Test Bed for Quantitative NDE

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Keywords
Nondestructive Evaluation

Disciplines
Materials Science and Engineering

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TEST BED FOR QUANTITATIVE NDE

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ABSTRACT

The ARPA/AFML Interdisciplinary Program for Quantitative Flaw Definition has demonstrated a number of new techniques for quantitatively sizing flaws, as are reported elsewhere in these proceedings. This paper describes a test bed program to assemble and demonstrate these techniques in a single integrated measurement system that will extend them from the idealized geometries that have been considered thus far to geometries that are a better approximation to those that are found in real parts. Included are discussions of the conceptual design of the system, the detailed design and construction of specific modules, and preliminary experimental results. The basic system consists of a Data General Eclipse 5/200 minicomputer, a multi-axis microprocessor controller, a Biomation A/D converter, an immersion tank, and a contour following system with six degrees of freedom. A detailed description of the operation of the various components of the system will be given. Included are discussions of the conceptual design of the system, detailed design and construction of specific modules, and preliminary experimental results.

A limitation of mechanically scanned systems is the time required to acquire data. To overcome this, the Test Bed includes a piezoelectric array transducer, to be used both for the imaging of flaws and the gathering of scattering data for use in other flaw characterization algorithms. Such an array has been received, and the construction of the necessary array electronics is in progress. Included in the paper is a discussion of the digital signal processing approach being implemented, which takes advantage of recent advances in A/D converters and array processors to achieve the near real-time formation of images with a high degree of flexibility for evaluating various signal processing algorithms.

The extended data gathering capability of the system has been demonstrated with several of the diffusion bonded samples that have been fabricated for the ARPA/AFML program. Preliminary measurements on a sample containing an 800μm spherical void were made. Subsequent analysis of these measurements using the Inverse Born Approximation predict a diameter of 820μm thus demonstrating the validity of the technique.

Conceptual Design

The ultrasonic test bed program has been initiated to complement the ARPA/AFML Interdisciplinary Program for Quantitative Flaw Definition. Specifically, we are implementing the variety of new techniques that have arisen for obtaining quantitative data about flaws such as the size, shape, orientation and stress intensity factor. These will be adapted into procedures for identifying flaws in parts of complex geometry such as turbine disks. The results will serve a twofold purpose. First, a new inspection capability will be demonstrated. Second, in cases where the practical constraints of the part geometry degrade the quality of some of the measured flaw parameters, this information can be fed back into the research program to guide that effort.

In order to implement these techniques, we must establish a protocol for their use. Although we remain quite flexible with regard to the final form of this protocol, the system we are starting with is shown in Fig. 1.

The part is first searched and the locations of all regions that possibly contain flaws are stored in the test bed memory. Each of these

*This work was supported by the Defense Advanced Projects Agency under Contract F33615-78-C-5164.

Fig. 1 System protocol.
locations is then inspected in detail to determine the quantitative parameters of the flaw. First an image of the flaw is made, and if it is resolved, the accept/reject criteria is used to decide if the part is acceptable. If it is unresolved, a map can be made to determine if there are multiple flaws within a small area. Next, appropriate scattering data is obtained so that a model-based reconstruction technique can be used to form an image of the flaw. If the flaw is still unresolved, we will examine the spectral content of the defect signal and determine the approximate $k_a$ value of the flaw. For cases where $0.5<k_a<3$, we will use adaptive learning techniques to extract the flaw parameters. If $k_a<0.5$, we will use long wavelength techniques and determine the stress intensity factor of the flaw.

Physical Test Bed & Microprocessor Controller

A photograph showing the current status of the test bed laboratory is shown in Fig. 2. One can see the water tank, the three rectilinear axes and a portion of the turntable. The cabinet on the right contains the microprocessor controller. In the background is the S/200 computer, a computer terminal, the color display, and an electronics rack containing the A/D converter and the pulser/receiver.

![Fig. 2 Test bed laboratory.](image)

The block diagram for the test bed system is shown in Fig. 3. The transducer has five degrees of freedom. It can be moved rectilinearly along $X$, $Y$ and $Z$, as well as having a double gimbal movement that will permit it to be rotated about two orthogonal axes. The two gimbal movements, as well as the $2$ axis motion, are incorporated into a standard manipulator arm that was purchased from Automation Industries. The $X$ and $Y$ motions are incorporated into an assembly that was built at the Science Center. In addition to the five degrees of freedom of the transducer, a sixth degree of freedom is provided by a turntable that permits it to be rotated about two orthogonal axes.

![Fig. 3 Test bed block diagram.](image)

In operation, the turbine disk will be rotated at a speed that is selected on the basis of the desired resolution for the inspection as well as the maximum pulse repetition rate of the transducer. The transducer will be moved radially along the turbine disk and will be kept pointing along the normal to the surface of the disk. The surface profile of the turbine disk will be separated into segments consisting of straight lines and circular arcs. A sample profile is shown in Fig. 4. Each of these curve segments will be stored in the S/200 minicomputer as a data block. The data block for a straight line segment such as segment 1, 2 in Fig. 4 will specify the coordinates of point 2, the angle of the transducer, the transducer offset from the surface of the part, and the speed at which the transducer is to be scanned. For a circular arc segment such as segment 2, 3 in Fig. 4, it will be necessary to also specify the coordinates $(I_3, J_3, K_3)$ of the center of curvature. In addition to these data blocks which allow the transducer to scan over the surface and take data, there are special non-data gathering blocks which are used when the part profile has a discontinuous slope and the transducer has to be rotated through an angle while still pointing at the same location on the part's surface.

It is the task of the microcomputer to accept these data blocks and convert them into interleaved trains of pulses that are sent to the stepping motors controlling the relevant axes. This must be done in such a way that the transducer follows the contour of the part with the required offset and with an accuracy that is within four stepping motor increments of the specified contour. A block diagram of the microcomputer system is shown in Fig. 4. The software for controlling these detailed motions is resident in the 16K PROM memory of the microcomputer and is entirely written in assembly language to make it as compact as possible.

The system has now been delivered to the Science Center. We are just beginning to learn how it operates with all six axes moving. We expect that there will be a period of debugging before the system is fully operational.
The software for controlling the operation of the Test Bed is resident in the S/200 minicomputer in the form of a multitasking program. A diagram of this program is shown in Fig. 5. The program allows 1) use of a master terminal to send commands to the host CPU (S/200) or the microcomputer (designated controller CPU in Fig. 5). Examples of these commands would be requests for the current coordinates of the transducer, Halt commands, or Continue commands. The microcomputer can 2) send data to the master terminal or to the disk memory. Examples of this would be error messages, confirmation that data was received, or transducer coordinates. Task 3) stores the control blocks for specifying the profile of the part on the disk memory, which can be read by the Host CPU and sent to the microcomputer. Task 4) allows the Host CPU (S/200) to send trigger pulses to the Biomation A/D converter and to the pulser. Task 5) allows the Host CPU to accept digitized data from the A/D converter and stores this data on the disk memory. After accepting the digitized data the host CPU will analyze the data. If it exceeds a predetermined threshold which may be a function of the location within the part, then the host CPU can request the microcomputer to send it the current coordinates of the transducer and, upon receipt, store these on the disk memory.

Ultrasonic Array

One of the objectives of the test bed program is to utilize an ultrasonic array for imaging and scattering measurements. The electronics for driving this array will have a somewhat different objective than some of the array based systems that are currently available. Our chief purpose will be to obtain a waveform that has as little distortion as possible, whereas for many systems the objective is to obtain an image in as little time as possible. In systems of the latter type one depends on the image enhancement ability of the eye/brain system to filter out the effects of the distortion that results. In the system that is being designed and built for the test bed, we would like to be able to display a single frame of an image and be able to recognize the important details of the object under study. In addition the system will be required to collect scattering data that can be used with the various inversion techniques.

The system is based on an ultrasonic array with 240 elements. This array will have a center frequency of 2.5 MHz and will be able to scan an ultrasonic beam over ±25°. The bandwidth will be adequate to produce pulses that have about 5 half cycles. Only 16 contiguous transmit and 16 contiguous receive elements will be used at one time. Since the particular group of 16 transmit and receive elements will be programmable, it will be possible to scan a beam over a part with a curved surface such as the one shown in Fig. 6. It will be possible to correct for the waveform distortion caused by refraction at the curved surface of a part by suitably delaying each of the received signals.

The array would be used to collect scattering data by the technique illustrated in Fig. 7 or by other similar techniques. In Fig. 7 one group of
elements is being used to insonify the defect and other groups are being used sequentially to collect scattered signals at various angles. If the array is rotated about an axis passing through the defect, then a complete set of scattering waveforms can be collected for use by the Inverse Born Approximation or by the POFFIS algorithm.

A block diagram of the ultrasonic array system is shown in Fig. 8. The S/200 minicomputer will send out a set of codes that will select the desired set of transmit elements, the desired set of receive elements and the set of time delays that will define the transmit beam direction. These codes will be stored in the control memory. The timing and control block will interpret the codes and activate the transmit and receive multiplexers so that the appropriate array elements are selected. This block will also send suitably delayed trigger signals to each of the 16 selected transmitter elements to synthesize an ultrasonic beam with the desired direction. The trigger signals which are positive going TTL level pulses will activate the pulser and cause a high voltage (200-300V) pulse to be applied to the transducer. The returning ultrasonic signal from the object under investigation will be received by each of the 16 selected receive elements. The received signals will each be amplified by 26 dB by a low noise, low distortion, hybrid preamplifier. They will then pass through the receive multiplexer to a line driver that will send them each to an 8 bit, 19 MHz A/D converter which will digitize the signal and load it into an 8 x 1K bit fast random access memory. All 16 of the A/D converters are started synchronously after a delay corresponding to the round trip time of the ultrasonic signal between the transducer and the front surface of the part. The contents of each of the sixteen memories will be sequentially clocked through the interface to the array processor at a rate compatible with the operation of the array processor and minicomputer (approximately 0.5 MHz). The array processor will have the task of shifting the waveforms and summing them to synthesize a beam from a specified direction. The array processor will also interpolate between data points in the waveform if the desired shift is not an integral number of clock cycles. This will reduce the sidelobe levels in the array response. The array processor will also be used to correct for amplitude errors in the response of a particular array element. The processed signals will be sent to the S/200 minicomputer for storage on the disk memory and to be displayed on the color display. The raw waveforms can also be sent to the S/200 for storage on the disk memory. The display unit can be programmed in a rather general way to display the data in many different formats. For image data, we anticipate that both B and C scan displays will be useful. For scattering data, other formats will be used to convey the maximum information about the signals. (We are currently exploring various techniques for doing this but have not yet reached any conclusions.) The 240 element array was just recently received. We plan to test it out as soon as we can. The documentation received from Battelle Northwest indicates that the acceptance angle for an individual element to the 6 dB level exceeds ±30° in water. The 6 dB bandwidth is between 30% and 35% with a center frequency of 2.6 MHz.

We are developing a hybrid pulser/receiver for use with the array. We were fortunate to be able to evaluate a unit furnished to us by William Sturrock of Northrup. This unit was in a 1 cm x 1 cm x 3 mm flat pack that we deemed to be small enough for our application. We are refining the design of the circuitry to have lower power consumption, a wider bandwidth receiver, and a pulser with more reproducible characteristics. Although the design of the receiver is firm, the details of the design of the pulser to accompany the receiver are still being modified. The crux of the problem is to obtain an active element 1) that can be used to generate a sufficiently sharp shock excitation pulse to fully excite the bandpass of the transducer, 2) that will hold off 300 volts and 3) whose characteristics will be virtually identical from one unit to the next. We are currently considering high voltage transistors operated in the avalanche mode, high voltage transistors operated in the silicon controlled rectifiers.

The design of the multiplexer to be used in the system is complete. The multiplexer can be divided into three separate units each of which is a 240 to 16 multiplexer. The first of these is a

![Fig. 7 Linear array used in a pitch catch mode for obtaining scattering data.](image)

![Fig. 8 Ultrasonic array signal processing systems.](image)
digital unit that is used to select the transmit elements. The second is also a digital unit that is used to select the receivers that are to be turned on. The third is an analog unit that will connect the active receivers to the A/D converter. The technique used for multiplexing is shown schematically in Fig. 9. Although each of the numbered rectangles could correspond to a single transducer element, we have decided to have the unit switch four elements at a time to reduce the space required. Consequently each of the numbered rectangles corresponds to four transducer elements. Each of the switches shown has 15 switch positions although only 5 are explicitly shown. This implies that there are 60 distinct groups of transducers that can be selected. The switching is accomplished by initially sending a master code on the line labeled 0 that selects the same corresponding position for each of the four switches. Note that this automatically selects four contiguous groups of elements or 16 elements. If we want to select a group of 16 elements that corresponds to a shift of an integral multiple of 16 elements (4 groups) then the master code is simply advanced or retarded by n where n is the appropriate integer. If we want to shift by less than an integral multiple of 16 elements, auxiliary codes can be sent on lines A, B, and C. A one on line A will provide a shift of 4 elements. A one on lines A and B will provide a shift of 8 elements. A one on lines A, B, and C will provide a shift of 12 elements. In this way it is possible to select groups of 16 contiguous elements in groups of four at any location on the array. Note that we are not required to have more than one wire connected to each element. Furthermore we only need eight 8:1 multiplexers for each of the three separate units.

The 16 receiving elements will each be connected to an 8 bit analog to digital converter operating at a clocking rate of 19 MHz. We are using the TRW Model TDC 1007J A/D converter that was mentioned in Interim Technical Report #1. Each of the A/D converters will clock the digitized signals into a fast 1K byte random access memory that will store the signal until it is clocked out to the array processor or the S/200 minicomputer at a rate compatible with their operation. The circuitry for operating the A/D converter, the circuitry for the interface between the A/D and the RAM, and the circuitry for operating the RAM has to be designed as a unit because of the clocking speeds that are being used and because everything has to work together. To help in optimizing the design, a prototype of the digitizer and memory for a single channel was constructed. A block diagram showing the major elements of this prototype is shown in Fig. 10.

![Ultrasonic array multiplexer](image)

**Fig. 9 Ultrasonic array multiplexer.**

![Ultrasonic digitizer](image)

**Fig. 10 Ultrasonic digitizer.**

Other than the A/D converter and the memory, the important blocks are the latch between the two units, a delay circuit for determining when the memory will start loading after an external trigger is received, and a delay circuit for determining when the transmit trigger will be sent to the pulser.

The performance of the unit was evaluated using the experimental setup shown in Fig. 11. A standard 2.25 MHz transducer was connected to a Panametrics pulser whose output was connected to the digitizer. The memory of the digitizer was clocked out to a digital-to-analog converter at a 2 MHz rate. The resulting analog signal showing a quantization due to the sampling was displayed on an oscilloscope. In Fig 12, the upper trace shows the signal sent in to the digitizer while the lower trace shows the signal after being digitized, stored in memory, and reconstructed. The reconstructed signal is a good replica of the input signal with the quantization added. This circuit has been very useful for optimizing detailed design features of the digitizer such as
Timing, gain setting circuitry at the input, and grounding techniques for minimizing noise effects. A photograph of the completed unit and the D/A converter is shown at the bottom of Fig. 12.

Simulated Turbine Bore Samples

One of the objectives of the program is to be able to inspect real parts and in particular to be able to inspect the inner bore of a turbine disk. The demonstration of this capability is somewhat difficult since it seems to be virtually impossible to obtain a turbine disk with a known flaw in the bore. To get around this problem we have fabricated some simulated turbine bore samples with known flaws in them. We have done this using the diffusion bonding process that Neil Paton developed earlier in the ARPA/AFML program.

The samples are shown in Fig. 13. Each sample has a cylindrical wall which has a 3.5" radius oriented differently with regard to the diffusion bonded surfaces represented by the bond lines. Each sample contains nine defects at varying depths. These defects range over the whole gamut of defects that have been previously tried. A list of the defects is given in Table 1.

We have been very careful to document all of these flaws as illustrated in Fig. 14 for the case of a prolate ellipsoidal void. Both dimensions of the void have been measured after the cavities were machined into the titanium and a micrograph has been made of the circular cross section. The samples have all been diffusion bonded and we are preparing to machine the cylindrical surfaces into them.

Early Data

The microprocessor controller is not fully operational yet but we have been able to collect some data from one of the diffusion bonded disks containing an 800 μm spherical void. This can

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Fig. 12 Performance of single channel digitizer.

Fig. 13 Simulated turbine bore samples.
TABLE 1
List of Flaws Contained In Simulated Turbine Bore Samples

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Defect No.</th>
<th>Defect Type</th>
<th>Distance From Surface (mm)</th>
<th>Diameter (μm)</th>
<th>Height (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>88</td>
<td>1</td>
<td>Prolate Spheroidal Void</td>
<td>6.4</td>
<td>800</td>
<td>1600</td>
</tr>
<tr>
<td>88</td>
<td>2</td>
<td>Penny Shaped Crack</td>
<td>6.4</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>88</td>
<td>3</td>
<td>Oblate Spheroidal Void</td>
<td>6.4</td>
<td>800</td>
<td>300</td>
</tr>
<tr>
<td>88</td>
<td>4</td>
<td>Spherical Void</td>
<td>2.5</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>88</td>
<td>5</td>
<td>Penny Shaped Crack</td>
<td>6.4</td>
<td>1200</td>
<td>100</td>
</tr>
<tr>
<td>88</td>
<td>6</td>
<td>WC Spherical Inclusion</td>
<td>6.4</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>88</td>
<td>7</td>
<td>Simulated Fatigue Crack</td>
<td>6.4</td>
<td>1200</td>
<td>---</td>
</tr>
<tr>
<td>88</td>
<td>8</td>
<td>Simulated Fatigue Crack</td>
<td>0.4</td>
<td>1200</td>
<td>---</td>
</tr>
<tr>
<td>88</td>
<td>9</td>
<td>Al₂O₃ Spherical Inclusion</td>
<td>6.4</td>
<td>400</td>
<td>100</td>
</tr>
<tr>
<td>89</td>
<td>1</td>
<td>Al₂O₃ Spherical Inclusion</td>
<td>6.4</td>
<td>800</td>
<td>100</td>
</tr>
<tr>
<td>89</td>
<td>2</td>
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<td>6.4</td>
<td>1200</td>
<td>100</td>
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<td>800</td>
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<tr>
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<td>1200</td>
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<tr>
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<td>3</td>
<td>Spherical Void</td>
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<td>400</td>
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<tr>
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<td>Prolate Spheroidal Void</td>
<td>9.7</td>
<td>800</td>
<td>1600</td>
</tr>
<tr>
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<td>Penny Shaped Crack</td>
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<td>9.7</td>
<td>800</td>
<td>800</td>
</tr>
</tbody>
</table>

serve as an example of the approach described earlier for locating and analyzing a flaw. Initially the sample was scanned in a raster pattern with an unfocused transducer. The signals were digitized and the maximum peak height of the signal for each transducer position was stored in memory. After the scan was completed these peak heights were displayed to form an image of the disk shown in Fig. 15. There is an indication that a flaw is present in the center of the disk. Therefore a focused transducer was substituted for the unfocused one and a small region in the center of the disk was scanned in a raster pattern. The resulting image is shown in Fig 16. Since the characteristics of the focal spot of the transducer have been previously determined, it is known that the flaw is not resolved and we are only seeing the profile of the focal spot. Subsequent analysis showed that ka = 2 for this flaw and it is known that the imaging mode cannot be used for ka values less than 6. The next step was to use the flat transducer and obtain a set of scattering data from the flaw. We chose to analyze this data using the Inverse Born Approximation. The bandwidth of the data extended from 1.8 MHz to 6 MHz. The characteristic function resulting from this analysis is shown in Fig. 17. The predicted radius of the flaw is 410 μm which agrees very well with the actual radius of 400 μm. This analysis was based solely on the scattering data from a single direction. In regular practice one would combine the analysis of many different directions to also obtain an estimate of the shape and orientation of the flaw. As soon as it is feasible to do so we plan to extend our measurements to nonspherical flaws and to parts with complex geometries.

Fig. 14 Sample 88-1 800 μm x 1600 μm prolate spheroidal void.
Fig. 15 Ultrasonic image of diffusion bonded disk #48.

Fig. 16 800 μm diameter spherical void in titanium disk #48.

Fig. 17 Inverse born approximation characteristic function for nominal 800μm diameter flaw.
SUMMARY DISCUSSION
(R. Addison)

John Brinkman (Session Chairman--Rockwell, Albuquerque Development Laboratory)
We have time for a couple of questions.

Paul Holler (Inst. fur Zerstorungsfreie Prufverfahren): What type of array processor
were you using?

Bob Addison: It will be an analogic array processor. I can't give you all the details
on it, but there are people here who can. It has been ordered and we anticipate
delivery in about a month.

# #