MEASUREMENTS OF ULTRASONIC SCATTERING FROM BULK FLAWS OF COMPLEX SHAPE

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ABSTRACT

The report summarizes the design and early results of scattering experiments on flaws of complex shape. In close collaboration with the various theoretical groups representing different inversion algorithms, a unique set of diffusion bonded samples have been designed. These samples contain a variety of irregular and multiple flaws whose scattering characteristics will be obtained in order to guide and evaluate developments of theoretical approaches and test specific theoretical predictions. The majority of these samples have been received and the measurements have begun. Results on selected samples are presented and compared with scattering from ellipsoidal voids. The measurements will include angular, frequency and time domain variations of the scattered signals made possible with a new ultrasonic data acquisition system.

INTRODUCTION

The objective of this task is to predict the fatigue life of a metallic component containing a defect in its interior, by ultrasonic nondestructive evaluation. We report on progress on data acquisition for testing inversion algorithms, the preparations of new diffusion bonded samples, and the characteristics of spherical voids with small perturbations.

DESIGN AND PREPARATION OF NEW TRAILER-HITCH SAMPLES

Earlier phases of this program were concerned with the development of methods for producing flaws of known size, shape and location for use as ultrasonic reference standards. A range of defect sizes and shapes for which theoretical solutions for the scattering of incident ultrasonic energy have been produced. In addition, a number of defect geometries such as fatigue cracks and crack-like defects in diffusion bonded samples were also prepared. Previous work has emphasized rather simple internal voids and inclusions such as spherical defects and prolate or oblate spheriods. The new effort places more emphasis on modifications of these basis defect types and on rather more realistic flaws such as actual fatigue cracks, multiple defects and regular defects such as prolate spheriods, but with controlled surface roughness such as might be found in a realistic flaw.

New samples produced during the current year's program are listed in the Sample Inventory in Table 1. Only those samples produced under the new program have been listed in Table 1. Samples prior to Serial No. 69 are described in previous reports under this program.1 Drawings for samples 69-74 and 95-100 are contained in Figs. 1-9. The sample code in Table 1 gives only a general description of the defect type, and a precise description must be derived from the appropriate figure. The figures typically show three views, a three-dimensional view of the lower half of the trailer hitch, a more detailed view of the defect with design dimensions, and a micrograph of the actual defect after machining, but before bonding. Sample No. 69 is a simple circular 3 mm-diameter crack-like defect produced by inserting a thin layer of yttria in the bonding plane before the bonding operation. This sample and all other samples through Serial No. 74 are machined to a spherical shape as was done previously in order to permit acoustic scattering experiments over a wide range of angles in three dimensions. Sample No. 70 contains two overlapping spheres, the purpose...
of this geometry being to test the applicability of summation procedures in the theoretical work. Sample No. 71 contains a single 400μm radius void surrounded by a 200μm wide simulated yttria crack in the form of a "Saturn" ring. This geometry simulates a crack initiating out of an internal void and is probably as close to a realistic defect causing a crack in an actual material as can be produced by the sample preparation procedures used in this study. Sample No. 72 is a simulated elliptical crack in the interior of a spherical sample, while sample No. 73 contains an overlapping sphere and a modified prolate spheriod of the form shown in the drawing. Sample No. 74 contains a rough oblate spheroid to simulate a void with a realistic internal roughness to study the interaction of this rough surface with ultrasound of various frequencies. The surface of the oblate spheroid was roughened mechanically prior to the bonding operation. Samples 75-87
have been described in a previous report and are basically 2 1/4-inch diameter, 1/2-inch high experimental samples for studying various means of producing internal defects in diffusion bonded samples. Samples 88-94 are 4-inch diameter blanks used to produce the ultrasonic test standards for the test-bed program, and are described more fully elsewhere in this report. 2

Sample No. 95 is a 2 1/4-inch diameter, 3 11/16-inch high sample, again with spherical external geometry, and contains two separated spheres, both with 400 μm with 1200 μm between centers. Sample No. 96 also contains two spheres, on a 400 μm radius, the other a 600 μm radius with a center-to-center separation of 1400 μm. Sample No. 97 contains a 6.35 mm sphere with pronounced machining grooves, sample No. 99 is a spare, while sample No. 98 is a 4-inch diameter, 1-inch high specimen with a simulated fatigue crack 3 mm diameter produced internally by a spark erosion method. The manner in which this simulated fatigue crack surface was produced is worth describing in detail since it is somewhat complex. A
fatigue fracture surface produced by a fatigue crack growth at high $\Delta K$ in a pure titanium specimen was used as a model fatigue crack surface. A 3 mm diameter disc was then cut from the Ti specimen and placed into a suitably cut recess in one of the specimen halves. The opposite face was left smooth and the two specimens bonded together to form an internal fatigue crack-like surface.

The last sample produced in the current series is illustrated in Fig. 10 and consists of a specimen bonded together such that an internal defect introduced at its center line was used to initiate a fatigue crack laterally out from the diffusion bond. By producing specimens in this manner, the bond line was not in a fatigue crack plane and therefore would not interrupt or perturb the crack propagation process. This sample is to be used in some experiments to simultaneously study fatigue crack growth while examining the crack using ultrasonic methods of various kinds from the exposed specimen surface. The grips used to load the specimen enable access to both top and bottom faces of the specimen, thus allowing the study of both transmitted and reflected waves during fatigue cycling of the sample. The design of this sample is described in detail in a later section.

![Fig. 10. Sample No. 98.](image)

In summary, as a necessary part of calibrating and evaluating new NDE procedures and test equipment, standard samples containing defects of known size, shape and location, some of which simulate real defects found in service, have been designed and fabricated under this portion of the program. Rather than using the conventional flat-bottom hole, internal defects of accurately controlled geometry have been produced by a diffusion bonding method, since in general, scattering from internal defects is more completely understood than scattering from surface defects. In the current year, an attempt has been made to produce realistic defects of the type that might appear in service, and fatigue cracks growing from internal voids is a good example of this type of defect. Most of the samples have been produced from Ti-6Al-4V by methods which have been described in detail in previous reports.  

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**DESIGN OF A CENTRAL CRACK FATIGUE SPECIMEN**

We have designed a dumbbell shaped specimen which will be used to monitor ultrasonically the growth of a central fatigue crack. Two Ti-6-4 plates, each with a 1/8 inch radius thumbnail EDM notch have been diffusion bonded together such that the two semicircular notches will form a circular starter notch (1/4 inch diameter). With suitable grips, the specimen can be installed into a 200,000 lbs electrohydraulic fatigue frame. The grips have been designed in such a way that the two end faces are accessible for placement of transducers. Growth of the central crack under fatigue conditions will be monitored in the pulse-echo mode. It is also intended to perform tests in which the signal scattered in the plane of the crack will be interrogated. For this purpose, a receiver transducer will be mounted to the cylindrical surface of the specimen.

In the tension-tension fatigue loading the cyclic stress intensity range for this specimen is given by

\[
\Delta K = 1.95 \Delta \sigma \sqrt{a} \sqrt{Q}
\]

where $\Delta \sigma = \sigma_{\text{max}} - \sigma_{\text{min}}$, $a$ is the instantaneous radius of the central crack and $Q = 0.5$ for an aspect ratio of 0.5 (circular crack). For Ti-6-4 the yield strength, $\sigma_y$, of the material is $\sigma_y = 130$ KSI. Using full load capacity of the fatigue frame the specimen can be cycled at $\sigma_{\text{max}} = 200,000$ lbs/3.14 (inches)$^2 = 0.5 \sigma_y$. A load ratio
R0 = \frac{dP}{dV} = 0.08 will yield \sigma = 26.5 \text{ ksi/\text{in}}\text{.}

For this stress intensity range, a fatigue crack growth rate \( da/dN \) of about 200 inches/cycle is deduced from published data. The growth of a fatigue crack will be continuously monitored in the pulse-echo mode. For verification of the growth, "marker cycles" will be applied periodically. For \( AK > 20 \text{ ksi/\text{in}} \) the growth should occur according to the Paris equation (5)

\[
\frac{da}{db} = A(\Delta K)^m
\]

with \( A = 7.2 \times 10^{-4} \) and \( m = 3.15 \). Combining Eqs. (1) and (2) and integration over the total growth regime yields the remaining cycles to failure

\[
\frac{\Delta N}{(m - 2)A(1.95\sigma_{\sqrt{m}}/\alpha a)^{m-2}} - \left(\frac{1.95\sigma_{\sqrt{m}}}{\alpha a}ight)^{m-2} = \frac{1}{a(m - 2)\sigma_{\sqrt{m}}} \]

where \( K_c \) is the fracture toughness of the material \((K_c = 45-50 \text{ ksi/\text{in}})\). Since the \( K_c \) is not that accurately known, we will actually determine \( K_c \) from the critical flaw size

\[
a_c = \left(\frac{Qd}{2}\right) \left(\frac{1.95\sigma_{\sqrt{m}}}{\alpha a}ight)^{2} \]

for our particular material and geometry. Equation (4) is a consequence of Eq. (3) for \( AB = 0 \).

**DATA ACQUISITION TECHNIQUES FOR TESTING INVERSION ALGORITHMS**

Data has been collected on two samples, one containing an 800\( \mu \) diameter spherical void and another containing 800\( \mu \) x 400\( \mu \) oblate spheriod (void) in accordance with the requirements for the POFIS algorithm used by N. Bleistein and J. Cohen of Denver Applied Analytics. The data set includes explicit timing information defining the velocity in the trailer-hitch for several different angles and the absolute arrival times of the flaw echos for the determination of absolute flaw position. Data has also been collected and sent to J. Rose of the University of Michigan, comprising waveforms along the longitude and equator of trailer hitches containing a thin elliptic disk and an oblate spheriod. New requirements on transducer placement have been received from A. Mucciardi of Adaptronics so that both pitch-catch and pulse-echo waveforms may be collected in a new window format to be used for inversion. The data were collected on a trailer-hitch with an oblate spheriod and sent to Adaptronics. Data obtained in the recent past on a variety of trailer-hitch defects have been transmitted to J. Gubernatis at Los Alamos.

In order to provide scattering data for use with the POFIS algorithm, it is necessary to record pulse echo waveforms of the flaw as viewed from a variety of angles including the absolute position of the flaw echo in each waveform. Given a knowledge of the velocity of the sound in the host material, absolute position can be determined from absolute arrival times of the flaw echos. In conventional ultrasonic NDE, arrival time is used as an approximate measure of flaw location. In that case it is not necessary to know the arrival time (position) more accurately than about one diameter of the flaw. However, in the POFIS algorithm, the position information directly affects the reconstructed shape and size of the flaw. It is therefore necessary to know arrival time (position) to a small fraction of the diameter of the flaw.

In order to obtain absolute position information for echos from the flaws in the spherical ("trailer hitch") specimens, the following data were collected:

1. The known shape of the surface of the specimen (in this case a sphere).
2. The velocity of sound in the measurement directions in the specimen.
3. The arrival time of the flaw waveform with respect to the instant when the peak of the incident sound pulse passed from the transducer into the specimen. For normal incidence immersion measurements, this instant can be measured directly from the received waveform, but for angle beam or (as in our case) contact measurements, it must be separately determined.

The procedures used to obtain the absolute arrival time and sound velocity measurements are described below:

**Arrival Time - Received ultrasonic waveforms are usually timed with respect to a trigger pulse which is approximately coincident with the generation of the transmitted sound pulse. In our apparatus, which consists of a Parametrics 5052PR Pulser/Receiver and a Biomation 8100 Transient Recorder, time is measured with respect to an instant, 50 sample intervals before the trigger pulse from the Parametrics crosses the trigger threshold of the Biomation. In order to be able to time the ultrasonic echos precisely, it is necessary to determine when the peak (or some other feature) of the ultrasonic pulse emerges from the face of the transducer. The peak is used because it is the time at which most of the frequency components of the pulse are in phase and is therefore a high signal-to-noise feature which can be identified in either the time or frequency domains.**

Because the transducer cannot be used as a receiver while it is transmitting, the pulse peak time is measured by placing the transducer in contact with a 1 inch thick layer of aluminum and measuring the first round trip time. Then the pulse peak time is calculated using the thickness and velocity of sound of the aluminum block. The velocity of sound in turn is determined by separating the transducer from the block by a water buffer and measuring the front surface and first round trip times and the thickness of the block.

The resulting pulse peak time is then used as the reference of time for flaw waveform measurements. It will vary if any of the components of the apparatus (transducer, pulser, transient recorder) are changed or even readjusted (for example, pulse damping or Biomation trigger
level). It is found in practice that the bio-
mation triggers about 1/8 cycle after the begin-
ning of the pulse and therefore about 5/8 cycle
before the pulse peak for each of the two 5 MHz
broadband transducers.

Sound Velocity - In order to convert the absolute
arrival times measured above into absolute posi-
tions, it is necessary to know the sound velocity
of the specimen. For anisotropic materials, such
as Ti-6Al-4V, this requires measurements in
several directions. We have made sound velocity
measurements in the trailer hitch specimens by
through transmission measurements along various
diameters of the hitches. The technique used is
to divide the thickness of the hitch (including
end caps) by the time when the peak of the pulse
reaches the receiving transducer minus the time
when the peak emerges from the transmitting trans-
ducer. This requires a 2-transducer reference
measurement analogous to the single transducer
reference measurement described above, consisting
of measuring and transmission arrival time through
the 1 inch aluminum reference block and subtract-
ing the known propagation time through the block.

The results of the sound velocity measurements
(for those angles where physical access allowed a
through transmission measurement to be made) are
given below. They show a consistent anisotropy as
well as a systematic variation between the two
samples.

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ELASTIC WAVE SCATTERING BY BUBBLE DEFECT

Next, we turn to study a non-spherical defect
shown in Fig. 2. The defect is a spherical cavity
diameter 80μ, to which a hemisphere cavity of
diameter 40μ has been added. The hemisphere will
be referred to as the "bubble"; it represents a
device of size b from a simple shaped smooth
cavity of characteristic size a. The questions
addressed were the following:

(1) At what frequencies (e.g., values of kb)
is the bubble observable?

(2) At what angles of incidence and
scattering is its effects most
pronounced?

To answer these questions preliminary exper-
iments were first carried out to compare the
backscattering by the large sphere to that of the
non-spherical defect. Figures (11a, b, c) show the
backscattered amplitude vs frequency for (a)
an 80μ sphere without the bubble defect (b) a
side view of the defect normal to the axis-of-
symmetry, and (c) a frontal view of the bubble
defect. The differences appear above about 4 MHz

(ka = 1.5, kb = 0.75). The largest deviation is
obtained for the case of Fig. 11c, i.e., when the
bubble is directly illuminated.

The frequency spectra were experimentally
obtained by Fourier analyzing and normalizing the
observed backscatter waveforms. The spectra of
Figs. 11b and 11c are modulated with about the
same periodicity as that obtained for a sphere,
Fig. 11a, but a modulation with longer periodicity
(in k) is superimposed. While for the sphere the
first three peaks are of approximately equal
amplitude, with the bubble present, the amplitudes
decrease in magnitude. These observations agree
qualitatively well with the findings of Domany et
al (6).

Fig. 11 Frequency spectra of pulse echo signals
from (a) a sphere, and (b) and (c) a
bubble defect.

Turning now to the angular distribution of
power, Fig. 12 shows the polar plot of power
versus scattering angle for an incident direction
along the normal to the axis of symmetry (side
view) and a scattering angle of θ = 135 from the
forward scattering direction. This work is for ka
= 2 and shows that the presence of the bubble has
caused noticeable loss of the symmetry associated
with a "true" spherical cavity. Also shown in the
plot are results of calculations by Domany et al
(6) and Opsol (7) in qualitative agreement with
the experiment. Domany's calculations are based
on the use of the Distorted Wave Born Approxi-
mation, while Opsol's results are based on the use
of Vissher's matrix theory (8).

We plan to extend this work to the other
defects described earlier and attempt to achieve a
quantitative comparison.
Fig. 12 Polar plot of power scattered (dB) as a function of scattering angle in a pitch-catch experiment.

ACKNOWLEDGEMENT

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REFERENCES

2. R. Addison, this volume.
7. J.L. Opsal, this volume.

MEASUREMENTS OF ULTRASONIC SCATTERING FROM BULK FLAWS OF COMPLEX SHAPE

B. Tittmann

DISCUSSION

JIM ROSE: Jim Rose, University of Michigan.

I notice that in your experiments that you just showed, you have the deeper split. Is that possibly true for --

MR. TITTMANN: That's fine structure that I think we can get rid of by being a little more precise in our normalization.

MR. ROSE: You don't think it's physical?

MR. TITTMANN: I don't think so.

MR. HÜLLER: When you showed your experiments with the sphere and the bubble, I didn't understand the designations on the axes.

MR. TITTMANN: This was a polar plot with the bubble oriented towards $\theta = 0$. The radial axis is calibrated in dB of relative power.
SUMMARY DISCUSSION
(B. Tittmann)

Jim Rose (University of Michigan): I notice that in your experiments you just showed, you have the deeper split. Is that possibly true for --

Bernie Tittmann: That's fine structure that I think we can get rid of by being a little more precise in our normalization.

Jim Rose: You don't think it's physical?

Bernie Tittmann: I don't think so.

Paul Holler (Inst. fur Zerst. Pruf.): When you showed your experiments with the sphere and the bubble, where the abscissa is, the ordinate with decibels, I didn't understand what you were -- must be an angle.

Bernie Tittmann: This was a polar plot. If we wanted to assign a reference, make the bubble direction zero degrees and this is 90 and that's 180; and so looking into that direction, then, you're looking away from the bubble and the amplitudes are in terms of DB.

# #