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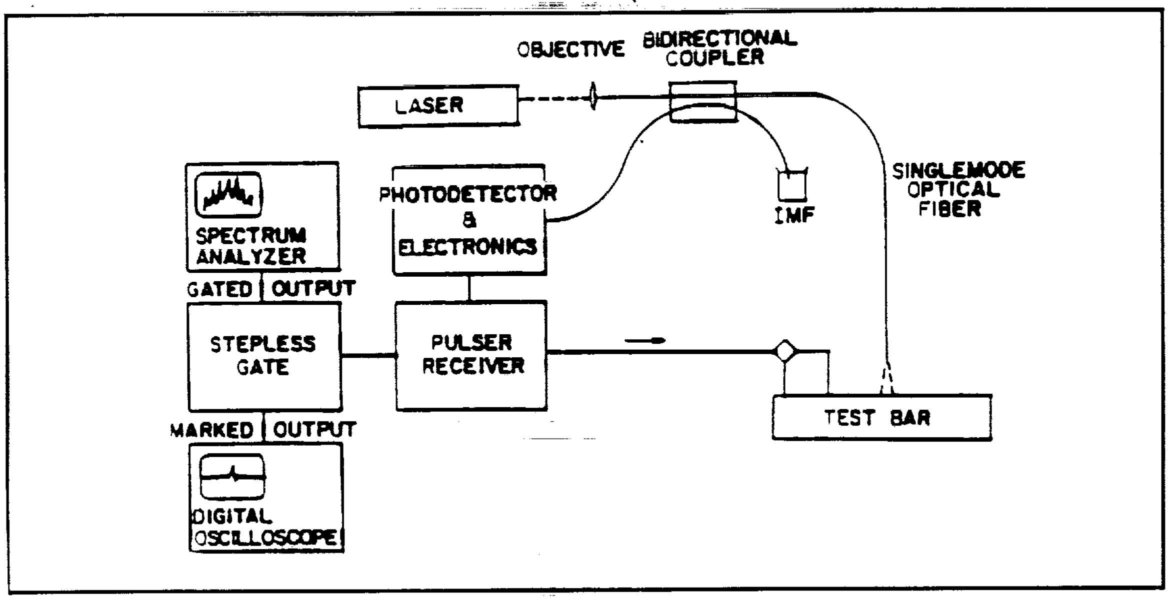
UAH Final Report

for

NASA Grant No. NAG8-821

DEVELOPMENT OF AN OPTICAL FIBER INTERFEROMETER FOR DETECTION OF SURFACE FLAWS IN ALUMINUM



(NASA-CR-186180) DEVELOPMENT OF AN OPTICAL FIBER INTERFEROMETER FOR DETECTION OF SURFACE FLAWS IN ALUMINUM Final Report (Alabama Univ.) 20 p CSCL 11F

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Submitted to

George C. Marshall Space Flight Center
National Aeronautics and Space Administration
Marshall Space Flight Center
Huntsville, Alabama 35812

Prepared by

John A. Gilbert, Ph.D.
Department of Mechanical Engineering
University of Alabama in Huntsville
Huntsville, Alabama 35899
(205) 895-6029

March, 1991

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1. Purpose of Research Effort

The objective of the study was to demonstrate within a nine month research and development cycle the potential of using an optical fiber interferometer (OFI) to detect surface flaws in aluminum samples. Standard ultrasonic excitation was used to generate Rayleigh surface waves. After the waves interacted with a defect, the modified responses were detected using the OFI and the results were analyzed for time-of-flight and frequency content to predict the size and location of the flaws.

2. Research Scheduled During the Performance Period

The tasks to be completed were to assemble and test hardware and software, determine the resolution of the optical fiber interferometer (OFI), refine the system to detect Rayleigh waves in aluminum, use standard ultrasonic excitation (a piezoelectric transducer) and OFI detection to locate and characterize known "flaws" in aluminum reference standards, and demonstrate the ability to detect unknown flaws in aluminum specimens with the potential to extend tests to include samples having complex surface geometries.

3. Work Accomplished During the Performance Period

Equipment Acquisition:

The hardware platform selected to meet the computational requirements for the data taken from the optical fiber interferometer was the 80386 microprocessor running on the standard AT bus under the MS-DOS operating system. A GPIB interface was developed using High Tech BASIC to facilitate high speed data transfer from a LeCroy 9420, 350 MHz digital oscilloscope to the computer; thereby allowing the flexibility of processing the acquired signals with a wide range of commercially available data analysis programs. Other items acquired under contract included an ultrasonic signal analyzer with a pulser-receiver and a stepless gate, piezoelectric transducers each having a 2.5 MHz center frequency and R-wave wedge, waveform processing software packages, conversion packages to upgrade existing hardware, a high frequency optical detector, and a high frequency signal generator.

Feasibility Tests Conducted Prior to October 1, 1990:

The Progress Report submitted for the period April 1, 1990 through October 1, 1990, and included in the Final Report as Appendix I, described tests conducted on an aluminum reference standard with a conventional pitch-catch system. It was determined that it took 10.5 μs for the acoustic signal to travel through the crystal and the lucite wedge of a transducer before an R-wave could be transmitted or received. In subsequent tests, two transducers were separated by a known distance and, based on the 10.5 μs delay, an R-wave velocity equal to 2.92 mm/μs was obtained.

In an attempt to confirm these findings, the receiving transducer was replaced by an optical fiber interferometer (OFI). These experiments were conducted using an older generation of electronics. New circuitry, specially built for the project, had to be returned to the manufacturer for repair when a strong, continuous, but erroneous signal was detected. This delay required the principal investigator to request the no-cost extension documented in Appendix II.

More recent and refined tests, performed using the new circuitry, accurately established the transducer delay at 10.91 μs. An R-wave velocity, equal to 2.946 mm/μs, was accurately measured independent of the transducer delay. These and other tests are described below.

Feasibility Tests Conducted After October 1, 1990:

Once the electronics were repaired and returned to the principal investigator, the circuitry was thoroughly tested for its frequency response using the output from a photodiode modulated with a high frequency signal generator. The output signal was passed to the optical detector via a fiber optic link and tests were conducted in the frequency range extending from 300 kHz to 50 MHz. Figure 1 shows typical results; the lower trace is the output from the signal generator, the upper trace is the response of the optical detector. The traces were nearly identical up to approximately 4 MHz. At this point, a phase shift was observed which became progressively larger as the frequency increased. At approximately 25 MHz, slight distortions were observed in the detector trace. Even though these became more pronounced as the frequency increased, the detector was able to track the signal easily up to 50 MHz.

Figure 3 of Appendix I shows four different aluminum samples prepared for the project. The unflawed specimen shown in Figure 3(a) serves as a reference standard; the other specimens contain a variety of different anomalies. The following paragraphs briefly describe some of the tests conducted using these samples; a more detailed analysis will be reported in an M.S. thesis being written by G. T. Large, one of the graduate students who worked on the project.

The setup shown in Figure 5 of Appendix I and the customized circuitry were used to measure the internal delay inherent in the piezoelectric transducer and the R-wave velocity in the

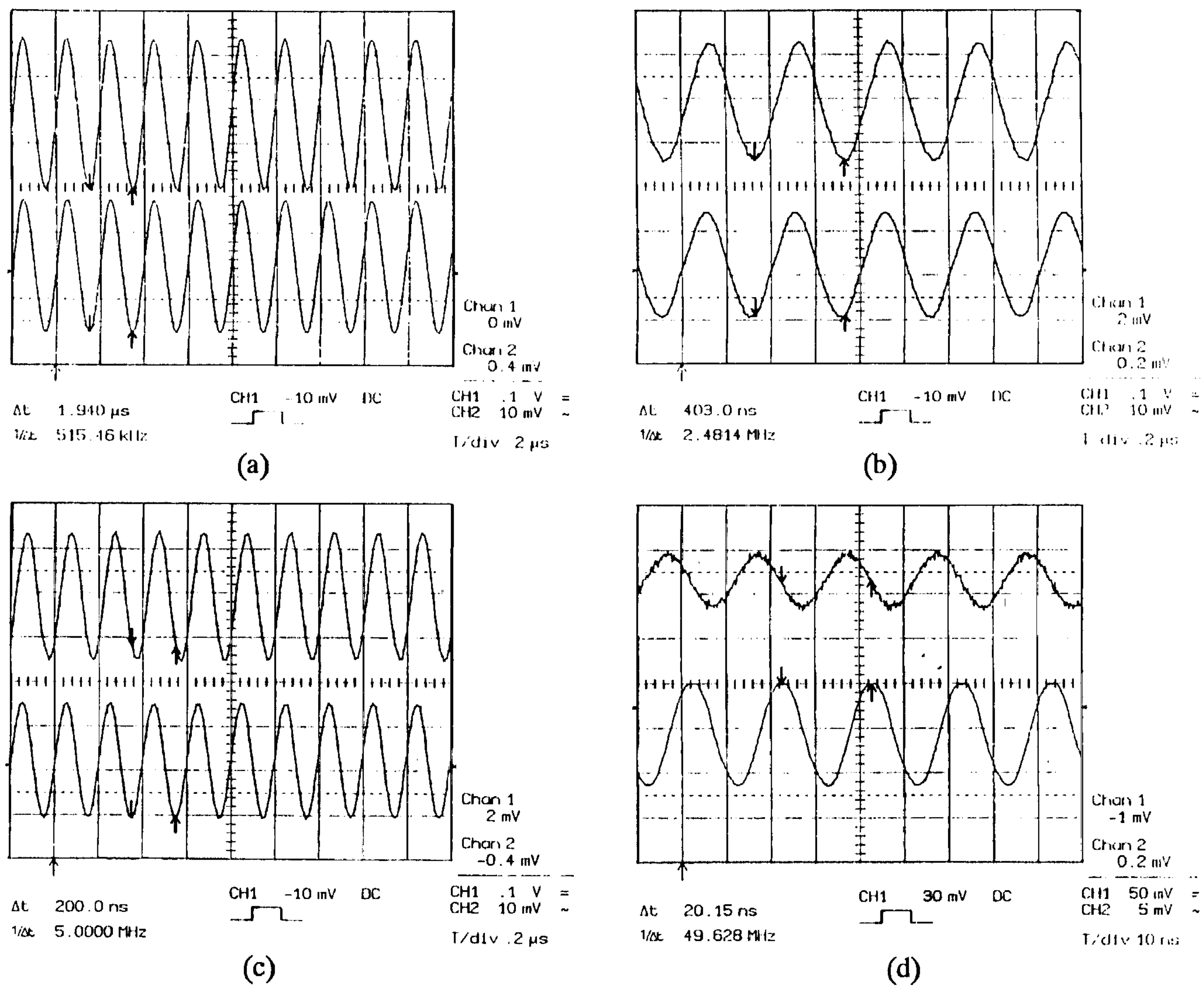
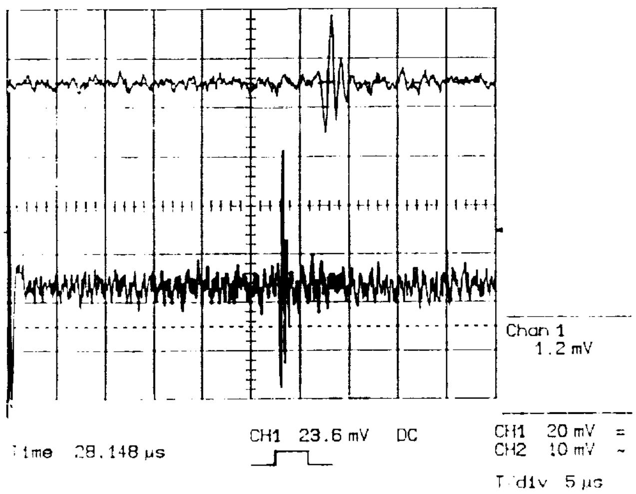
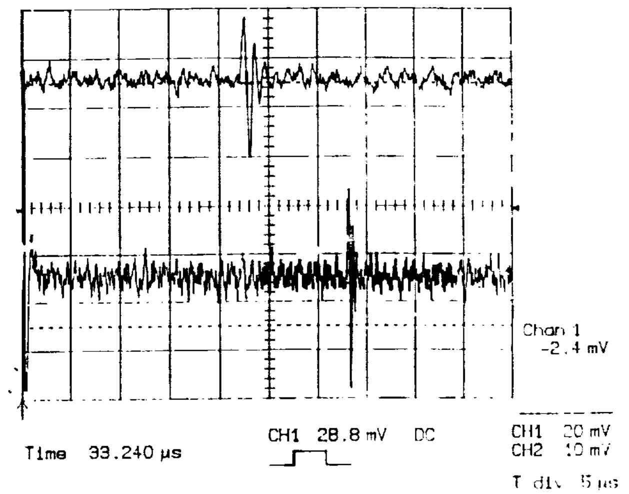


Figure 1. A comparison of the output from a signal generator (lower oscilloscope traces) and the response of an optical detector (lower oscilloscope traces) specially built for the project at (a) 0.5 MHz, (b) 2.5 MHz, (c) 5 MHz, and (d) 50 MHz.



(a)



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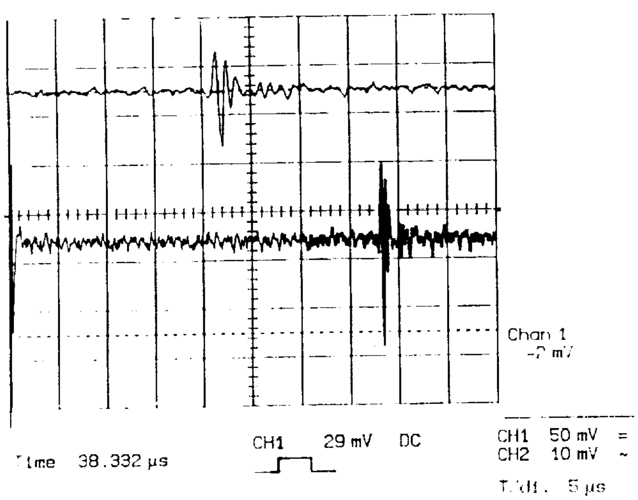
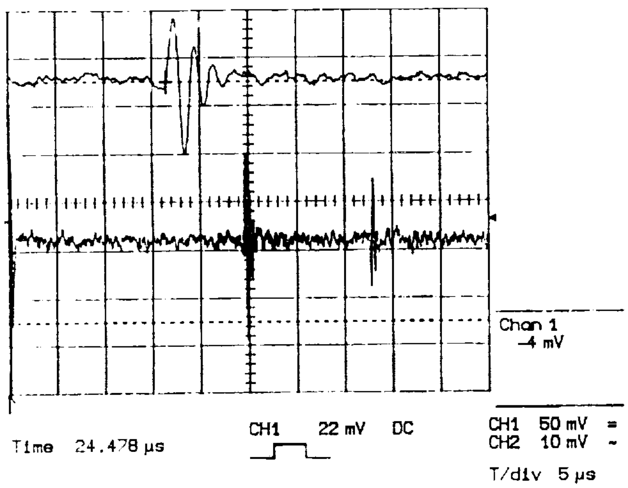


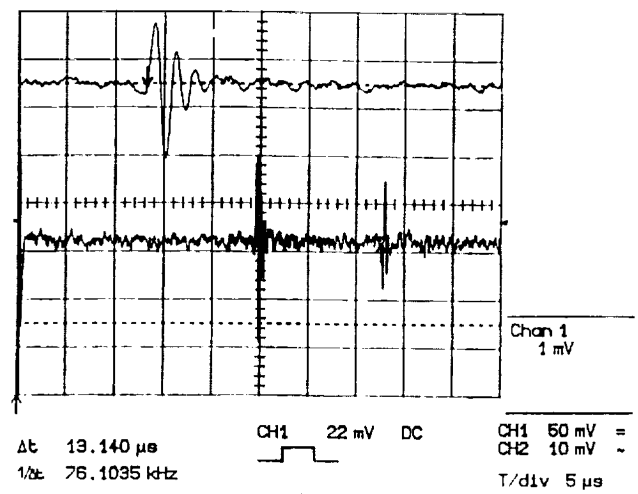
(c)

Figure 2. Oscilloscope traces for R-waves captured by an OFI located (a) 50 mm, (b) 65 mm, and (c) 80 mm, respectively, from a transducer. The upper traces represent a total time of 20 µs and correspond to the highlighted areas in the lower traces.

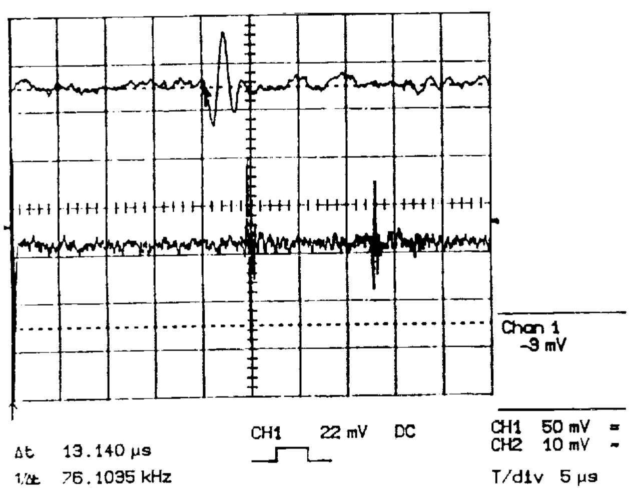
aluminum reference standard. This was accomplished by placing one leg of the coupler at distances of 50, 65 and 80 mm, respectively, from the transducer. The other output leg of the coupler was deactivated by immersing it in an index matching fluid. Figure 2 shows the results of these tests; in each case, the upper trace represents a total time of 20 µs and is an expanded version of the highlighted area contained in the lower trace. The R-wave velocity was established at 2.946 mm/µs, independent of the transducer delay, by taking the difference in position of the OFI relative to the transducer and then dividing by the difference between arrival times. In every case, the time base was established for the first distinct zero crossing which lagged 0.267 µs behind the leading edge of the trace. By subtracting this value from the total travel time and knowing the position of the OFI and the R-wave velocity, it was possible to accurately measure the internal delay in the transducer at 10.91 μs. The velocity and delay were verified in subsequent tests as described below.



(a)



(b)



(c)

Figure 3. Oscilloscope traces showing initial and reflected R-waves captured using an OFI. The distance from the transducer to the OFI was 40 mm; a 2 mm deep crack slanted at 45 degrees was located 19.5 mm further beyond the OFI. The upper traces corresponding to the highlighted areas in the lower traces show the reference positions taken to extract time-of-flight data.

Figure 3 illustrates typical time of flight data taken for a 2 mm deep crack slanted at 45 degrees. In this case, one leg of the OFI was placed between the excitation transducer and the flaw; consequently, a reflected signal is observed. The distance from the transducer to the OFI was 40 mm; the flaw was located 19.5 mm further beyond the OFI. The arrival time of the initial R-wave verified the results obtained for the R-wave velocity (2.946 mm/μs) and the transducer delay (10.91 μs). The difference in arrival times between the initial and reflected R-waves (13.1 μs) is within one percent error of that predicted for the wave to travel the distance of 39 mm to, and back from, the flaw.

Relatively weak transmitted signals were obtained as illustrated by the trace in Figure 4. In this example, the OFI was positioned at 65 mm from the transducer; a 5 mm deep vertical flaw was placed in between the OFI and the transducer. A comparison of the time of flight for the expected versus the actual delay in arrival times resulted in a 1.3 percent error. However, careful evaluation showed that the flaw size was underpredicted by 13 percent. This may have been due to machining errors, a change in material properties caused during machining, dirt or coupling fluid in the flaw, or mode conversion. The latter may have caused the anomalies observed in the trace located to the right of the transmitted signal.

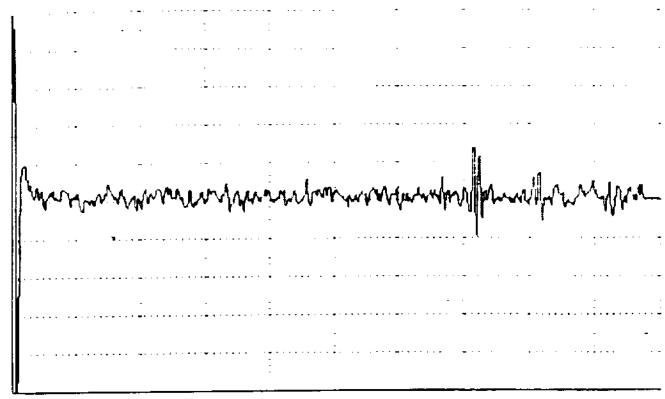


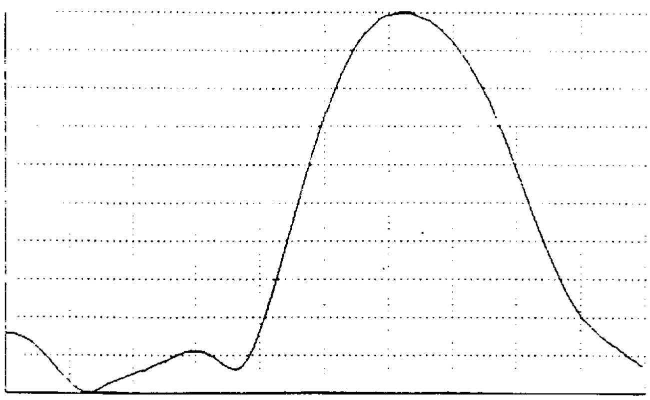
Figure 4. Oscilloscope trace showing the transmitted signal from a 5mm deep vertical flaw. Each horizontal division corresponds to 5 μs.

Spectral analysis was also conducted using a waveform package written by Professor Katsinis of the UAH's ECE Department. Figure 5, for example, compares the frequency response of the signal captured using a conventional piezoelectric transducer with that obtained using an OFI. Figure 7 of Appendix I was provided by the manufacturer of the excitation transducer and shows that its frequency band is relatively narrow and centered at 2.5 MHz. The response of the receiving transducer is similar to that of the exciter; whereas, the OFI detects a wider range of frequencies with a peak observed at a lower frequency.

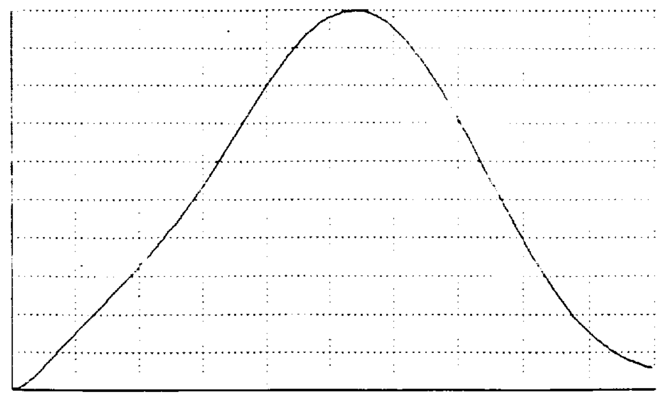
Figure 6 illustrates the frequency response obtained by analyzing the R-wave reflected from a 5 mm deep vertical flaw using an OFI. A comparison of the frequency plot with that shown in Figure 5b shows an attenuation at approximately 0.7 MHz. This corresponds to the undersized crack size predicted from time-of-flight analysis.

Theoretically, the minimum flaw size that can be detected is proportional to the wavelength. It can be obtained using the simple relationship $\lambda = C_R/f$, where C_R is the R-wave velocity and f is the signal frequency. For excitation at the central frequency of 2.5 MHz and an R-wave velocity of 2.946 mm/μs, the minimum flaw size which can be detected is slightly larger than 1 mm. However, the analysis of the data obtained from the study showed that the OFI worked reasonably well on flaws with dimensions approximately three times the theoretical minimum flaw size (3 mm and larger).

Since the electronics have been shown to measure frequencies in excess of 50 MHz, the



(a)



(b)

Figure 5. A comparison of the frequency response of the R-wave signal captured (a) using a conventional piezoelectric transducer, and (b) using an optical fiber interferometer. Each horizontal division corresponds to 5 μs.

characterization of flaws with dimensions on the order of 0.05 mm is theoretically possible (suggesting a practical limit of 0.15 mm). This, of course, will require an excitation transducer capable of producing output in that range. Such transducers are commercially available and could be secured should the project be targeted for additional funding.

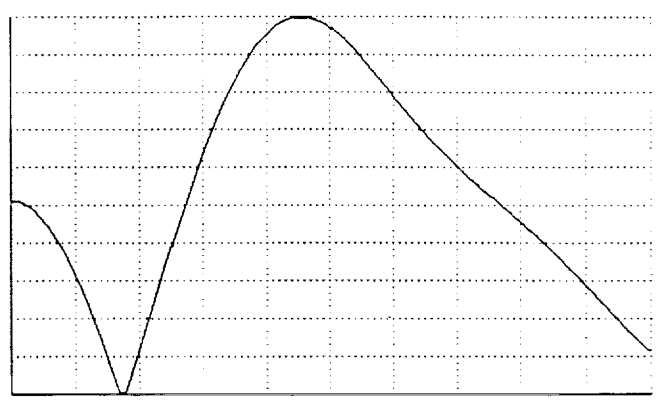


Figure 6. Frequency response obtained by analyzing the R-wave reflected from a 5 mm deep vertical flaw. Each horizontal division corresponds to 5 μs. Note the attenuation at 0.7 MHz.

4. Personnel

The following graduate students worked on the project:

1. Bruce R. Peters (Ph.D. granted 12/90).
2. George T. Large (M.S. expected 6/91).

5. Conclusions and Future Research

The potential of using an optical fiber interferometer to detect Rayleigh waves generated in aluminum samples using a standard piezoelectric transducer has been clearly established. Further refinements are necessary, however, to measure smaller flaws and to adapt the OFI system for use under field conditions. Then, the approach could be extended to detect bulk (pressure or shear) waves. Once these refinements and extensions have been made, the contact transducer used for excitation could be replaced by noncontact laser excitation. In this approach, called thermal acousto-photonic nondestructive evaluation (TAP), acoustic waves would be generated first by focusing the laser directly onto the surface, and later by guiding laser light to the specimen using a flexible fiber optic. This TAP research would require a one year performance period and would cost approximately $150k.

Specifically, the tasks proposed to be undertaken are:

(1) Standard ultrasonic excitation and OFI detection.

Use standard ultrasonic excitation and develop a high frequency, high resolution optical fiber interferometer (OFI) for acoustic detection. Both surface waves (R-waves) and bulk waves (P- or S-waves) in aluminum samples with and without "flaws" will be studied using the OFI. The most promising methods for flaw detection using either single transient events or repeated pulses will be identified. These methods will subsequently be refined and exploited through the use of FFT waveform analysis, boxcar averaging, etc., as appropriate to identify flaws and characterize their salient features.

(2) Direct laser coupling and OFI detection.

Using the OFI methods developed above, repeat Task 1, but with energy input coupled directly to the surface using the focused beam produced by a Nd-YAG laser. This approach will eliminate the requirement for contact with the surface, and will generate standing acoustic waves and rapidly pulsed wave trains that can be sampled sequentially with the OFI.

(3) Fiber optic coupling and OFI detection.

Using the OFI repeat the successful experiments from Task 2 with the laser excitation transmitted through a flexible fiber optic.

(4) Demonstration of the technique.

At the end of the contractual period, a prototype system for flaw detection will be demonstrated. Data will be taken from the optical fiber interferometer using a microprocessor running on the standard AT bus under the MS-DOS operating system. A GPIB interface will be developed using High Tech BASIC to facilitate high speed data transfer from a digital oscilloscope to the computer where the acquired signals will be processed using a wide range of commercially available data analysis programs.

A tentative timetable for the project is shown on the following page.

OUTLINE AND TENTATIVE TIMETABLE FOR FUTURE TAP RESEARCH

```
DESCRIPTION                                MONTH   0          4          8          12

1. Standard ultrasonic excitation and OFI detection.

  - assemble and test hardware                     ^--------^
  - surface wave detection                                  ^----------------^
  - bulk wave detection                                                       ^----------------------^

2. Direct laser coupling and OFI detection.

  - design illuminating system                              ^-------^
  - surface wave evaluation                                          ^----------------^

3. Fiber optic coupling and OFI detection.

  - design fiber optic delivery system                                          ^-------^
  - surface wave evaluation                                                             ^-------------^

4. Progress reports

  - interim report                                                     ^_^
  - demonstrate prototype                                                                    ^_^
  - final report                                                                             ^_^

DESCRIPTION                                MONTH   0          4          8          12
```

More advanced studies would involve complex structures, where it should be possible to tailor the input for optimum coupling efficiency and beam shapes through the use of state-of-the-art devices such as optical delay lines, rod lenses, etc. Moreover, laser excitation will also produce thermal conduction fronts which can be monitored using thermographic techniques. These thermal measurements could be used in conjunction with the acoustic methods to reduce the chances of false calls or failures to detect.

With all these potential advantages, it is anticipated that the TAP technique will be of great value in improving the efficiency and effectiveness of quantitative NDE in many classes of structures where conventional methods of flaw detection and characterization are at present difficult, unreliable, or even impossible. These include internal inspection of elements in propulsion units such as turbine blades, rocket nozzles, fuel lines, valve housings, and similar enclosed assemblies with limited access and/or complex surface geometries. The point to point feature of the TAP technique will also permit very localized inspection of structural details such as welds and rivets, or damage initiation in materials.

Appendix I

Progress Report

April 1, 1990 - October 1, 1990

Progress Report on NASA Contract No. NAG8-821

Title of project:	Development of an Optical Fiber Interferometer for Detection of Surface Flaws in Aluminum
Name of institution:	University of Alabama in Huntsville
Period covered by report:	April 1, 1990 - October 1, 1990
UAH contract number:	5-32385
NASA contract number:	NAG8-821
Author/PI:	John A. Gilbert, Ph.D.

1. Purpose of Research Effort

The objective of the study is to demonstrate within a nine month research and development cycle the potential of using an optical fiber interferometer (OFI) to detect surface flaws in aluminum samples. Standard ultrasonic excitation is used to generate Rayleigh surface waves. After the waves interact with a defect, the modified responses are detected using the OFI and the results are analyzed for time-of-flight and frequency content to predict the size and location of the flaws.

2. Research Scheduled During the Performance Period

The tasks specified for the first six months were to assemble and test hardware and software, determine the resolution of the optical fiber interferometer (OFI), refine the system to detect Rayleigh waves in aluminum, and to begin studies that use standard ultrasonic excitation (a piezoelectric transducer) and OFI detection to locate and characterize known "flaws" in aluminum samples.

3. Work Accomplished During the Performance Period

Equipment Acquisition:

The hardware platform selected to meet the computational requirements for the data taken from the optical fiber interferometer was the 80386 microprocessor running on the standard AT bus under the MS-DOS operating system. A GPIB interface is being developed using High Tech BASIC to facilitate high speed data transfer from a LeCroy 9420, 350 MHz digital oscilloscope to the computer; thereby allowing the acquired signals to be processed using a wide range of commercially available data analysis programs. Other items acquired under contract included an ultrasonic signal analyzer with a pulser-receiver and a stepless gate, piezoelectric transducers each having a 2.5 MHz center frequency and R-wave wedge, waveform processing software packages, conversion packages to upgrade existing hardware, a high frequency optical detector, and a high frequency signal generator.

Feasibility Tests:

The standard pitch-catch arrangement shown in Figure 1 was used to test the ultrasonic signal generator, the piezoelectric transducers and the R-wave wedges. The system was initially used to measure the internal delay inherent in each transducer by reducing the distance between the transducer faces, b_1, to zero. The results of the test are shown in Figure 2. The 21 μs total delay between the input pulse initiated by the sending transducer and the output pulse detected by the

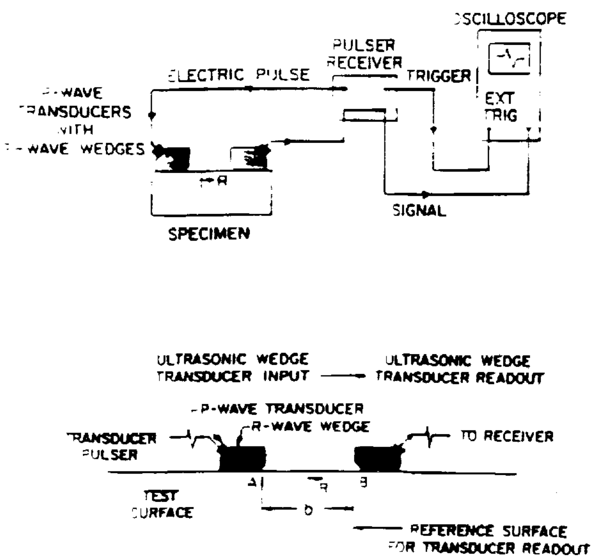


Figure 1. Standard piezoelectric transducer pitch-catch system.

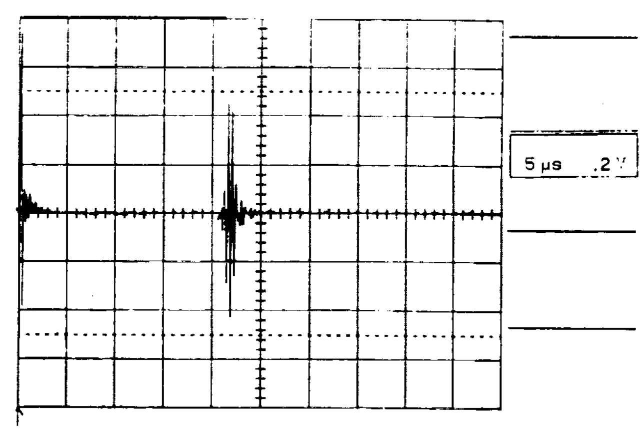


Figure 2. Oscilloscope trace showing the internal time delay attributed to the two transducers.

receiving transducer was divided in half (under the assumption that both transducers were identical). The 10.5 μs internal delay in each transducer is associated with the time that it takes for the acoustic signal to travel through the crystal and the lucite wedge. This delay must be known in all subsequent tests so that it can be subtracted from the time base displayed by the oscilloscope. This is particularly important when time of flight measurements are made either to establish the Rayleigh wave velocity, or to accurately locate a flaw.

Figure 3 shows four different aluminum samples prepared for the project. The unflawed specimen shown in Figure 3(a) acts as a reference standard; the other specimens contain a variety

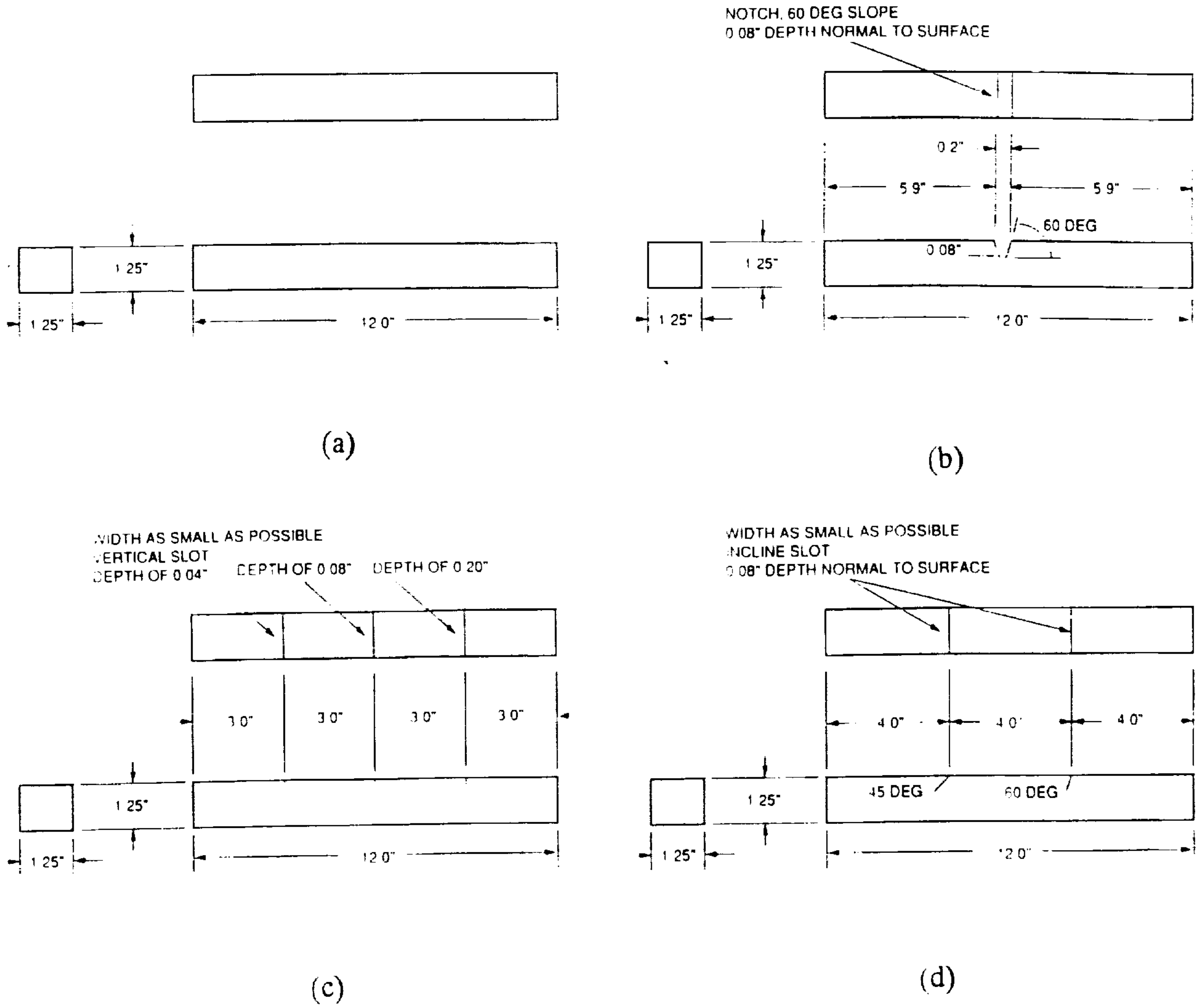


Figure 3. Aluminum samples machined for the project: (a) unflawed reference standard; (b) 60° notch; (c) straight cracks; (d) slanted cracks.

of different anomalies.

The setup shown in Figure 1 was used to establish the velocity of the Rayleigh wave in the aluminum reference standard by placing the transducers at known distances apart and applying the standard formula $C_R = \lambda f$ where C_R is the R-wave velocity and f is the signal frequency. Figure 4, for example, shows a typical result obtained with b_1 = 50.8 mm (2.0"). When the internal delay of 21 μs is subtracted from the total travel time of 38 μs, an R-wave velocity, C_R,

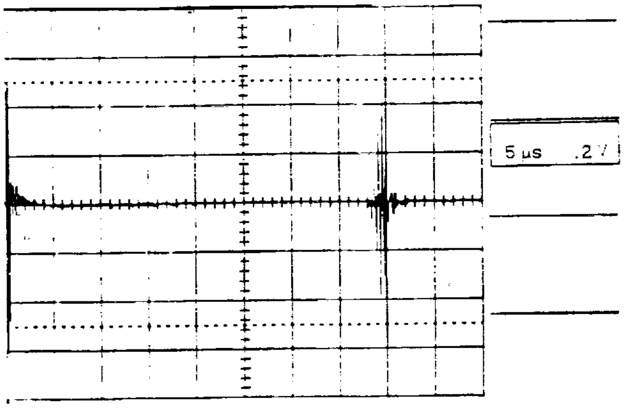


Figure 4. Oscilloscope trace used to determine the Rayleigh wave velocity in an aluminum standard with two piezoelectric transducers separated by a distance of 50.8 mm (2").

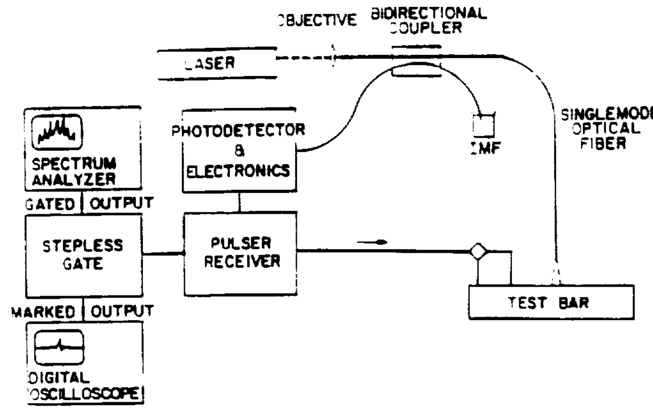


Figure 5. Setup of a dual leg optical fiber interferometer (OFI) with one leg of the coupler immersed in index matching fluid (IMF).

of 2.92 mm/µs is obtained. This value falls within the range of values predicted and measured by other investigators.

One of the transducers was incorporated into the OFI system shown in Figure 5. Laser light, launched into one leg of a bidirectional coupler, is split between the output fibers (yielding, ideally, half power in each) so that each fiber can serve as a separate OFI if so desired. In this OFI system each internally reflected reference wavefront interferes with the corresponding object wavefront, and the return signals pass back through the remaining leg of the coupler to the common or shared photodiode and electronics. When the lengths of the output legs are properly matched, the returning waves from the different interferometers can interfere with one another. If this response is unwanted, it can be avoided either by trimming the output legs so that they differ in length by half the coherence length of the excitation laser, or through deactivation of one of the interferometers by immersing its output end in an index matching fluid.

The system shown in Figure 5 was used to verify the R-wave velocity and the internal delay inherent in the piezoelectric transducer by placing one leg of the coupler at a distance of 44 mm (1.75") from the transducer on the aluminum reference standard. An analysis of the trace shown in Figure 6 confirmed the expected arrival time.

The ability to characterize a flaw using the OFI system depends on the overall resolution. Figure 7 shows that the frequency band produced by the excitation transducer is relatively narrow and centered at 2.5 MHz. The minimum flaw size that can be detected is proportional to the wavelength and can be obtained using the simple relationship $\lambda = C_R/f$ mentioned earlier. For excitation at the central frequency of 2.5 MHz and an R-wave velocity as measured in aluminum of 2.92 mm/μs, the minimum flaw size which can be detected is slightly larger than 1 mm. This resolution can be achieved provided that the OFI detects a clean signal.

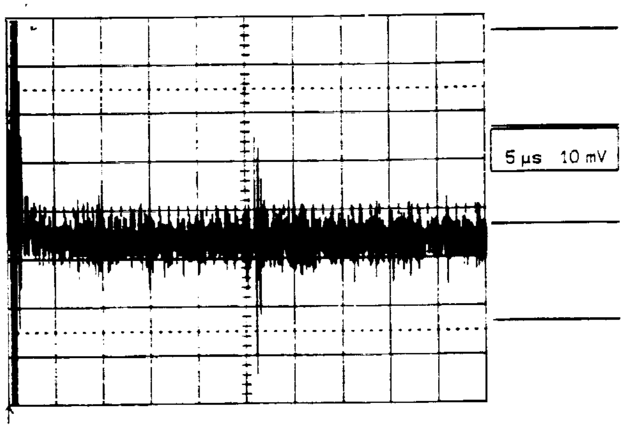


Figure 6. The R-wave detected in an aluminum standard using an OFI positioned at a distance of 44 mm (1.75") from a piezoelectric transducer (see Figure 5).

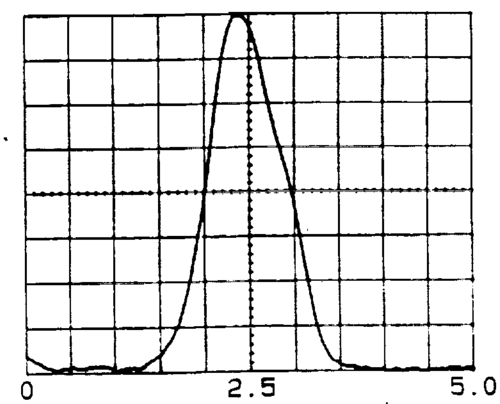


Figure 7. MHz Frequency band produced by the excitation transducer.

The results shown in Figure 6 were obtained using an older generation of electronics, customized for analog detection of high frequency optical signals up to 4 MHz. The R-wave detected by the OFI is suitable for locating a flaw using time-of-flight analysis, but characterization of flaw geometry and flaw size is hindered by the low signal to noise ratio. New circuitry, designed and manufactured for the project, was secured in late September.

The circuitry was initially tested for its frequency response using the output from a photodiode modulated with a high frequency signal generator. The output signal was passed to the optical detector via a fiber optic link. Unfortunately, a strong, continuous, but erroneous signal was detected in the frequency range where signal analysis is required to determine the salient features of the flaws machined into the specimens shown in Figure 3. After extensive diagnostic testing, the electronics were returned to the manufacturer for repair. The problem was reported solved on October 18, 1990, and the equipment is being returned for reevaluation.

The much higher signal-to-noise ratio of the new detector circuit will facilitate flaw characterization. In addition, the electronics have been designed to measure frequencies in excess of 25 MHz, making the characterization of flaws with dimensions on the order of 0.1 mm theoretically possible. This, of course, will require an excitation transducer capable of producing output in that range. Such transducers are commercially available and could be secured should the project be targeted for additional funding.

4. Personnel

The following graduate students have been working on the project:

Bruce R. Peters (Ph.D. expected December, 1990)
George T. Large (M.S. expected June, 1991).

Dr. Constantine Katsinis of the Electrical Engineering Department at UAH has expressed an interest in the project and has been working to develop the computer interface for high speed data transfer. His expertise was invaluable when diagnosing the problem associated with the detector circuit.

Appendix II

No Cost Extension

December 7, 1990

The University Of Alabama In Huntsville

Huntsville, Alabama 35899
(205) 895-6000
Telefax: (205) 895-6677

Research Administration

December 7, 1990

R. B. Smith/AP43-P
National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, AL 35812

RE: No-Cost Extension for NAG8-821, Dr. John A. Gilbert, Principal Investigator

Dear Ms. Campbell:

The P.I. has requested a sixty-day no-cost extension of the referenced grant. If this extension is approved, the new end date will be March 1, 1991. This request is being initiated due to a delay encountered in the design and delivery of electronics specifically manufactured for the project. In addition to this delay in procurement, an unforeseen problem was encountered during calibration tests conducted with the equipment at UAH. This problem was reported by the P.I. in his November 1990 Interim Progress Report on page 5. Specifically, "a strong, continuous, but erroneous signal was detected in the frequency range where signal analysis is required to determine the salient features of the flaws" in question. After extensive diagnostic testing, the electronics were returned to the manufacturer for repair. The circuitry has since been reevaluated, and the problem appears to have been corrected.

The P.I. and Dr. Bershears, Technical Monitor, have agreed that the extra time is necessary to fully develop the potential of the optical fiber interferometer. The extension will also provide the P.I. with an opportunity to adequately document the developments he makes under contract in his final report.

The University
Of Alabama
In Huntsville

Huntsville, Alabama 35899
(205) 895-6000
Telefax: (205) 895-6677

Research Administration

Please contact Michele Gray at (205) 895-6000 should you have any questions.

Sincerely,

Kathy Niemi

Kathy Niemi
Contract Administrator

cc: Dr. Gilbert/ME
C. Burns/ACCTG