

## QUANTITATIVE ULTRASONICS - OVERVIEW

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I would like to give an overview of our work in quantitative ultrasonics in the ARPA/AFML program. The goal is to use ultrasonics to determine failure related or fracture critical properties of a flaw. In practice, this implies the use of ultrasonics to determine the geometric shape of the flaw: its size, its shape and its orientation with respect to a stress field.

The two types of techniques that one might imagine that could be used to do this are summarized in Fig. 1. I'm sure they are familiar to everyone, but it is worthwhile to review them just so that we're all starting off on the same footing. I have identified the first technique as imaging. I think you're all familiar with what imaging does. The ultimate goal is to directly draw a picture of the defect. Such an approach is, however, not optimum in all situations. For example, one can only resolve features that have dimensions on the order of the wavelength of ultrasound. Specular objects are poorly imaged because the ultrasonic reflection is in a narrow beam and may not strike the receiving elements. Also, an image can be severely distorted if the object itself has internal elastic resonant modes which are excited by the ultrasonic radiation. As an example, consider a 1/32 inch defect in titanium. It's size is equal to the wavelength of a 8 MHz longitudinal wave. To image this defect with sufficient resolution to say something about its detailed shape, one would need an imaging system operating in the 10 to 20 MHz range. Such systems certainly are feasible, but they would be very expensive right now. Furthermore, if the material has a high attenuation and/or if the defect is very deep within the material, it may be very difficult to obtain sufficient penetration at these frequencies. Therefore, despite the great importance of imaging approaches, it is equally important to seek other types of measurements which can be used to characterize defects in such situations. These have been classified as scattering techniques and are designed to deduce key geometric features of the defect from some particular detail of the scattered fields. Specific examples of both types of measurements will follow.

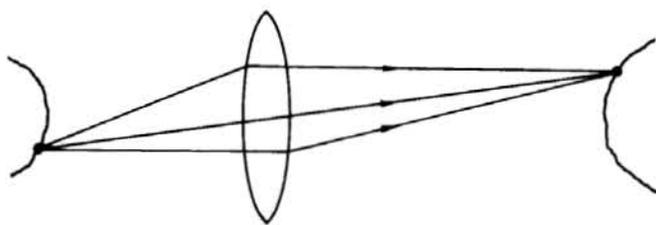
First, let us consider imaging, as indicated in Fig. 2. I'll treat the optical case, with the understanding that the ultrasonic case is very similar. The role of a lens in imaging is familiar. One can imagine that a point on the object emits a bundle of rays which are all converged by the lens to some common point in the image plane. Alternately, one can view this process as the emission of spherical wave fronts which are changed in curvature as they pass through the lens and are brought to focus in the image plane. One can also describe this process analytically. I'm not going to go through the equations in detail. The point is that if the field amplitude and phase are known at some plane, which I have taken to be  $x = 0$ , then the image intensity at all points can be determined from the appropriate integrals. Subsequent papers will discuss some systems that are based upon the use of electronic techniques to evaluate these integrals in a very rapid fashion.

FLAW CHARACTERIZATION CONCEPTS

TYPE OF MEASUREMENT	GOAL	CONDITIONS FOR BEST PERFORMANCE
IMAGING	DIRECTLY DEFINE GEOMETRIC OUTLINE	<ul style="list-style-type: none"> <li>• WAVELENGTH &lt; DIMENSIONS</li> <li>• SURFACE ULTRASONICALLY DIFFUSE</li> <li>• OBJECT HAS NO MAJOR ELASTIC RESONANCES</li> </ul>
SCATTERING	DEDUCE KEY GEOMETRIC FEATURES FROM PARTICULAR DETAILS OF SCATTERED FIELDS	<ul style="list-style-type: none"> <li>• DIMENSIONS &lt; WAVELENGTH</li> <li>• SPECULAR OBJECTS</li> <li>• RESONANCE OBJECTS OR ANISOTROPIC MEDIA</li> </ul>

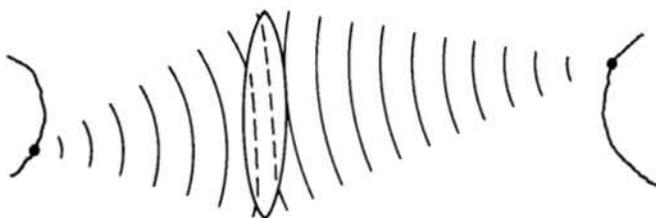
Fig. 1. Comparison of Flaw Characterization Concepts.

IMAGING



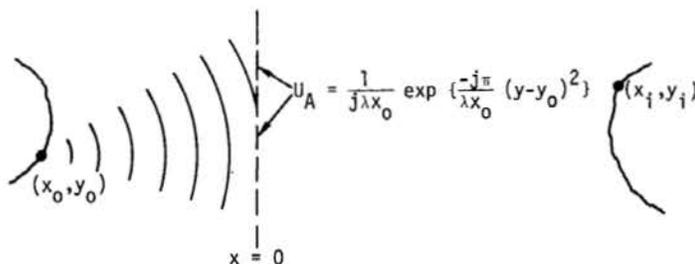
(a)

RAY PATHS



(b)

HUYGHENS WAVEFRONTS



$$U(x_i, y_i) = \frac{1}{j\lambda x_i} \int U_A \exp\left\{\frac{j\pi}{\lambda x_i} (y_i - y)^2\right\} dy$$

$$= \frac{-1}{\lambda^2 x_0 x_i} \int \exp\left\{\frac{j\pi}{\lambda} \left(\frac{y_i}{x_i} + \frac{y_0}{y_i}\right)\right\} dy$$

(c)

MATHEMATICAL IMAGE FORMATION

- INTEGRAL CAN BE APPROXIMATED BY ELECTRONICALLY PROCESSING OUTPUT OF TRANSDUCER ARRAY

Fig. 2. Models for Image Formation.

Figure 3 illustrates scattering systems. Consider first a single transducer irradiating a flaw with an ultrasonic wave where wavelength is comparable to the flaw dimension. A second transducer can then be used to measure the scattered energy as a function of the angle and frequency. Several subsequent papers discuss techniques to exploit characteristic features of the scattered energy to learn the nature of the flaw. A modification of this approach utilizes a single transducer operating in the pulse-echo mode to scan the flaw. If the echo amplitude is plotted as a function of position, a signature is obtained which can also be used to distinguish between different types of defects.

Figure 4 illustrates the type of signatures that might be expected in an angular scattering process. This figure presents the scattering from several acoustically soft prolate spheroids as predicted by Senior and Uslenghi.<sup>1</sup> The term "acoustic" refers to a fluid medium which cannot support shear waves. The solution in a solid would be somewhat different, but these results at least qualitatively indicate the influence that defect shape can have on ultrasonic scattering. At the top is shown the incident ultrasonic wave with the wavelength to scale with respect to the size of several prolate spheroids of equal area projected on the transducer. Below is plotted the scattered energy as a function of angle. You can see that these different shaped objects have very dramatically different features of angular scattering. The spherical defect has a very smooth nearly symmetric scattering. As the defect becomes more elongated, much more of the energy is scattered in the forward direction, and there's considerable fine structure that really doesn't show on this scale. These kinds of solutions are not available at present for the elastic case although a subsequent paper discusses how they might be developed.

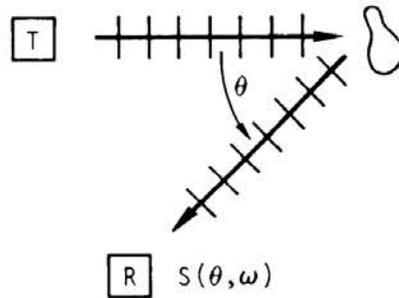
I would like to now become a little more specific about the sorts of things we have been doing. First, I would like to show the steps that we feel are needed in a quantitative flaw definition system, Fig. 5. One can imagine this as applying to either an imaging type system or a scattering system; these same general steps must be followed in either case. One is trying to measure geometric characteristic of a flaw, independent of instrumentation and part geometry. First, ultrasonic energy must be introduced, so one needs a transducer. This should have characteristics that are well known functions of the input electrical signal. Conversely, one would like to know the quantitative relationship between the ultrasonic fields striking the receiving transducer and the electrical signal. Supposing that one knows these relationships, then he should be able to isolate the ultrasonic scattering information, which contains the characteristics of the defect, from the total response. It is then necessary to process this information in such a way as to accentuate key features and ultimately to interpret these in terms of fracture critical parameters or parameters of some other failure model.

Both the ARPA/AFML research program centered at the Science Center and the program of this meeting are organized according to these topical areas. Subsequent papers deal with each of these different steps. Included are a number of excellent papers from other laboratories which fit very nicely into this same schemework.

FREQUENCY OR ANGULAR DEPENDENCE

WAVELENGTH  $\sim$  DIMENSIONS

FLAT OBJECT WITH SCATTERING DOMINATED BY EDGES



INDICIA

EASILY SET-UP WITH PRESENT INDUSTRIAL APPARATUS

TRANSLATE



OTHERS - TO EVOLVE FROM ANALYSIS AND EXPERIMENTAL EXPERIENCE

Fig. 3. Scattering Measurements.

SCATTERING FROM ACOUSTICALLY SOFT PROLATE SPHEROIDS

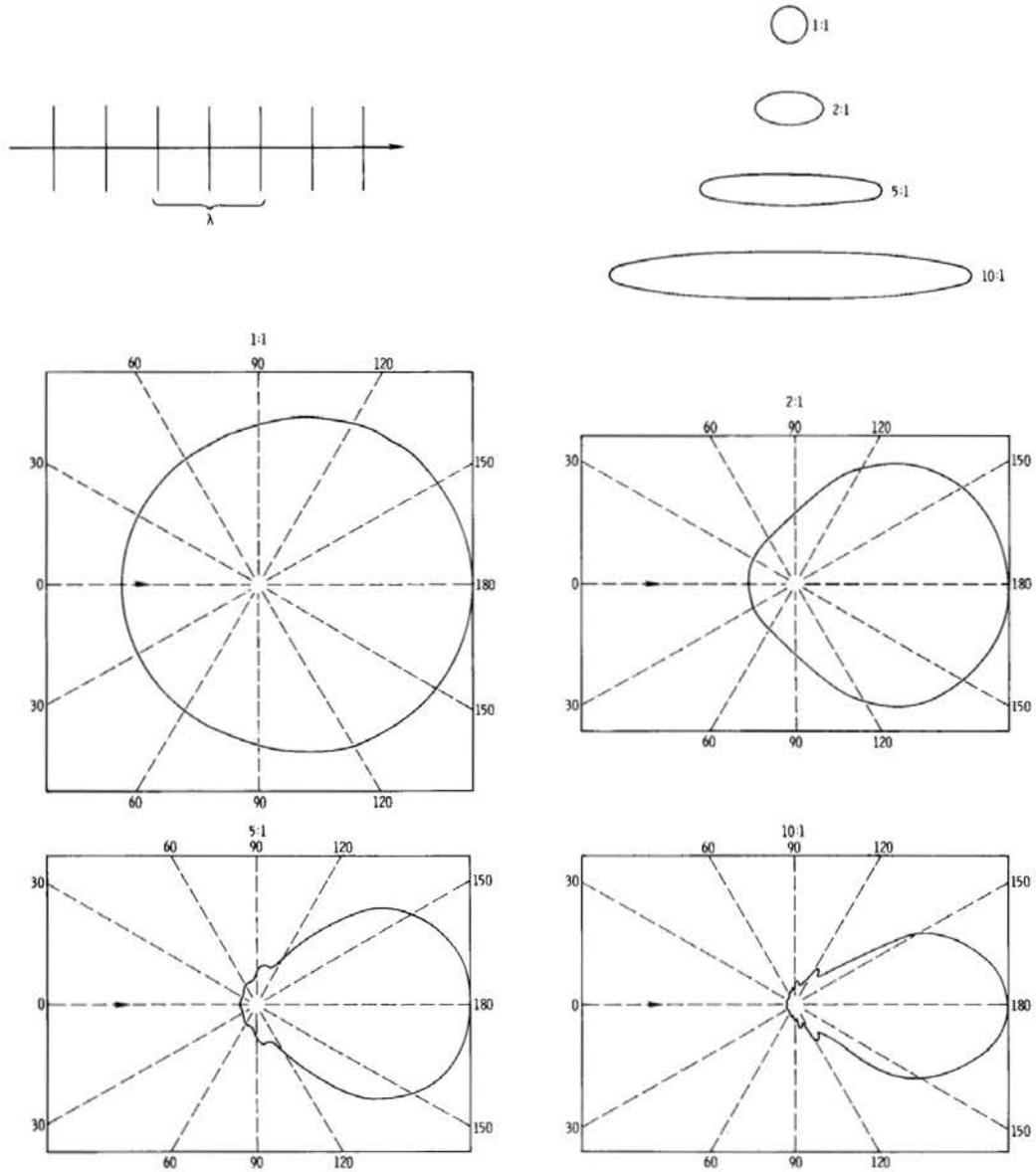


Fig. 4. Scattering from Acoustically Soft Prolate Spheroids (after Senior and Uslenghi).

Session V includes papers on transducers. Work on piezoelectric transducers is presented which is aimed at the development of transducers which behave in accordance with models so that the quantitative understanding of the transfer between ultrasound and electrical signals can be established. There are also some papers on other types of transducers, including electromagnetic transducers, which have a number of interesting features for quantitative NDE. Session IV includes a discussion of one way of processing the scattered signals, the formation of an image. Papers in Sessions II and III discuss the previously mentioned scattering techniques.

I would now like to discuss the boxes marked "part" and "fracture critical parameters" in Fig. 5. In our research program, we would like to have available samples with defects of well known geometry so that the various candidate techniques for defect characterization can be accurately evaluated. This also serves an important role in evaluating models for ultrasonic interactions with various shaped objects. These models must be on a firm foundation if we are to interpret scattering measurements in terms of fracture critical parameters.

We have used the diffusion bonding technique to implant a number of different shaped cavities in cylindrical titanium samples (Fig. 6). They are constructed of two halves which are diffusion bonded together with a machined-in defect of carefully controlled shape at the bond plane. We find that the bond plane is essentially invisible after the bonding process, so that we essentially have a homogeneous solid with a well characterized defect in it.

The shapes of defects are shown here in scale. They vary from 400  $\mu\text{m}$  dimensions, which is 1/64 of an inch, on up to 1200  $\mu\text{m}$ . On the lower part of this figure, I've shown the wavelength of various frequency ultrasonic waves, again to scale, so you can get an idea of what regime of scattering is taking place.

There were a number of philosophies that went into this choice of the defect shapes, and I think I should discuss them briefly. I have already implied the first philosophy. We wanted some shapes that were simple enough that we could develop a theory for the ultrasonic interaction with the flaw. Therefore, all of these are spheroids of revolution about the axis of the sample. However, that really wasn't enough. We wanted to have samples that would have considerably different failure characteristics because, of course, we ultimately must find what features of the scattered fields give us information about when a defect will fail. If one imagines these samples in an axial tension, there are some very elongated defects in which there is insignificant stress concentration so that the sample would not fail at a much lower stress than if the defect were not present. There are also pancake shaped defects which would fail at a considerably lower stress. Our program is to look at the scattering from these defects to understand the scattering, and then to see which features are associated with these sharp edges and corners which will lead to early failure. In addition, we have included in our studies flat bottom holes. This is very important. These are used as standards and provide a good tie with work in the NDE community that is presently going on and, I'm sure, will continue to go on for some time.

## QUANTITATIVE FLAW DEFINITION

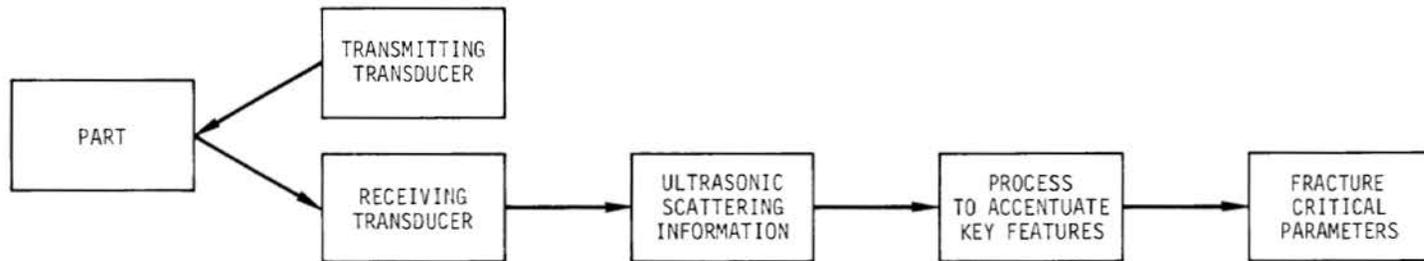


Fig. 5. Steps needed for quantitative flaw definition.

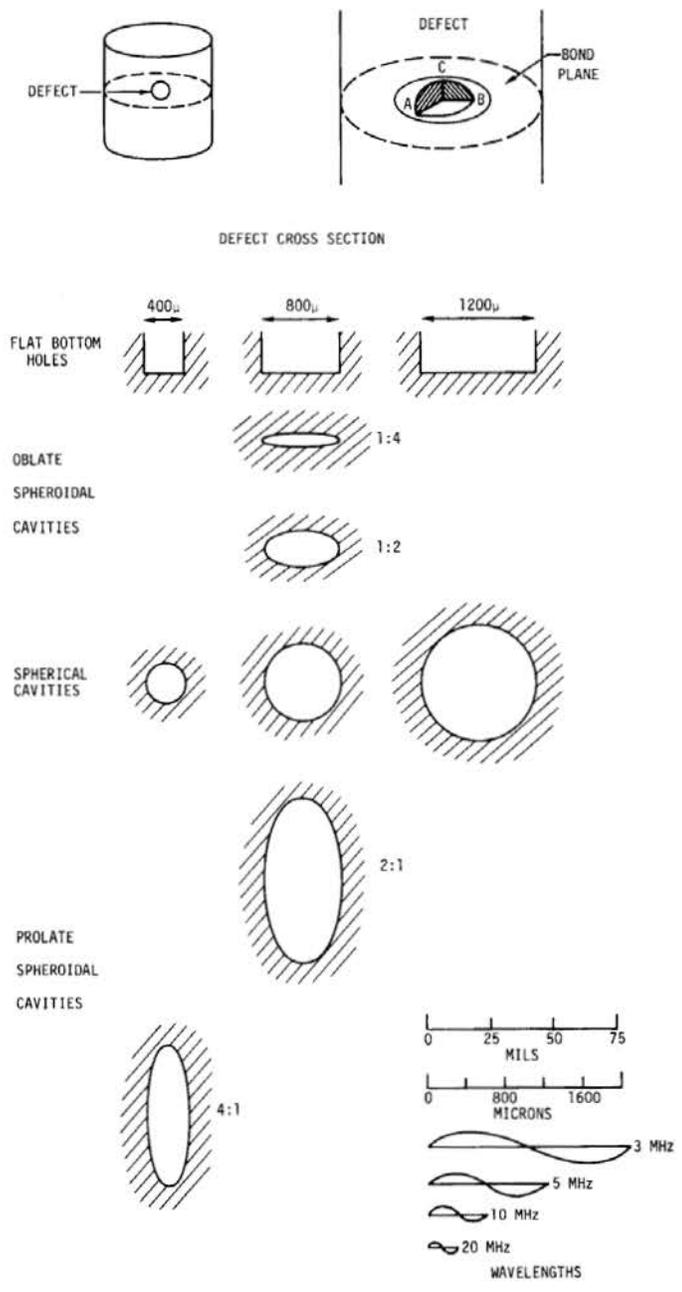


Fig. 6. Defect shapes in diffusion bonded samples.

Another advantage of having this set of samples is the ability to circulate these samples among the various experimental investigators in the program. This gives us an opportunity to compare the results obtained with different experimental systems and procedures. It puts everything on a common ground.

All of the investigators haven't had time to look at these since we just started making them less than a year ago. The papers by Bill Yee and Paul Packman will deal with these diffusion bonded samples explicitly.

Figure 7 deals with the question of scattering and some of the questions we have to ask before we can obtain fractural critical parameters. I was somewhat surprised when we started out the program that as little had been done in the area of ultrasonic scattering in elastic solids as is the case. I think a number of the other people also were surprised. An important question that arises is, "Can one use a scalar theory to describe scattering in a solid." Ermolov<sup>2</sup> has published a paper that says, "Yes, it works very well for flat bottom holes." Golubev<sup>3</sup>, another scientist in the Soviet Union, has said, "It doesn't work at all well for cylinders." There's clearly a question here. Under exactly what conditions can the theory that would be used to describe compressional wave phenomena in the fluid case be extended to solids? Here again, I draw from the literature. Sengupta<sup>4</sup> has calculated the scattering from rigid and soft objects in a fluid, and these calculations can be profitably compared with those of Cohen, which follow, for a cavity in an elastic solid. All three calculations are performed for the case  $ka = 1$  as illustrated at the top of the figure.

For the acoustically hard sphere (a rigid obstacle in a fluid) one sees that most of the scattering is in the backward direction. However, for the case of the acoustically soft sphere (a low density bubble in a fluid) most of the scattering is in the forward direction. The differences are substantial. For a spherical cavity in titanium, one again has a different response. Shear waves are excited in the solid, which probably isn't surprising. In addition, the longitudinal wave scattering has a considerably different spatial characteristic than either of the two acoustic cases. We are pursuing these questions in order to develop the quantitative tools necessary to interpret scattering measurements. Included are both experimental and theoretical efforts. At the present time, the scattering characteristics are only known for the sphere, and we are developing approximate theories that will enable us to extend these results to real defects. In other words, we want to find exact solutions to simple geometries and use them to evaluate approximate techniques which can be extended to other shapes such as rough cracks for which one can never hope to solve the scattering problem.

#### References

1. T. B. A. Senior and P. L. E. Uslenghi, "The Prolate Spheroid" in *Electromagnetic and Acoustic Scattering by Simple Shapes*, J. J. Bowman, T. B. A. Senior, and P. L. E. Uslenghi, Eds. (John Wiley, N.Y., 1969) p. 416 ff.
2. I. N. Ermolov, *Sov. Phys. - Acoustics* 5, 248 (1959).
3. A. S. Golubev, *Sov. Phys. - Acoustics* 7, 138 (1961).
4. D. L. Sengupta, "The Sphere", in *Electromagnetic and Acoustic Scattering by Simple Shapes*, J. J. Bowman, T.B.A. Senior, P.L.E. Uslenghi, Eds. (John Wiley & Sons, Inc., N.Y., 1969) p. 353 ff.

SCATTERING FROM SPHERE  
 $ka = 1$

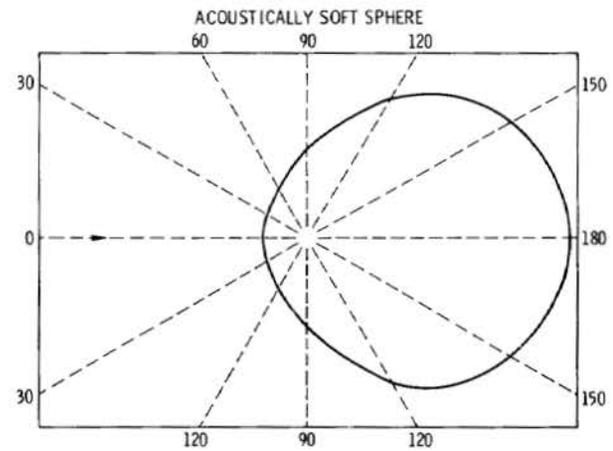
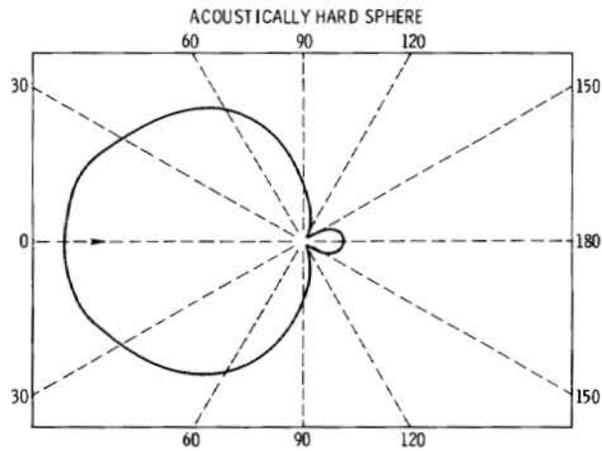
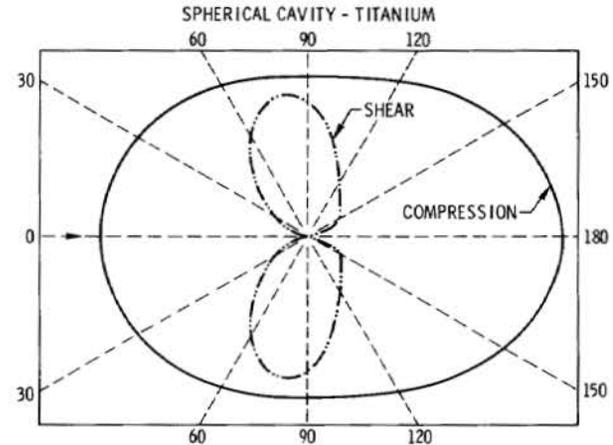
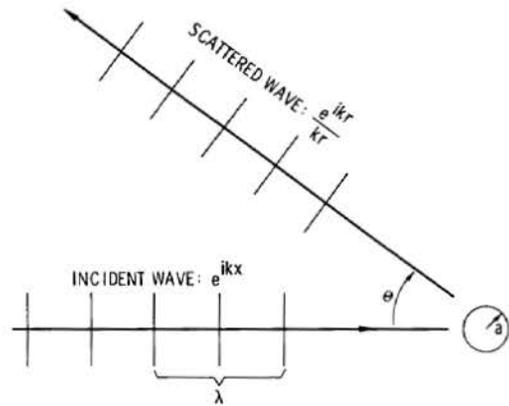


Fig. 7. Scattering from spherical objects in solids and liquids (after Sengupta and Cohen ).

## DISCUSSION

- DR. DON THOMPSON (Rockwell International Science Center ): Questions or discussion?
- DR. ROBERT GREEN (John Hopkins University): A comment and a question. The comment is that I think that when you are using imaging systems you have to be very, very cautious, as you probably are aware, of drawing analogies between elastic imaging systems and optical imaging systems. You can do sort of a loose thing on it, but you have to be very, very careful, in my opinion, not to go too far.
- Also, when you make the diffusion bonded specimens, have you pulled any of them yet, and if you have, don't they break at the diffusion bond which indicates the diffusion bond is the weakest point in the bond even though you don't pick it up ultrasonically?
- DR. BRUCE THOMPSON (Rockwell International Science Center ): With regard to your first comment, we would certainly agree with you in regard to the imaging. Secondly, Neil Paton has prepared the diffusion bonded specimens and I think he can probably best answer the second question.
- DR. NEIL PATON (Rockwell International Science Center): If you intentionally make the bond line defect-free, then it fails away from the bond line. If you have a large bonding fracture defect in the bond line, then, of course, it does fail at the bond line, because the defects grow. But if you intentionally make what you want to be a good bond, then it fails away from the bond line. We have every reason to believe from the microscopy, metallography, ultrasonic work, and various other experiments with advanced properties that we've done, that the bond line is essentially invisible by whatever technique you want to use.
- DR. GREEN: Well, I don't doubt that it's invisible, but I've done some work with them and I can't make good diffusion bonds.
- DR. PATON: It is very difficult.
- DR. GREEN: I don't pick it up ultrasonically, but it does break there.
- DR. PATON: Well, our bonds don't break there.
- DR. CRAIG BIDDLE (Pratt/Whitney Aircraft): As far as diffusion bonds are concerned, I agree with this gentleman (Dr. Paton) that a good diffusion bond will not break at the bond line unless you put a defect in it.
- DR. DON THOMPSON: Neil thanks you.
- DR. SY FRIEDMAN ( NRDC, Annapolis): I have a question. As a matter of principle, can one say that from the total knowledge of scattering properties, one can get a Lietz characterization on the scattering site? In other words, can you determine in principle the size and shape of the scatterer from a complete knowledge of its scattering properties?

- DR. BRUCE THOMPSON: That's, of course, an excellent question that should be asked. I think in principle, from a complete knowledge of the scattering fields, one can get to this, but I, myself, have not gone through this proof. I think the question here, the real question of practical importance, is going to be how little information can we have and still get a good idea of what the defect is. But there are others in the audience who are much better able to answer that question than I, and if they would care to, I would--
- DR. DON THOMPSON: I'll call on Dave Lee.
- DR. DAVID LEE (Air Force Institute of Technology): That is a very good question, indeed. For the electromagnetic and simple acoustic cases, the answer to it is "yes", but the problem is ill-posed, so you have a difficult time actually achieving it. It's a very tough question even in some simple cases where you know you could instinctively do it.
- DR. DON THOMPSON: One more question.
- DR. GORDON KINO (Stanford University): Bruce, are you referring here entirely to cavities or to defects which are much smaller than the wavelength? In terms of angular dependence of scattering and so on?
- DR. BRUCE THOMPSON: You mean the figures I showed?
- DR. KINO: Yes.
- DR. BRUCE THOMPSON: Those are frequency sensitive, so they will change with the wavelength of the ultrasound.
- DR. KINO: Okay. In other words, you weren't trying to get down to a limit where you are--
- DR. BRUCE THOMPSON: That was not in the Rayleigh limit--
- DR. KINO: That's what I was wondering.
- DR. BRUCE THOMPSON: Where it would be totally frequency insensitive. The reason I gave there is that these are the smallest kinds of defects people look at today and the wavelengths are those available with conventional instrumentation. They are not necessarily small enough to be truly in a Rayleigh limit.
- DR. KINO: I know that a lot is being done, but when you look in this range you keep on going down in size. Is there a major qualitative difference, I mean, once you're done to something comparable to the wavelength?
- DR. BRUCE THOMPSON: I think we'll probably see something about this, perhaps, in some of the later papers. I'm not really prepared to discuss it.
- DR. DON THOMPSON: We'll take one more question.

- DR. PAO (Cornell University): I was surprised to hear your comment about the limited availability of the scattering cross-section data you showed. As far as I know the whole theory was worked out in the early 60's. As a matter of fact, Dr. Mau of the Rand Corporation has a computer program available to compute anything you want to know about scattering by a sphere or by a cylinder. Both computer programs were well developed in the mid-60's. The main difficulty here is in the interpretation. Once you get the results, how do you go back to find out what is the diameter of the source of the scattering, even from a sphere or cylinder? That is the main question right now.
- DR. BRUCE THOMPSON: Okay. I apologize for that. I believe I said, "except for the sphere" and I should have included the cylinder. The reason I did not mention the cylinder was because it is an infinitely long object which is not the kind of defect one looks for in a solid, but I agree with your comment and I apologize for any misrepresentation. Also, the interpretation is an extremely important problem and I agree with that statement.