OVERVIEW OF ULTRASONIC DEVELOPMENTS

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ABSTRACT

An overview of the ultrasonic developments which have occurred in the DARPA/AFML Interdisciplinary Program for Quantitative NDE is presented. The paper is introduced by a discussion of the philosophy of the program and a review of the progress made during the last five years towards the development of quantitative techniques and criteria for accepting or rejecting parts. This is followed by a summary of the relevant papers presented at this meeting and of the role which they play in the evolution of this new technology. The paper concludes with a discussion of the use of these technical building blocks in establishing on-line systems and stand alone spin-offs for DoD application.

This paper will present a slightly broader perspective than an overview of the papers in this session. It will cover those papers, but it will also delineate the relationship between them and a number of papers presented in other sessions. In this way, a picture of the thrust and philosophy of the DARPA/AFML Interdisciplinary Program for Quantitative Flaw Definition can be presented.

The first figure is a summary of results obtained by Rau.* It provides us with a very good description of the motivation for the development of quantitative NDE techniques. The left hand part of the figure uses the example of turbine disks to illustrate the wastes that occur when part service lives are based on average fatigue behavior rather than the condition of individual parts. Since the distribution of failure times is broad, one must select a design life that is quite conservative for most parts in order to avoid the premature failure of more than a few. As shown for this example, if one requires that only one part in a thousand will fail during the design life, one finds that 50 percent of the parts would

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PROBLEM

STATISTICAL NATURE OF FAILURE
CAUSES MUCH WASTAGE FOR A SPECIFIED RELIABILITY.

STRATEGY

NONDESTRUCTIVE EVALUATION TO ALLOW LIFE EXTENSION OF INDIVIDUAL COMPONENTS UNTIL DAMAGE DEVELOPS.

CRITICAL ELEMENTS

- NONDESTRUCTIVE METHOD OF MEASURING FLAW SIZE
- QUANTITATIVE
- RELIABLE

INSTRUMENT ADJUSTED TO MINIMIZE COSTS.

- QUANTITATIVE METHOD TO SELECT ACCEPT/REJECT CONDITION
- FAILURE MODELS
- ECONOMIC ANALYSIS

Fig. 1 Economic benefits of quantitative NDE.
have lasted more than four times the design life. This excess life is wasted. To overcome this problem, one must, in some way assess the condition of individual parts by the use of NDE techniques or other approaches. One is then no longer governed by the statistical distribution, but can retire specific parts as needed: Retirement-for-Cause.

The center of the figure presents economic data illustrating how, when using NDE, the system costs can be minimized by the proper selection of the accept-reject criteria. Improving the ability of the NDE technique to quantitatively separate good and bad parts increases the depth of the cost minima and further reduces costs. The objective of the papers that you will hear today, and in several other sessions, is to ultimately make such savings possible.

Figure 2 presents some further background on the role of NDE in lifetime prediction, as also noted by Thomson and Marcus. One of the models commonly used to predict part lifetimes or failure is fracture mechanics, coupled with crack growth rate models. To use these models, one needs three inputs. One needs environmental inputs, including both loading and any gaseous or aqueous environmental conditions that might influence crack growth rates. These inputs can be determined during design or by monitoring of the part during its service. The second inputs one needs are material properties, such as resistance to crack growth. Thirdly, one needs to know flaw sizes and orientations. Material properties have been studied extensively and can be found in handbooks and other sources. However, no satisfactory techniques are available on line for determining flaw size and orientations. The present program is addressing this deficiency.

Figure 3 indicates the philosophy that has been utilized in developing a quantitative NDE capability. In order to predict a part lifetime, three types of information must be combined: a failure model, measurement results which have been processed by an inversion technique to give estimates of flaw parameters, and if possible, independent information, or a priori information about what types of flaws might be expected in the part under study.

The a priori information is needed since, under many conditions found in practice, it is not possible to experimentally make enough measurements to uniquely determine the state of the flaw. Examples of these conditions include high ultrasonic attenuation, which limits the use of high frequencies, or complex geometries, which restrict the range of angles that can be used in a measurement. Under such conditions, the measurements can rule out many possible flaw types, but they can not uniquely define the flaw. Independent information about the flaws likely to be present for the particular processing and service history of the part may eliminate other possibilities and improve the flaw estimate.

Once a lifetime prediction has been made based on these inputs, an accept-reject criteria must be applied to determine whether or not the part should be removed from service. This criteria must be based on a risk-benefit analysis for the part in question.

Before proceeding with this overview, it should be emphasized that only work performed as a part of the DARPA/AFML Interdisciplinary Program for Quantitative NDE will be addressed. Many other papers are included in this meeting which were supported by other agencies. They also form important parts of the same technology but will not be explicitly discussed.

Referring again to Fig. 3, it should be noted that a major emphasis of the DARPA/AFML Program

![Diagram](image-url)
has been the improvement of measurement sciences (including inversion techniques). This has been treated generically, with the objective of developing basic techniques which could be applied to many different material systems. Additional efforts have been directed towards applying these techniques to specific material systems, ceramics and metals.

In order to discuss the technique development, it is useful to review briefly what has been done during the previous years of this program and what appears to lie on the horizon. Figure 4 illustrates just a few of the highlights of the past years. Also included is a schematic flow diagram that presents the steps needed to develop inversion techniques. One must first solve the forward problem of the interaction of energy with a known flaw. In this session, ultrasonic energy is being considered but the same concepts apply to the electromagnetic techniques that were discussed in a previous session. Solution of the forward problem involves an interaction between theory and experiment. Once that is in hand, one must concentrate on the inverse problem, which ultimately will lead to a predictor that can be used in life prediction. Of course, at the same time, one must continue to study the forward problem because extensions to more difficult situations are needed to enable these inverse techniques to become more widely applicable.

In 1975, the DARPA/AFML Interdisciplinary Program for Quantitative NDE was initiated, and an interdisciplinary team was gathered which established active communications between a group of scientists and set the stage for major contributions from the different disciplines. Also during the year, some basic elements of scattering theory and experiment were developed. The next year a set of several different experimentally verified scattering models were completed, particularly for the case of bulk inclusions.

In 1977, the annual conference was held at Cornell. One of the high points of the meeting was the first demonstration of quantitative inversion of experimental data. In that case, the adaptive learning technique had been trained on theoretical solutions and then used to predict flaw parameters from experimental data. In addition, work was initiated on the problem of characterizing surface cracks.

By 1978, last year, a family of inversion algorithms had been developed. Techniques for shape reconstruction, adaptive learning, and long wavelength techniques for parameter estimation were included. There was further extensions for the case of surface cracks. In ceramics, a framework for life prediction was developed, and strategies were defined for incorporating failure modeling and risk analyses to quantify the determination of the accept/reject criteria.

In this meeting, the work to be presented will include refinement of inversion techniques, extension of the scattering models to the case of irregular flaw shapes and multiple flaws, a more detailed demonstration of the life prediction strategy for ceramics, and an initial demonstration of the life prediction strategies for the case of metal fatigue. Also included will be a discussion of an ultrasonic test bed which will play a key role in reducing some of these techniques to practice.

Figure 5 illustrates one of the future directions of the program. One question that must be addressed is, "How good are the models that have been developed for inversion of data from ellipsoidal flaws when the models are applied to more realistic shapes such as irregular or multiple
flaws?" A program that will answer this is schematically indicated. Measurements, or theoretical predictions, of scattering from irregular and multiple flaws will be obtained and used as inputs to the existing inversion algorithms (which were optimized for ellipsoidal shapes). The algorithms will then give, as outputs, a set of equivalent flaw parameters. These flaw parameters will then be used to make a prediction of the lifetime of that equivalent flaw. Finally, this lifetime will be compared with the actual life of the flaw. The degree of agreement is actually the bottom line in evaluating the performance of any inversion technique. It's not really important whether the technique tells exactly what the flaw shape is. It is important whether it predicts the lifetime of that flaw with sufficient accuracy.

In order to perform this test, it is necessary to have a theoretical and experimental understanding of the behavior of flaws that do not have simple geometries. A number of the papers that are presented in this session provide the foundation for this understanding.

Figure 6 summarizes the papers to be presented in this session. The Distorted Wave Born Approximation will be presented by Domany. In this integral equation approach to ultrasonic scattering, a general flaw shape is viewed as a perturbation of a spherical shape. For flaws with irregular surfaces, but generally spherical shapes, this can be expected to give quite accurate results. Gubernatis will then discuss the use of PADE Approximates to improve the accuracy of scattering calculations at higher frequencies. The PADE Approximates are functions in a series expansion of the ultrasonic scattering. They can be derived from various classical expansions of the scattered fields, but often have much better convergent properties and therefore a finite number of terms give useful results at higher Ka values. The T-matrix approach will be treated by the Varadans. Through the use of a technique known as the extended boundary condition, with somewhat greater computational effort than is needed in the other techniques presented, they are able to obtain very precise scattering predictions. Again, the results are useful for rough and multiple flaws, Tittmann will discuss experimental investigations of the predictions of these theories. The measurements were made on a new set of diffusion bonded samples containing irregular and multiple flaws.

Papers will be presented on the scattering from cracks as well as volumetric flaws. The Crack-Opening Displacement Representation Theorem, which is a reformulation of elastodynamic theory to avoid some of the difficulties that occur at caustic points and shadow boundaries, will be discussed by Achenbach. Adler will present experimental tests of this theory.

Figure 7 illustrates some of the fundamental information that will be included in these talks. This is a result obtained by the Varadans in the study of the effects of surface roughness on scattering. The dependence of the scattering at 45 degrees is shown, as a function of Ka, for three flaws. These are characterized by a parameter σ, which is a ratio of roughness to size, and N, which gives number of roughness periods around the circumference. The solid line shows...
the results for a smooth flaw, \( \sigma = 0 \). The dashed line gives the results for a roughness of 0.05 for the case of 16 periods around the periphery. The dash-dotted curve presents the results for the same roughness parameter but with 64 roughness periods, i.e. a finer scale roughness. It can be concluded from results such as these that the flaw characterization techniques based on ideal ellipsoidal shapes should still work fairly well when surface roughness is present, as long as that roughness is fine with respect to the ultrasonic wavelength.

Once the forward scattering problem has been solved, attention must focus on the inversion problem. Figure 8 summarizes some of the approaches presented in this area. The inversion techniques are classified into two categories. Reconstruction techniques can be used when \( K_a \) is greater than two or three. Then there is enough information to draw a picture of the flaw. The papers presented in the imaging session fall in this category. In particular, Kino's work on electronically focused and scanned imaging systems, and Lakin's work on wave front reconstruction imaging were a part of the DARPA/AFML program. Two other techniques, which can be categorized as reconstruction techniques, will be presented today. The work of Bleistein and Cohen on Physical Optics Farfield Inverse Scattering (POFFIS) and the work of Rose on the Inverse Born Procedure.

Each of these reconstruction techniques has been optimized on the basis of slightly different physical assumptions about the flaw, as is indicated by the table in the figure. There are various approaches in the classical imaging approaches of Kino and Lakin, the basic processing algorithm is optimal when the flaw itself has diffusely reflecting surfaces. On the other hand, the POFFIS algorithm is probably optimal when the surfaces are smooth and specular. That is, there is not an intrinsic roughness built into that algorithm. The Inverse Born Approximation is based intrinsically on an elastic wave model. Approaches of that type promise to be able to treat some of the more complex phenomenon associated with elastic wave propagation, internal reverberations, and mode conversion. This is shown as a broken check in the table of Fig. 8 because the simplicity of the Born Approximation precludes all of those effects from being included in detail. Nevertheless, they are implicitly included.

On the other hand, if sufficiently high frequency information is not available to reconstruct flaw shapes, another family of techniques are available. These are techniques which require some independent information or assumptions about the flaw state. For example, if one knows that the flaw is an elliptical crack, then its axes and orientation can be determined. Examples of this are the adaptive learning technique of Mucciardi, the long wavelength technique that will be dis-
cussed by Richardson, and also some unified algorithms which contain elements of several techniques which will be discussed by Fertig.

Figure 9 presents an example of a reconstruction result. Here, the POFFIS algorithm has been used to reconstruct a picture of the shape of an elliptical flaw.

Figure 10 presents a flow diagram of a technique applicable at lower frequencies. Here, Fertig has integrated two independent flaw characterization techniques, and some a priori information, to develop a unified prediction. In the left hand sketch is shown the case of a long wavelength scattering measurement. From the initial curvature of the scattered amplitude versus frequency plot, one derives a parameter known as $A_2$. This is combined with a second piece of information, illustrated in the right hand sketch, which provides a measure of the distance from the front surface of the flaw to the center of the flaw. These two pieces of information are combined in an algorithm which incorporates the a priori assumption that only inclusions of a few specific materials can be expected. For ceramics, this assumption is based on known processing conditions. In addition, the flaw can be assumed to have either a spherical, or spheroidal shape. The output of the algorithm is the material of the inclusion and its dimensions. This, then, is an example of the application of the technique where a priori information is explicitly used to allow us to determine key flaw parameters.

Thus far, the measurement science part of the DARPA/AFML Program has been discussed. These general results have been applied to two distinct material systems: metals failing under fatigue and ceramics failing under brittle fracture.

As shown in Fig. 11, three papers will be presented on the fatigue problem: one on fatigue life prediction in the microcrack regime by Buck, one on fatigue life prediction in the macrocrack regime by Tittmann, and one on the theory of the surface wave scattering from macrocracks by Auld.

![Fig. 8 Summary of ultrasonic inversion session.](image)

![Fig. 9 Reconstruction of oblate spheroid using POFFIS algorithm.](image)

![Fig. 10 Unified inversion algorithm.](image)

![Fig. 11 Summary of ultrasonic surface wave session.](image)
The relationship between these three talks is illustrated in Fig. 12. As discussed in previous papers by Marcus and by Morris, metal fatigue can be broken down into two regimes. The fatigue starts with an initiation process, in which microcracks are nucleated at a material discontinuity, for example, intrametallic particles. These microcracks gradually grow and coalesce to the point of the formation of a macrocrack, which ultimately then grows to failure in accordance with the rules of fracture mechanics.

The relationship of the experimental results is as follows. In the microcrack regime, Buck has studied the use of ultrasonic harmonic generation to predict a remaining fatigue life in initiation. From that remaining life in initiation, combined with the crack size at the end of initiation, one can use the results of the fracture mechanics and growth laws to predict remaining life in propagation. The total remaining life is the sum of the two.

If one of these microcracks has already become a macrocrack, one can directly measure its depth by surface acoustic wave NDE, as will be discussed by Tittmann, based on some of Auld's models. Here one can predict a remaining life in the propagation regime, now equal to the total life. The three papers comprise an integrated approach to the detection of metal fatigue. This is a very limited demonstration because the work is just beginning. However it provides an example of a methodology which has the potential of finding widespread application in fatigue life detection.

Figure 13 summarizes the application of the general measurement techniques to the prediction of ceramic strength. An overview of the strategy will be presented by Evans. Experimental results obtained using a number of specific ultrasonic measurement techniques will then be presented: high-frequency bulk wave scattering by Chou, surface wave scattering by Khuri-Yakub, long wavelength bulk wave scattering by Graham and Allberg, and acoustic microscopy by Kessler and Yuhas. Finally, the decision theory which is necessary to derive conditional probabilities of failure and to optimize accept/reject criteria from these inputs will be discussed by Richardson.
applications which is, of course, the ultimate objective of DARPA/AFML NDE effort.

Figure 16 summarizes the evolution of the quantitative ultrasonics capability, which is based on the building blocks of scattering theory and experiments, inversion theories and experiments, and engineering developments. From each of the building blocks, long-term capabilities are developed. The scattering work improves our understanding of the flaw-ultrasound interaction, and it has some specific applications in the areas of standards and calibration techniques. Inversion theories lead to flaw characterization techniques, which are being used in the ceramics and metal fatigue work, and which are finding application in slightly different form in a program to detect cracks under fasteners. Engineering development is transferring these techniques into advanced NDE prototype systems, including imaging systems and test beds. Also in this category are EMAT transducers, which were part of earlier DARPA/AFML engineering developments and which are now finding a number of applications.

The final use of all of this technology is in on-line systems for the DoD mission agencies.

REFERENCES


SESSION VII. MISCELLANEOUS DISCUSSION

Gerald Posakony (Session Chairman): We have a few minutes before adjournment. Are there any other questions?

Mark Weinberg (RADCOM): I have a question for Dr. Lakin. It's on your multiple 64 by 64 eight-element unit, isn't that essentially -- can we draw a parallel between that and a radar antenna? If you're handling the data somewhat differently in that you're scanning across there and reconstructing it.

Ken Lakin (Univ. of Southern Calif.): I think not. I'm not that familiar with the radar, but I suspect the pulse-echo systems are more analogous to radar. For example, I don't think in radar they bother to try to focus. They are usually too far away.

Mark Weinberg: One can scan it, of course, by control of phasing on the elements.

Ken Lakin: That sort of thing is really more analogous to pulse-echo imaging arrays where you program a time delay, whereas they program a phase shift through radar and you send a pulse through the system. In their case, the pulse is coherent not by design but by physical constraints. It might be more similar to the synthetic aperture where they take data for long, long distances and they try to correlate it. In that case it would be a huge angle on the target.

Paul Gammell (Jet Propulsion Lab): I would like also to ask Dr. Lakin a question. It looks like the basic principles are very similar to Dr. Jahn's description where the only difference is that yours uses the same transducer. So it looks like a true synthetic aperture they're moving along at angles.

Ken Lakin: I'm talking about the USC system, synthetic aperture, several transducers.

Paul Gammell: The main question I have is: you have one constant transmitter sitting up here; is that correct? How does the mathematics compare when you transmit and receive?

Ken Lakin: You don't get the double phase shift as you would on others. You get a change in phase from the object, from the object to the receiver element. You have a constant transducer and the transducer to the scatter.

Unidentified Speaker: Does it make your reconstruction easier or more difficult?

Ken Lakin: It pulls it.

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