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R. Bruce Thompson
Rockwell International

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IMPLEMENTATION: PRESENT STATUS AND FUTURE DIRECTIONS

R. B. Thompson
Science Center, Rockwell International
Thousand Oaks, California 91360

ABSTRACT

The previous papers present a number of techniques for quantitatively identifying the size, shape and orientation of defects in solid parts from the ultrasonic scattering information available at a single surface. This paper summarizes these results and discusses their interrelationships. A "decision tree" is presented which identifies the options that should be selected in various situations. Areas where future or in-progress work can be expected to have an impact on such procedures will be identified.

Figure 1 repeats Fig. 3 from my introduction because I want to again emphasize the methodology that has been involved in this program. We first were concerned with the development of both theoretical and experimental understanding of the interaction of an ultrasonic wave with a flaw. This is, to a great extent, complete and we are now attacking the inversion problem, whereby fracture related parameters of flaws are directly deduced from data obtained during ultrasonic measurement. This information will then be available for use in conjunction with fracture mechanics to define specific accept-reject criteria. In each of the general subject areas, there remain many things that we have not yet done. There are limitations on the accuracy of the theories that have been used; all possible types of defects have not been studied, and studies of certain inversion techniques have just begun. Nevertheless, we have made very significant progress by demonstrating how these individual building blocks fit together and by demonstrating successful inversion results for the case of ellipsoidal cavities. In this paper, I will summarize the progress that has been made and indicate the future directions that will be followed in order to ensure effective implementation of these ideas.

Figure 2 lists the specific technical approaches that have been used within each of the building block areas. Resources that are available, but not yet incorporated, are indicated by parentheses. In the theoretical area, much attention has focused on the Born approximation because of its simplicity and the ease with which it can be generalized to complex shapes. Most of the experimental and inversion work has also been based on this model since it was the first available. Some additional more accurate models, the quasi static and extended quasi-static approximations have also been discussed, but these were developed relatively recently and there has not yet been time to fully integrate them into the program. These are available for future efforts. Experimentally, ellipsoidal cavities, disc shaped cavities, spherical cavities and inclusions, and some simulated cracks have all been studied. The effort primarily was concentrated on L-L scattering measurements. The adaptive learning work only utilized L-L scattering information as did the discussions of Domany and Tittmann. However, Adler did present some data on the mode converted L-L scattering which suggest that these signals contain important information that should be utilized. Most of the work utilized only the amplitude information. Phase does contain very important information, again as demonstrated by the work of Adler, and it should be incorporated in the future. For example, recalling the discussion of Bleistein which treats the shape reconstruction process as an inverse Fourier transform, it is clear that phase information is essential. Both the angular and frequency dependencies of the scattering have been discussed and used in detail. Inversion procedures have been developed based on adaptive learning, direct interpretation of observed physical features, and a direct mathematical solution of the inverse problem. The results of the adaptive learning procedure are very impressive in view of the fact that much of the available information was suppressed during the training phase because of systematic errors in the model. Incorporation of more accurate models in the future should yield further improvements in these encouraging results.

Figure 1. Philosophy of development of quantitative defect characterization techniques.
Figure 2. Specific technical approaches used within each of the building block areas.

Figure 3 repeats a comprehensive defect characterization scheme which Tittman presented but did not have time to discuss in depth. On the right-hand side is shown the parameters one would like to know about a flaw, on the left-hand side the types of measurements that might be utilized in determining these parameters. The information is organized sequentially, starting at the top with an unknown flaw and ending at the bottom with an output for fracture mechanics. The time delay of an ultrasonic signal can first be utilized to determine the position of the defect. Then from backscattered data at a number of transducer positions, one can determine an orientation of the defect. The shape can then be deduced from certain observations of the angular dependence of scattering from a central transmitter to an array of receivers. (Alternatively, Donnay would make use of the frequency dependence at two different angles in these determinations.) At this point, by looking at certain features of the ultrasonic fields one can determine whether it was an irregular crack-like defect or a smoother, ellipsoidal defect. For example, a T indicates that the ultrasonic signal is split and appears to be two distinct pulses. For crack-like defect with very sharp edges, one tends to see two signals that are produced by scattering from the edges whereas these edge signals are much less prominent in the ellipsoidal defect. After such observations have been used to make a separation between these two types, more quantitative size information can be produced by a phase measurement technique. As Tittman briefly indicated, a comparison of the phases of the low frequency and the high frequency reflected signals can produce a quantitative measure of the dimensions of the defect. Once all of this is known, it is a relatively easy matter to obtain the acoustic impedance from the total scattered power. It is useful to look at the work of Mucciarini in the perspective of this defect characterization procedure. He assumed that the flaw had already been determined to be an ellipsoidal cavity. He then developed independent nonlinear networks which determined the two size parameters, the major and minor axes of the ellipsoids of revolution, and the two orientation parameters. This then provides us with a very powerful way of performing some of the operations in the more comprehensive procedure.
way to perform the inversion operation which is consistent with any pre-knowledge of the sorts of defects which may be present and the sources of noises in the experimental measurements.

Figure 4 summarizes what has been presented this morning. The building blocks of scattering theory, experimental observation and interpretation, and solutions of inverse scattering problems have been joined to demonstrate the capability to measure the size, shape, and orientation of ellipsoidal flaws. This, coupled with a number of things you will hear about in other sessions and which were summarized in Fig. 2 of my introductory talk, provides the basis for a defect characterization system which, in relatively simple cases, could be constructed in the near future. We hope to make such demonstrations in the next stages of this program. For some of the more complicated part geometries and defect types, there is need for additional theoretical, experimental, and inversion work. However, it is believed that this can be fitted into the framework indicated in Fig. 1 to provide an orderly and timely extension of capabilities.

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\begin{align*}
&\text{JOINED THE BUILDING BLOCKS OF} \\
&\quad \bullet \text{ SCATTERING THEORY} \\
&\quad \bullet \text{ EXPERIMENTAL OBSERVATION AND INTERPRETATION} \\
&\quad \bullet \text{ SOLUTION OF INVERSE PROBLEM} \\
&\text{TO DEMONSTRATE CAPABILITY TO MEASURE} \\
&\quad \bullet \text{ SIZE} \\
&\quad \bullet \text{ SHAPE} \\
&\quad \bullet \text{ ORIENTATION} \\
&\text{OF ELLIPSOIDAL FLAWS}
\end{align*}
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Figure 4. Summary of presentation.
**DISCUSSION**

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R. B. Thompson, Moderator  
Science Center, Rockwell International  
Thousand Oaks, California 91360

B. P. Hildebrand (Battelle-Northwest): In all of this morning's session, and as far as I can see on the program, imaging is pretty well avoided. Is there a reason for it?

R. B. Thompson, Moderator (Rockwell International Science Center): I wouldn't say that imaging is avoided.

B. P. Hildebrand: Well, it's certainly not nearly as important, apparently, as the more indirect methods.

R. B. Thompson: I wouldn't necessarily want to say that. There are fewer papers on the program, but these represent a substantial effort. Gordon Kino will be presenting the work that he's done on imaging systems on Friday. He's also done some work that relates closely to imaging in ceramic materials. Also, the work to be presented by Lakin on transducer characterization makes use of imaging techniques. I think imaging is very important and I don't wish to minimize its importance.

There are some essential differences in the state of the art. As I see it, the imaging problem is primarily a technological problem. I think we know what we want to do with the signals. There are some very significant technological problems, of course. There's the problem of properly driving the elements, processing the received signals in real time, and so forth. The philosophy of this program has been to devote effort to understanding the generic physical principles underlying ultrasound-flaw interactions and to make use of these as appropriate in imaging or other signal processing schemes. We would like to see the "imaging" and "scattering" come closer together. For instance, I feel there is merit in trying to construct some sort of a hybrid system which would combine L-L and L-T scattering information to synthesize an image that might have higher resolution than an image formed in the classical way. One thing that does worry me about imaging in the context of certain production line applications is that it seems that what one does once he has formed the image, How is it interpreted? How is it converted into a red light or a green light? Some of the scattering approaches may be simpler to convert into such an indication, but that's a personal opinion and you might well feel differently. I think those are the kinds of questions that are the key technical issues of the next few years.

G. S. Kino (Stanford University): ...but irrespective of that, how can you say that imaging doesn't give you more information? The eye is a tremendous recognition source--it's a hell of a good recognition source...

R. B. Thompson: Well, you're right and...

G. S. Kino: ...a sphere is a sphere and you can see it.

R. B. Thompson: You're absolutely right, Gordon. But the problem that I hear when I talk to a lot of people who are working on production lines is that the man gets tired. His eyeball doesn't say the same thing when he is bored after three hours that it said early in the morning. It is not that the information is not there, I certainly don't mean to say that because, it is. The real point is that an imaging system is a particular way to process ultrasonic fields. In the case of wavelengths that are small with respect to the size of the object, it's probably the optimum way. However, if experimental constraints are such that one cannot operate in those regimes, it may not be the optimum way and in fact I think it is probably not. But I really don't want to draw lines that clearly. Imaging is a fine way to go but what I'm trying to say is, "Let's find out what the basic principles are and determine in which regime each particular processing way is best."

V. L. Newhouse (Purdue University): One more comment to make about this question of imaging versus signal processing. We all believe in the validity of signal processing but we have to recognize that the human recognition ability is very superior and will be for a long time. To back up what Gordon said with regard to visual imaging, I'd like to point out that in the Tissue Characterization Conference (which has been cleverly arranged to take place yesterday and today at Gaithersburg, Maryland, which, of course, is unfortunate because there is a lot of overlap between the kind of topics that they're handling there and the kind of topics we're handling here), there have been suggestions made that it might even be advantageous to take the data that we get out of A-scan systems and frequency convert them to the audio range because it's known that the human audio pattern recognition capability is very, very powerful. So, what this means is that it's apparently even possible for people to recognize the bark of their dog from the bark of a pack of dogs.
So, audio recognition has been used a lot in medicine, for instance, for pattern recognition. Therefore, it would appear that we shouldn't ignore the human factor and we should try to do our signal processing in many cases so as to produce a pattern which is capable perhaps of being recognized by the audio or visual senses of the human operator. That may well be a very powerful technique. Possibly an alternative to the computer technique that Tony's been so ably working on at Adaptronics. Certainly it's something that shouldn't be ignored.

R. B. Thompson: Let me say one word in response to that. This issue was discussed at great lengths at one of the meetings we had a couple of years ago at the Science Center - I don't remember which one - and the point was made that in the medical field, the interpreter of data is a very highly paid individual and is, in general, highly skilled. In the nondestructive testing field, for whatever reason, that's often not the case. So there may be a difference in the approaches taken because of this external boundary condition that none of us can really address.

V. L. Newhouse: That is not so. I have a lot to do with the medical field because of our research programs. It turns out that the initial research is done by the highly paid physician but the routine examination is done by people who are called technicians. They are not highly paid but they are highly skilled.

R. S. Gilmore (General Electric): I'd like to come down on the side of Bruce, here. One of the problems in a practical environment where you apply an inspection is that usually you have to look at a large number of pieces. The problem is that humans are very unreliable under such conditions. We're working very hard to get people out of the decision making process so that we can improve the reliability of our inspections. When we consider imaging or medical applications, I would suspect that the number of decisions that have to be made are relatively few in comparison to the normal industrial production environment.

H. Guttwein (U. S. Army R&D Command, Dover, New Jersey): I'm jumping ahead, I realize here. Has any thought been given to the methodology in using this particular inversion data to correlate between your artificially produced defects and, say, some natural type defects that have occurred? Has there been any correlation work done?

R. B. Thompson: Not in what you've heard this morning. I think in the area of the ceramics, there's been some of that.

H. Guttwein: The second question is that I notice that all your standards are titanium. Is that by accident or is there a reason for it?

R. B. Thompson: There is a reason. It turns out that the diffusion bonding process works very well in titanium.

H. Guttwein: How does it work for aluminum or steel?

R. B. Thompson: We have done work in the program in developing diffusion bonding techniques for both of these materials. The basic problem is that if you do the bonding in a room atmosphere, there is an oxide formation which can inhibit bonding. This is soluble in titanium at bonding temperatures so there is no problem. In steel, we have found that when we do the bonding in a reducing atmosphere, we can, in fact, fabricate such samples. In aluminum we have also had success by sputtering off the oxide layer, then bonding the samples in vacuum. This has been done in the laboratory.

H. Guttwein: But it can be done?

R. B. Thompson: It can certainly be done. It is more expensive so we didn't choose to use it to prepare samples for this program.

H. Guttwein: My last comment is that, considering the industrial environment and the need for accurate and high volume type inspection, you have to eliminate the human being as the inspector. You have to make an electrical and mechanical inspection but not a human inspection. Thank you.