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Abstract
This paper describes the Lawrence Livermore Laboratory (LLL) Ultrasonic Imaging Project. The project's purpose is to increase resolution and produce accurate graphic ultrasonic images. Sub projects directed at achieving these goals are: (1) mathematic modeling of elastic wave scattering for realistic defects, (2) developing signal analysis techniques to allow thorough quantitative ultrasonic field measurements, (3) design and fabrication of a high precision, versatile, computer controlled two-transducer ultrasonic test bed with on-line computerized data acquisition, analysis, and image display. Improved methods for quantitative evaluation of bond strength, cracks, and joining are required by current LLL programs. From these requirements the necessity for a two transducer test bed has become evident. The major emphasis of this paper is to describe the sophisticated new concept in ultrasonic test beds now under development.

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ULTRASONIC IMAGING PROJECT AND TEST BED

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ABSTRACT

This paper describes the Lawrence Livermore Laboratory (LLL) Ultrasonic Imaging Project. The project's purpose is to increase resolution and produce accurate graphic ultrasonic images. Sub projects directed at achieving these goals are: (1) mathematic modeling of elastic wave scattering for realistic defects, (2) developing signal analysis techniques to allow thorough quantitative ultrasonic field measurements, (3) design and fabrication of a high precision, versatile, computer controlled two-transducer ultrasonic test bed with on-line computerized data acquisition, analysis, and image display.

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INTRODUCTION

An Ultrasonic Imaging Project is in progress at Lawrence Livermore Laboratory (LLL). The purpose of the project is to increase resolution and produce accurate graphic ultrasonic images. The word "image" is used in a broad sense to include a variety of methods for displaying quantitative test results. A central feature of the project is the two-transducer ultrasonic test bed shown schematically in Fig. #1.

Our motivation comes from the need to satisfy an endless variety of LLL ultrasonic inspection requirements. The overall project goal is to make pertinent quantitative material evaluations with the highest attainable accuracy. Our requirements generally fall into four categories: First, bond strength evaluation; second, accurate surface crack depth measurement, third, definition of the size, shape and orientation of material defects, and fourth, the inspection of one of the above three categories in some complex configuration.

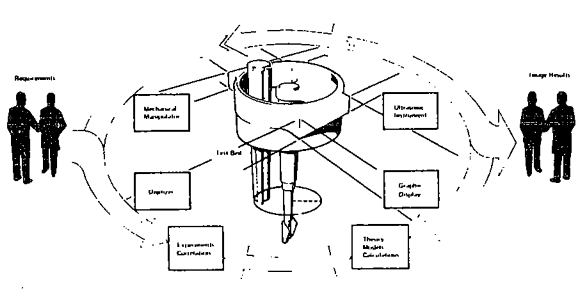


Fig. 1. Ultrasonic Imaging Project Schematic

The present state-of-the-art in ultrasonics is limited in its ability to produce quantitative measurements. To minimize these limitations, we have concentrated our efforts on improving our theoretical understanding and developing advanced test hardware. The theoretical research involves mathematical modeling of the scattered elastic fields from realistic defects and perfecting signal analysis techniques necessary for quantitative field measurements. The development effort involves upgrading existing ultrasonic test beds in terms of versatility, accuracy, online data analysis, and graphic display. The concepts for the new two-transducer ultrasonic test bed now under development have evolved out of practical experiences of the past 15 years. These experiences include ultra-precision machine tool design, ultrasonic instrument design, computer control of manipulators and data acquisition, and study of a wide range of theoretical approaches to the imaging problem. The versatility and precision of this test bed are absolutely necessary to realize the full potential of ultrasonics.

LLL PROGRAM REQUIREMENTS

There is a wide variety of ultrasonic tests which we are asked to do. They differ primarily in the geometry of the objects to be inspected. In our Lab, as in many others, the trend towards more efficient designs has made quantitative nondestructive testing extremely important. More complex designs, high strength requirements, composite materials, and a number of new joining techniques have made dramatic changes in ultrasonics, particularly with regard to the required resolution. In general, the test requirements can be divided into four categories which are discussed in the following section.

Bond Strength Evaluation Problems - In bond strength evaluation our task is to image the size and distribution of "island of unbond" and correlate the results with reduced bond strength. There are three types of evaluations of immediate interest. The first and simplest geometry is the plain bonded surface. Examples are diffusion bonding and plating where the bond interface position is well defined. The second, and more complicated, is the multiple plain bond interface. An example is the bonding of two dissimilar materials with a thin plating of a third material between them. The third category, which includes a braze, is referred to as a "graded interface". These interfaces are more complicated because the lack of knowledge of exact depth of unbond defects within the bond zone, the variation of material constituents after solidification, and the uncertainty of the reflectivity of a normal braze.

<u>Surface Crack Depth Measurements</u> - Cracks which terminate at a free surface are of great concern. Our task is to describe the crack accurately. Fracture mechanics concepts can then be used to calculate the serviceability of a structure given the dimensions of the crack. An example is the "crack" that is the result of incomplete penetration of a butt weld. Since the position and orientation of such a crack is known, our objective is simply to measure its depth. The complications involve variations in material properties in the weld zone and adequate resolution when the crack critical dimension is on the order of a wavelength.

<u>Material Defect Evaluation</u> - Quantitative measurement of the size, shape, and orientation of material defects such as cracks, voids, and inclusions is an extremely broad category. It is an area where significant advancements have recently been made, particularly in mathematical modeling of the scattering of idealized defects such as ellipsoidal voids and penny shaped cracks. We intend to put a sizable effort into both the theory and experimental verification of the mathematical models predicted by the theory.

<u>Inspection of Complex Configurations</u> - LLL designers are extremely clever at producing objects that are <u>almost</u> impossible to inspect. A great deal of our effort involves fixturing to handle complex configurations or items which are one of a kind. The greatest difficulty occurs when it is necessary to manipulate two transducers independently to perform the inspection. A simple example is a small tube brazed into a cylinder with the tube axis not normal to the cylinder wall.

LIMITATIONS

The limitations of ultrasonics are easily stated. We need to increase resolution and produce intuitive images, or displays. The simplest way to increase resolution is to increase frequency as is done with an acoustic microscope. There are problems in inspecting industrial products which limit the frequency we can use, but in general our trend will be toward higher frequency. We need to improve the precision of our systems in an overall sense. We must design mechanical and electronic systems with a primary objective of accuracy and "built in" methods of maintaining and checking the accuracy over the life of the system. In other words, a fundamental limitation is the lack of imaging systems which can be calibrated.

There are two theoretical limitations which we are working on. First, we don't know what the fields "look like" that are being scattered by the various material anomalies we seek to evaluate. The mathematical models which presently exist describe only the simplest geometries, and these rarely appear in practice. Second, signal analysis techniques are inadequate. Improvements in range resolution and spectral analysis are necessary to perform the complex correlation between ultrasonic data and physical requirements of the test object.

SOLUTION ACTION

Looking at the requirements stated in a previous section we have recognized some fundamental limitations in our system. Our approach to correct these limitations is two phased. First, research aimed at mathematical modeling of the scattering process and development of improved signal analysis methods are in progress. Second, we have a continuous development project intended to upgrade existing test bed hardware, control technique, and data acquisition/analysis methods.

<u>Research</u> - We presently have a two man effort in the area of theoretical work. Specifically, we are interested in solutions or approaches which can be applied to practical problems. We have reviewed the literature on solutions to elastic wave equations. In general we are interested in the approximate theories. Two examples are the diffracted ray theory and the series of integral equation solutions which started with the Born approximation and have evolved to the extended quasistatic approximation.

We are perfecting the signal analysis techniques which we use for time and frequency domain analysis. Our major effort at this point is improvement in range resolution. Recent experiments have shown (Fig. 2) that we have the capability of resolving two pulses which are separated in time by 35 nanoseconds. Estimates of the relative amplitudes were also calculated.

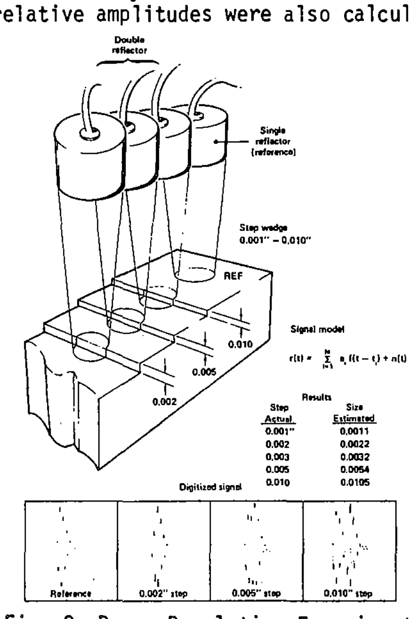


Fig. 2 Range Resolution Experiment

<u>Development</u> - A five man development effort is directed toward design and fabrication of the two transducer ultrasonic test bed. The features of this test bed represent the highest precision,

versatility, and reliability. The central features are shown in Fig. 3. The mechanical motions are completely computer controlled. Data acquisition, signal processing, graphic displays, and ultrasonic feedback control are also computerized. The base of the test bed is a five meter square granite block one meter thick. Both a horizontal and vertical spindle are included for rotating symmetric test objects. The sturdy overhead ways provide rectilinear motion of both transducers simultaneously in a controlled scan mode or for positioning the central cylindrical section relative to the test object. The central section provides two cylindrical motions (Figs. 4 and 6) which allows the two transducers to be independently positioned to any point within a 0.40 meter diameter cylinder 0.30 meter high. The accuracy goal is to position the transducer at a point in the space of the cylinder within a sphere of uncertainty 125 microns in diameter with reproducibility of position within 10 microns. There are two orthogonal angular motions which allow the transducer to "look at", or be directed at, any point in the cylinder completely independent of the position motions. This is a new concept for positioning the transducers relative to the test object. (See Fig. 5)

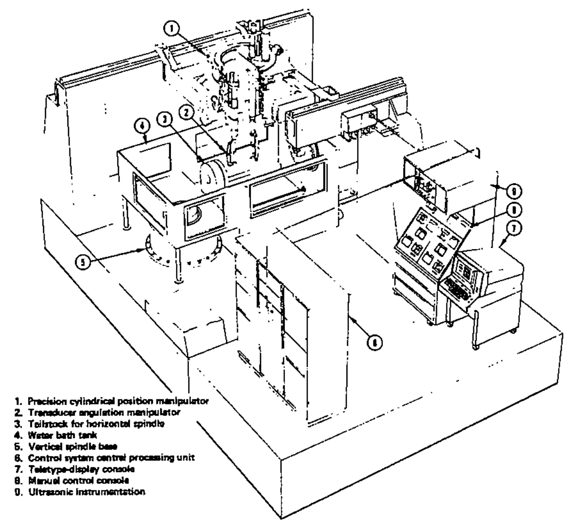


Fig. 3 Two Transducer Ultrasonic Test Bed

The principal of the concept is to maintain a fixed point in space at which the transducer is "looking" while changes in transducer angle relative to that point are made. The simplifying features which make this possible are: First the motions used to position the transducers in space are completely independent of the motions used to control the angular direction of the transducer and second the angular manipulators rotate about a fixed point in space. This greatly improves accuracy and simplifies the motions necessary to "map the field". I consider mapping the field at the water-to-part interface the most common mode of operation. For example, suppose we were to inspect a weld in a sphere. We would mount the sphere on the horizontal spindle with the weld in the vertical plane. The transmitting transducer would be positioned and the angle set for a refracted shear wave incident on the weld zone. The scattered field at the outside surface of the sphere would be recorded by manipulating the position of the receiving transducer over the necessary surface area while constantly changing its angular directions at each point to be normal to the wave fronts of the scattered field.

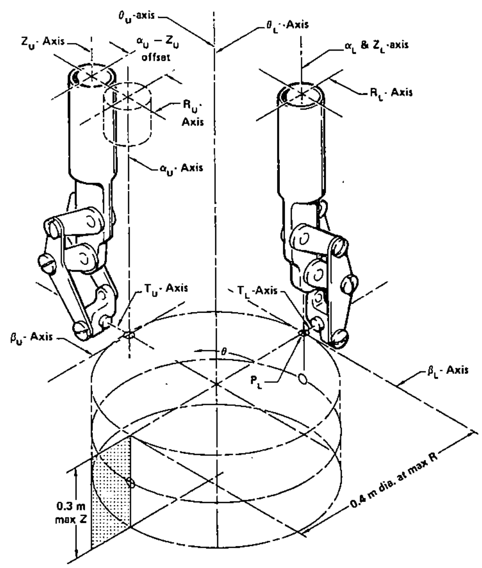


Fig. 4 Cylindrical Manipulation Schematic

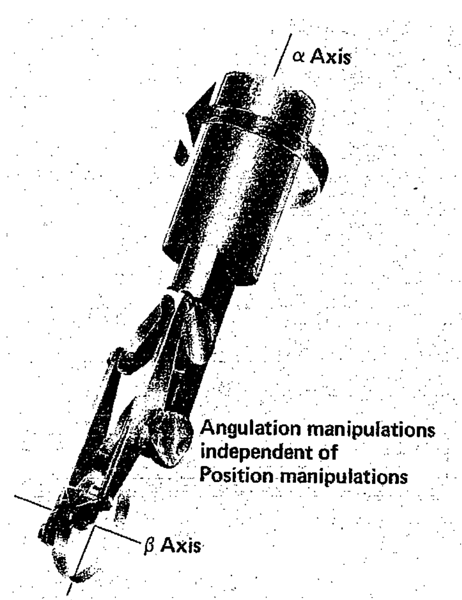
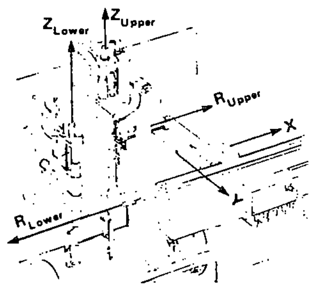


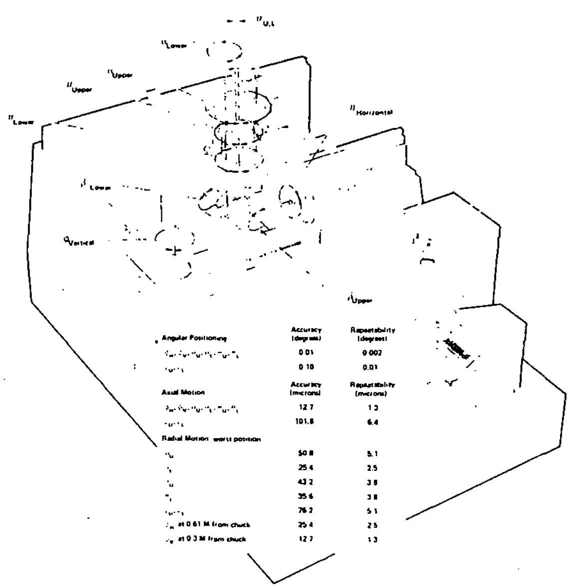
Fig. 5 Transducer Angulation Manipulator

There are fourteen precision axes of motion on this test bed. Figures 6a, and 6b, show the position accuracy and reproducibility for all axes, the straightness of the linear slideway axes and the axial and radial runout of the rotating axes. The computer control system, Fig. 7, will provide various control modes, including a "learning" mode which allows the operator to establish a routine for moving the transducer over an object. This is especially important when the test object is not a simple shape or accurate dimensions are not available.



Position	Accuracy (microns)	Repeatability (microns)
X Axis		
1.8 M travel	127.0	10.2
0.15 M travel	25.4	
Y Axis		
0.5 M travel	76.2	10.2
0.15 M travel	25.4	
R_U, R_L Axis		
0.2 M travel	50.8	10.2
Z_U, Z_L Axis		
0.3 M travel	50.8	10.2
Straightness		
X Axis	177.8	12.7
Y Axis	127.0	12.7
R_U, R_L Axis	50.8	10.2
Z_U, Z_L Axis	50.8	10.2

Fig. 6a Linear Axes Accuracy



Angular Positioning	Accuracy (degrees)	Repeatability (degrees)
[illegible]	0.01	0.002
[illegible]	0.10	0.01
Axial Motion	**Accuracy (microns)**	**Repeatability (microns)**
[illegible]	12.7	1.3
[illegible]	101.6	6.4
Radial Motion worst position		
[illegible]	50.8	5.1
[illegible]	25.4	2.5
[illegible]	43.2	3.8
[illegible]	35.6	3.8
[illegible]	76.2	5.1
[illegible] at 0.61 M from chuck	25.4	2.5
[illegible] at 0.3 M from chuck	12.7	1.3

Fig. 6b Angular Axes Accuracy

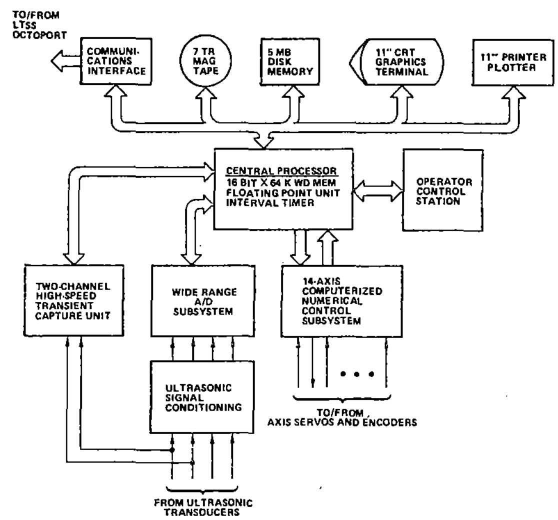


Fig. 7 Computer Control

Ultrasonic instrumentation is constantly being upgraded as new electronic innovations become available. The latest addition to our system is a high speed transient waveform digitizer. It has a 500 MHz sampling rate with six bit accuracy for a single recording cycle of 1024 data points. Improved resolution is easily attained by averaging.

The ultrasonic system was designed with calibration in mind. For example, it has a built in 25 MHz reference signal which is used to calibrate amplifiers and the peak RF amplitude to DC conversion section. We are looking for better methods of making this conversion which will increase the linear dynamic range. We periodically calibrate or at least tabulate the following system parameters:

Pulser - peak voltage, width, overshoot, repetition rate

Receiver - gain bandwidth, linearity, sensitivity/noise figure, overload recovery time for both large and small overloads

Gates - width, position accuracy (jitter)

Peak Sampling - linearity, dynamic range, effective bandwidth

UNIQUE TEST BED CAPABILITIES

The most fundamental motive for building the two transducer ultrasonic test bed is the growing necessity in routine inspection for two transducers, a transmitter and a receiver, which are accurately and independently manipulated.

The mathematical models now being generated are new approximate solutions for which no complete solutions exist. The mechanical versatility and accuracy of the two transducer ultrasonic test bed is absolutely necessary to verify the approximate solutions.

A very significant use of this test bed will be in feasibility studies where we identify, quantitatively, all the parameters necessary to design a production-line inspection fixture. The largest portion of our effort has been in the design of the fixturing. A problem we constantly face is the one of designing a test bed to do a feasibility study which later is used in the production test. There are several problems with that approach: More versatility must be designed into the system to do the feasibility study than is necessary to do the actual test. There is a problem with the time lapse necessary to build anything. The cost of adequate systems is prohibitive for a small program. When the job is complete the system goes to the production line and we are left with nothing but a technical report from which to start on the next task.

CONCLUSION

An ultrasonic imaging project is underway at Lawrence Livermore Laboratory. We are addressing the theoretical problems of scattering by realistic-defect geometries. We are perfecting the instrumentation and analytical techniques necessary for adequate ultrasonic signal analysis. We are building the sophisticated, high-precision, two-transducer ultrasonic test bed necessary to achieve the full potential of ultrasonics as a quantitative NDE tool.

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