 MHz. We do allow ourselves to look at mode converted signals. When a longitudinal wave strikes a defect, both longitudinal and shear waves are scattered. Since these can both be detected and differentiated in a standard water bath configuration, such information could be used in an industrial setup. Given the information available within this experimental window, we have sought techniques to characterize the size, shape, and the orientation of the ellipsoidal flaws. The next question was what sorts of measurements would we like? The details of how we developed these techniques will be presented in the following papers.

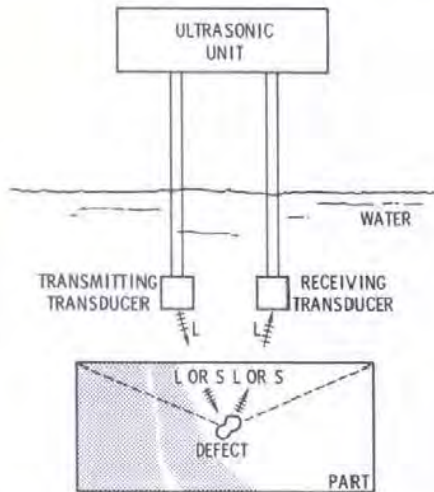


Figure 7. Schematic ultrasonic immersion configuration illustrating geometrical limitations and mode converted signals.

Figure 8 shows a result presented at the Asilomar meeting last year. Here, equal contours of scattered ultrasonic power are shown for two defect geometries as calculated by Krumhansl and a number of his colleagues here at Cornell using the Born approximation. The plots are orthogonal projections of a frequency average of the scattered ultrasonic power for: (1) a spherical inclusion, and (2) an oblate spheroidal inclusion tilted at 45° with respect to the angle of incidence of the ultrasonic energy. Both the direct L+L scattering and the mode converted L+T scattering are shown. From such information it is possible to design experiments which will distinguish between the two types of defects. Strictly speaking, the Born approximation is only accurate for cavities. However, direct experiment has shown that many of the features shown in these plots apply to strongly scattering defects such as cavities as well.

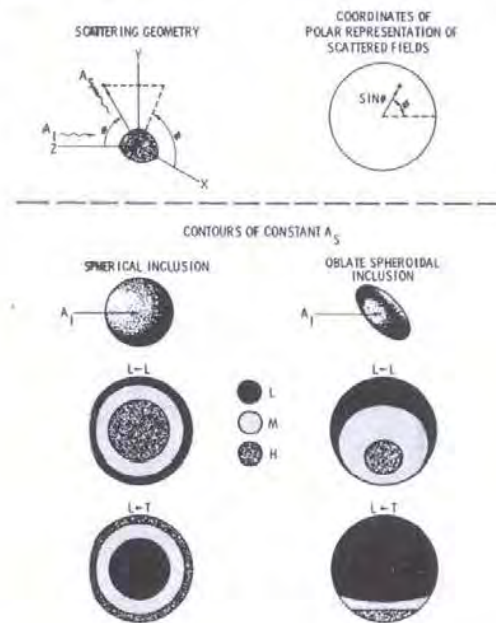


Figure 8. Variations in equal amplitude scattering contours for two defect types.

The simplicity of the Born approximation, plus the fact that it predicts the results of many experiments performed on cavities, suggest that it may be useful as a model in the design of experiments. For example, one can consider in detail the inverse problem. Figure 9 illustrates the various relationships involved. In the Born approximation, simple expressions are derived for the amplitude of a scattered longitudinal wave A and a scattered transverse wave B in terms of the properties of the scattering object. The expression is a product of two terms. One is a rather slowly varying angular function which depends only on the change of the elastic constants and the density within the inclusion, but which is independent of its shape.

COMPARISON OF DIFFERENT SCATTERING CONFIGURATIONS BASED ON BORN APPROXIMATION

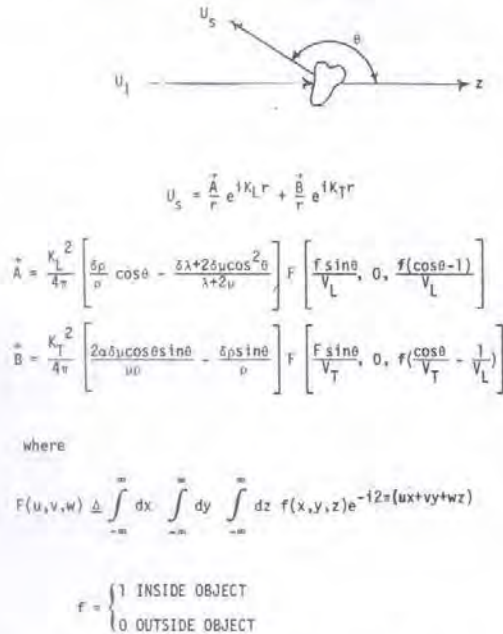


Figure 9. Comparison of different scattering configurations based on Born approximation.

This shape information is contained in the second factor, F, which is the spatial Fourier transform of the shape of the object. In other words if $f(x, y, z)$ is defined to be 1 inside the object and 0 outside the object, then F is the spatial Fourier transform of f. To solve the inverse problem, one must obtain enough components of F from scattering experiments so that the shape function f can be reconstructed by taking the inverse transform. Within this framework, one can determine how much data is needed to determine the shape of an object and can compare the performance of systems, spectroscopic systems, and other approaches to defect characterization.

Figure 10 presents a specific example. Here the region of Fourier transform space which is sampled by different experiments is indicated for a two-dimensional example. One can see that in a spectroscopic system at a single angle, one is essentially measuring components along a line passing through the origin. If one uses the angular variation of direct L+L scattering with a central transmitter and moving receiver at a fixed frequency, one measures components along an arc. If one measures L+L backscattering over the same aperture, one obtains information over a considerably greater range in Fourier transform space. Still more information is obtained if one is able to measure the mode converting signals. Examples of each of these approaches will be presented in the papers that follow. They can be compared to a common framework by an analysis

such as this. In the next two years of the program, emphasis will focus on the inverse problem, and a much more extensive analysis of this type will be carried out.

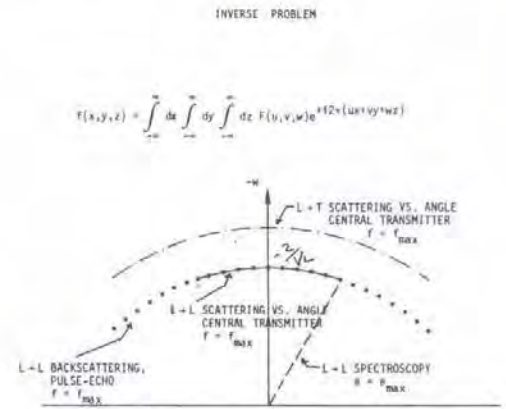


Figure 10. Inverse problem.

Figure 11 summarizes the work that has been done on inversion techniques at this time. Papers will be presented on three distinct techniques for inverting ultrasonic data. Dr. Mucciardi will discuss empirical, derived, nonlinear predictions which have been developed using the adaptive learning capability of Adaptronics. These have been derived using a new concept. In order to develop and verify the predictive relationships, one needs to have a training set of data and a second, independent set of data against which the results can be checked. In this program, theoretical solutions have been used to train the network, and then experimental data has been used to test the network. This is important because one does not need to construct a large training set of samples of every possible configuration if one has an adequate model. Other defect characterization procedures have also been quite successfully pursued by Domany based on symmetry principles, physical observations of the natures of the scattered fields, and again incorporating some of the theoretical scattering data. A third paper by Bleistein presents a more formal inversion procedure which has been recently developed based on previous experience in electromagnetics and geophysics and incorporating ideas similar to those presented in Fig. 11.

In conclusion, it should be emphasized that all of the results that will be presented have been the direct product of many detailed interactions between all of the investigators and represent their cooperative interaction. Several meetings have been held at the Science Center and all participants involved have contributed substantially to the ideas developed.

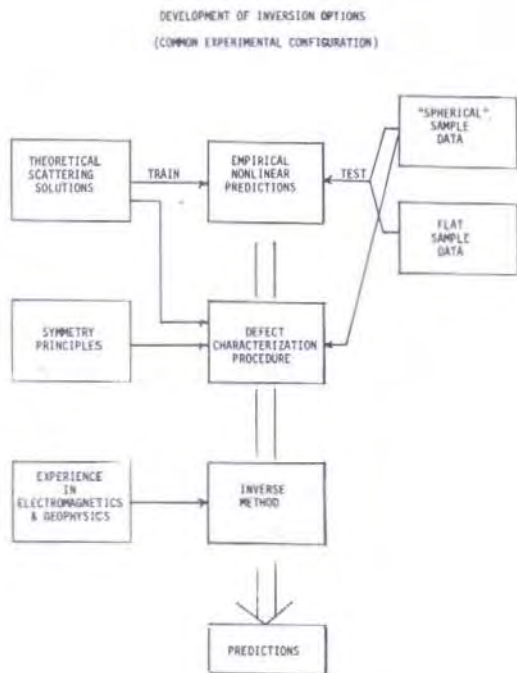


Figure 11. Development of inversion options (common experimental configuration).