ML TDR 64-278

DEVELOPMENT OF NONDESTRUCTIVE TESTING METHODS FOR THE EVALUATION OF THIN AND ULTRATHIN SHEET MATERIALS.

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FOREWORD

This report was prepared by the General American Transportation Corporation, MRD Division, Niles, Illinois, under USAF Contract No. AF 33(657)-11228. The contract was initiated under Project No. 7360, "The Chemistry and Physics of Materials," Task No. 736002, "Nondestructive Methods." The work was administered under the direction of the Air Force Materials Laboratory, Research and Technology Division, with Messrs. R. R. Rowand and W. L. Shelton acting as project engineers.

This report covers work conducted during the period 30 May 1963 to 1 June 1964.

ABSTRACT

This report describes activity on the subject program for the first year including a survey of literature, equipment, research efforts, and nondestructive testing needs. As a result of this survey, the second portion of the first year's activity was directed toward the development of thin sheet nondestructive test instrumentation in the field of high frequency eddy current equipment, Lamb wave ultrasonic techniques, and electrostatic testing techniques. The eddy current instrument operates at 5 Mc. with future work being planned for frequencies to 50 Mc. The Lamb wave techniques are directed toward finding material parameter variations and laminations in thin sheet. The electrostatic tests utilized thin nonconductive samples with application to ceramic coated refractories considered.

This technical documentary report has been reviewed and is approved.

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SECTION 1

INTRODUCTION

The increasing application of thin and ultra-thin sheet materials in our defense and space effort has necessitated the search for improved non-destructive testing techniques for these materials. The sample or batch testing techniques often used in the past are not adequate for many of the critical applications of the aerospace industry. This program has as its purpose the investigation of new and more effective nondestructive test methods for thin materials. This purpose is being achieved through the investigation of the basic physics of both the nondestructive test methods and the material properties, taking advantage, where possible, of previous research in this or related fields.

The program delineates the areas of need in material, flaw type, testing technique, and the applicability of presently used methods and instruments. The project covers the complete range of materials including metals, ceramics, plastics, and resin bonded fibers. It encompasses inspection techniques for properties such as hardness, tensile strength, grain size and toughness and flaws such as cracks, laminations, seams, and inclusions. The thickness range of interest extends from 0.1 mil to 250 mils.

The project goals are being achieved by a three part program consisting of:

1. Survey Effort
2. Experimental Effort
3. Refining and Correlation

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The survey effort was accomplished in the first six months of the program. The results of the survey were reported in the second quarterly report. Abstracts of literature gathered as part of this effort were collated and indexed as well as the results of surveys of test equipment manufacturers and thin sheet manufacturers and users. The conclusion drawn and the program direction that resulted from this survey phase will be briefly reviewed in this report.

The experimental effort is proceeding in the following areas: 1) High frequency thin sheet eddy current testing, 2) Thin sheet ultrasonic investigations, 3) Electrostatic testing, 4) Combined techniques.

Although the experimental results in some areas have been encouraging, the inspection equipment has not evolved to the point that flaw detection parameters can be determined. This report discusses the survey and the experimental results obtained to date.

SECTION 2

SURVEY EFFORT

During the six month study which comprised the first part of this program, extensive surveys were conducted. Substantial literature pertinent to nondestructive tests for thin sheets and materials characteristics was uncovered; 254 manufacturers of pertinent test equipment, many NDT researchers, and manufacturers and users of thin sheet materials were contacted during the survey.

A file of NDT literature and a file of test equipment data sheets has been prepared for the Air Force as a result of those surveys. In addition, an annotated bibliography and a cross-indexed listing of pertinent manufacturers were prepared, and included as appendices in the second quarterly report issued in February of this year.

As a result of the manufacturer and user survey, an insight has been gained in some of the problem areas in fabrication and use, and a knowledge obtained of the extent to which NDT techniques are currently used in thin sheet application. No instances of thin sheet NDT for physical properties have been found to date. Most manufacturers and some users test the thin sheet by performing destructive tests on samples taken from a lot, which provide sufficient quality control for the majority of applications. However, the ever increasing use of thin materials, including honeycomb and sandwich materials in aerospace applications, requires further exploitation of NDT techniques. In view of the latter, a major concern is the refractory metals common to such applications.

Typical quality control tests for properties are those based on visual examination, metallurgical tests for hardness, tensile strength, etc., and a "bend test" to detect laminations. Similar tests are also performed on finished products, for example, the vacuum test for honeycomb panels. In this test, bad brazing is indicated by the face plate bulging as a vacuum is pulled on the panel. Thin sheet welding inspection is also being performed.

Some of the problem areas determined during the survey were:

1. Lamination in tungsten and high strength steels.
2. State of anneal in titanium.
3. Surface conditions of titanium for pickling baths that affect bonding.
4. Rolled-in surface inclusions, including nonmetallic inclusion in several of the materials such as steel and titanium.
5. Surface conditions, such as rolling mill marks in all materials investigated.
6. Hardness
7. Formability - This is not in all instances directly related to hardness.
8. Pinholes - This lack of integrity has caused failures in almost all uses of thin materials. This difficulty was mentioned in cases extending from space vehicles and honeycombs, to steel tin can stock.
9. Weldability
10. Gas embrittlement - Evidence of this on materials such as columbium alloys are often visible on the surface and due to faulty control of annealing or pickling.
11. Failures in oxidation resistant coatings on thin refractory substrates.

State of anneal, strength, and contaminants are also of interest to this program and appropriate NDT methods are being studied. However, a large number of the problem areas are related to surface phenomena, as might be expected due to the high ratio of surface area to volume of sheet products. Pinholes and surface defects that do not involve material properties can, and presently are, being successfully detected by optical means. Because of this, program efforts are not being expended in that direction.

In addition, several models of commercially available NDT instruments were solicited from manufacturers for review. Although there exist no NDT equipment specifically intended for testing thin materials, the equipment in the areas of eddy currents and ultrasound were evaluated to determine the limit of their applicability to thin sheet and to determine the most fruitful areas of research.

As a consequence of these study efforts, a need was demonstrated for the development of NDT means in several areas, including ultrasonic, eddy current and electrostatic methods. Accordingly investigations have been initiated along these lines. A high frequency eddy current instrument is being constructed to investigate its applicability in the detection of material properties, flaws and inclusions, in thin materials and the detection of incipient failures or the progression of diffusion in coated refractories. Ultrasonics, centered on Lamb wave testing, is being investigated for application to the detection of material property changes, flaws and laminations. The electrostatic tests may have some application to ceramic coated refractory metals. The following sections discuss the work done in these areas to date.

SECTION 3

EXPERIMENTAL EFFORT

3.1 Thin Sheet Eddy Current Instrument

The experimental work done on high frequency eddy currents for thin sheet testing has been directed toward the design of a versatile eddy current test instrument. The highest frequency of operation for commercial instrumentation is about 256 KC. This is glaringly inadequate for thin sheet.

The frequency of the electromagnetic radiation in these schemes is important because of the relationship of frequency to the depth of eddy current penetration. The higher the frequency the less the depth of the energy penetration. This is the result of the skin effect, and is discussed and analyzed in the many references on eddy current testing. If the material is of insufficient thickness or the frequency too low, the electromagnetic waves from the probe are not sufficiently attenuated by the materials and a low sensitivity to the material parameters will result. For this reason, present instruments are limited as to the minimum thickness of material that can be measured. Consider for an example, the Magnaflux FM-100 Conductivity Meter, an instrument used extensively for nondestructive testing. For materials of 98% I.A.C.S. conductivity, the sample must be thicker than 0.080 inch while for 0.8% I.A.C.S. conductivity, the minimum thickness is 0.120 inch. A short table of frequencies and the depth of penetration for some materials and thicknesses of interest are shown in Table 1. Testing for the conductivity of materials of these thicknesses requires a higher frequency than any of the

TABLE I

EDDY CURRENT CHARACTERISTICS AT VARIOUS FREQUENCIES

	100KC	1MC	10MC	100MC
	Velocity cm./sec.			
Al., 6061-T6	2.12×10^4	6.43×10^4	2.12×10^5	6.43×10^5
Steel	2.98×10^3	8.95×10^3	2.98×10^4	8.95×10^4
Stainless	9.07×10^4	2.73×10^5	9.07×10^5	2.73×10^6
	Depth of Penetration - δ - inches			
Al., 6061-T6	0.014	0.004	0.0012	0.0004
Steel	0.0018	0.0005	0.0003	0.00014
Stainless	0.048	0.015	0.005	0.0016

After Hochschild 1/*

*References listed on page 40

available conductivity instruments. The depth of penetration given in this table is the depth at which the eddy current magnitude is 37% of that at the surface.

From this table, the frequency at which the thickness variation is a small portion of the indication from an eddy current test is seen to be above 100 Mc. for 0.0004 inch thick aluminum. The frequency must be higher if all thickness effects were eliminated. The 10 Mc. to 100 Mc. range has received little emphasis in previous eddy current work done because of the inherent limited depth of penetration. This is consistent with the earlier emphasis on commercial application. However, an eddy current detector operating in this frequency range is of definite advantage to the inspection of thin material. This instrument would be nominally independent of thickness over the thickness range above those listed in Table I for the various frequencies. Therefore, initial experimental effort was directed at developing eddy current inspection equipment for operating in this frequency range.

The tuned radio frequency pulse from the ultrasonic instrument was used as the excitation for the first tests. Using a tuned pulse, or tone burst, for probe excitation, has several advantages. First, the average power dissipated by the probe is small and thermal problems are minimized. Second, the pulse waveshape contains harmonics not in a steady state signal and information about the material tested can be contained in these frequencies. The main disadvantage in using a pulse is the wide bandwidth that must be maintained throughout the amplifiers and balancing equipment to prevent distortion of the pulsed radio frequency signal.

An early probe configuration is illustrated in Figure 1.

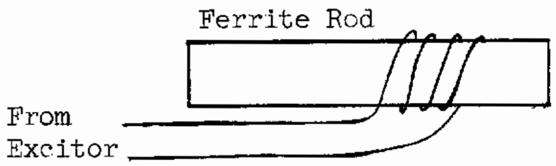


Figure 1 EDDY CURRENT PROBE

A similar configuration was used for a receiving coil. The receiving coil was used to determine the amount of penetration of the field from the transmitter and the resolution of the transmitting probe. Although this configuration is useful in some applications, the transmitter-receiver combination with the sample material between is particularly useful for these tests. An aperture or masking plate was used on the transmitting coil to improve the resolution. Since an aperture plate is a shorted turn when coupled into the primary field, a slit was cut from the aperture hole to the edge of the plate. Although the signal was decreased by the use of a smaller aperture, the resolution was not increased by a significant amount. Figure 2 shows the results of different apertures.

To increase resolution the probe core was shielded with a sleeve of ferrite to provide a return path for the flux. This probe configuration is shown in Figure 3.

Figure 3 ANNULAR PROBE CONFIGURATION

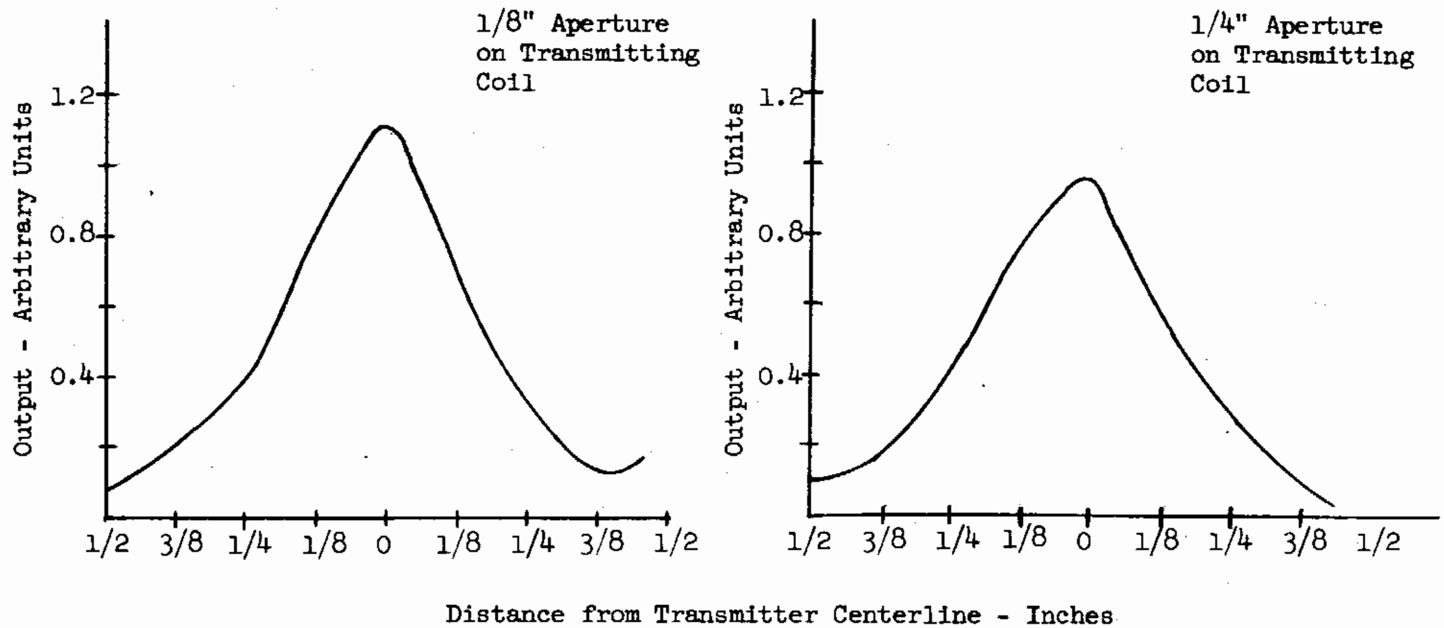


Figure 2 EFFECT OF APERTURE

This probe had a resolution equal to the outside diameter of the sleeve.

A sample was introduced between the transmitter and receiver, and the received signal plotted as a function of material thickness. As can be seen in Figure 4, a sensitive thickness meter is thus formed.

To facilitate one-sided testing and to increase resolution, a balanced gap probe was constructed. Figure 5 shows the configuration of this probe.

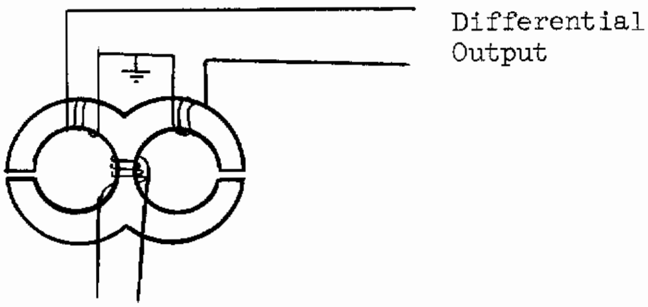


Figure 5 GAP PROBE CONFIGURATION

Although the pulsed RF excitation was tried with this configuration, the wide bandwidth requirements on both the amplitude and phase balancing components made balancing for maximum sensitivity very difficult. For this reason a continuous source was constructed. This source of primary power can operate at 5, 10, 15 or 20 Mc. Because the bandwidth of the pulse need no longer be accommodated, a radio receiver with a limited bandwidth was used. This has the advantage of reducing noise. A diagram of the instrumentation is shown in Figure 6.

The probe was mounted in a copper enclosure. The probe had sensitivity to material resistivity when energized at 5 Mc. Table 2 shows this variation.

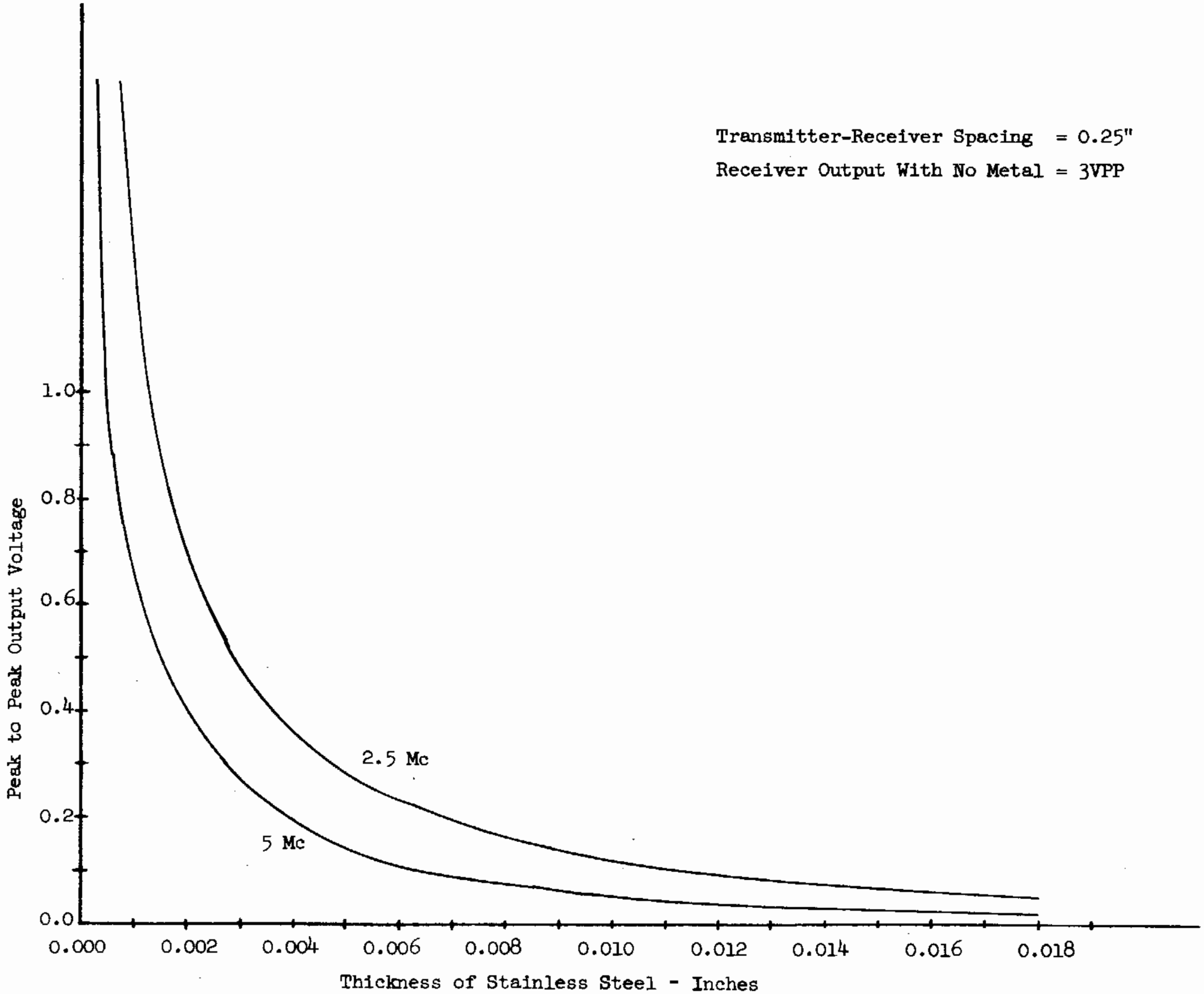
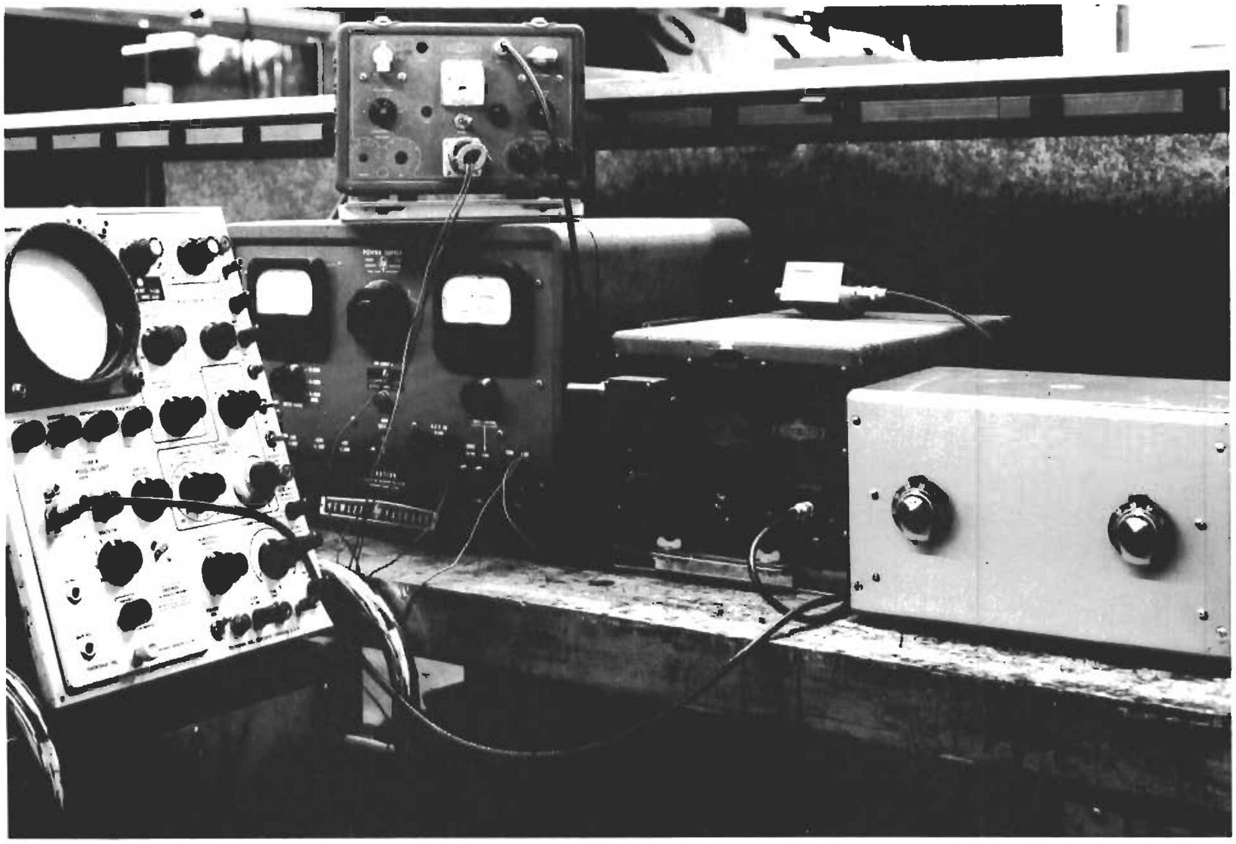


Figure 4 EDDY CURRENT PENETRATION CHARACTERISTICS



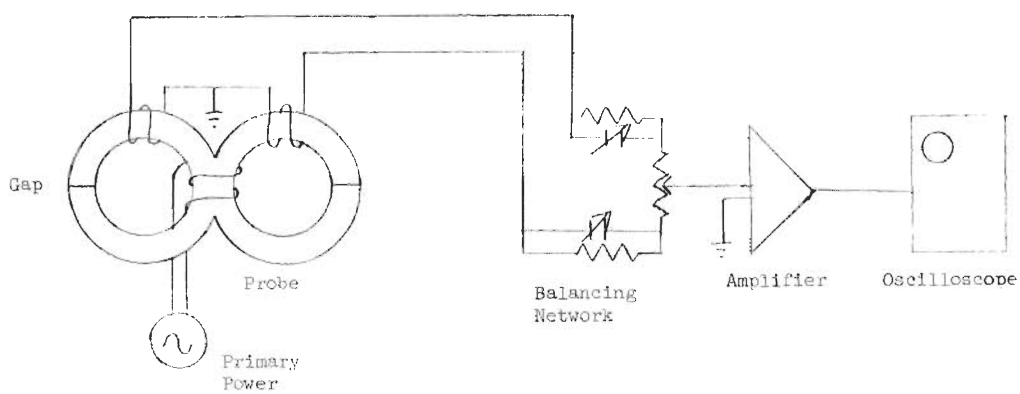


Figure 6 EDDY CURRENT INSTRUMENTATION

TABLE 2

PROBE SENSITIVITY

Material	Thickness - In.	Signal Voltage - mv.(p.-p.)
Stainless	0.010	1.0 (Null)
Brass	0.031	3.3
Aluminum	0.0625	2.8
Aluminum	0.001 to 0.006	1.8
Copper	0.0005	1.8

The probe was balanced on the stainless sample and the shift from balance observed for other materials. The probe was provided with a Faraday shield to reduce capacitance effects. A DC magnetic field unbalanced the probe as no shielding was incorporated for this effect. A drift in the null voltage due to thermal effects and some microphonics due to the mechanical construction were also observed. These difficulties are being reduced in a second model of this instrumentation.

An instrument capable of detecting resistivity variations and the lack of material integrity is expected to result from these experiments, and be ready to test early in the second year of effort on the program. The instrument will also be used for investigating the conductive, oxidation resistant coatings on refractory metals. Parameters of interest will be progression of diffusion, local areas of excess diffusion, and coating thickness.

3.2 Ultrasound

Ultrasound has been successfully employed to determine such material characteristics as elastic constants, grain size and residual stress. Measurement techniques generally utilize wave characteristics such as attenuation and propagation velocity of either pulsed or continuous wave propagation. The use of pulsed ultrasound gives rise to harmonic-rich signals, an added advantage, as the spectral content of the received pulse may bear useful data, although techniques based on this latter characteristic are not common.

The greater the extent of the wave propagation into the media, the greater the perturbation imposed by the material characteristics. Thus, one of the problems of ultrasonically determining the parameters of thin sheet is exposing the wave to a sufficient amount of material. One method of accomplishing this would be propagation of an ultrasonic wave parallel to the sheet surfaces, thus implying the use of Lamb waves at frequencies conventionally employed for contact testing (to 10Mc.) when sheets of thickness 0.010 to 0.050 inch are considered.

The sensitivity of ultrasound to material characteristics increases with frequency and as a result, VHF ultrasound also was considered. The Ultrasonic Attenuation Comparator has been used extensively for accessing material parameters with a straight-beam pulse-echo test. Pulses (to 200 Mc.) are transmitted and the attenuation rate of the echo decay pattern displayed is measured. However, its usefulness is limited, by the duration of the transmitted pulse, to specimens of minimum thickness equivalent to 0.125 inch of steel. It was conceived that the useful range of the device could be extended several-fold by the application of artificially induced damping techniques that have been successfully employed at lower frequencies 2/, but even then, sheets of 0.030 inch thickness would probably be troublesome.

The application of a high frequency surface wave was considered, but it was concluded that coupling would prove difficult, for generation by refraction with plastic wedges would give rise to excessive losses in the thin material. Additionally, water coupling would not be practical.

The use of cancellation and resonance techniques have also been considered. While these appear to have some promise, they have not yet been investigated experimentally due to such work elsewhere, and the complex equipment required.

As a result of these considerations, it was felt that Lamb wave investigations warranted prime consideration for ultrasonically determining the properties of thin sheet material parameters.

Initial experiments with Lamb waves were of an exploratory nature to determine the conditions for a useful test. Subsequently, experiments were conducted to determine the sensitivity of different Lamb wave modes to the parameters of dissimilar 6061-T6 aluminum samples. The samples were 8" x 12" sections cut from the same sheet; one section was kept in the as-supplied condition while three others were subjected to various heat treatments to reduce their hardness and tensile strength. Thus, a set of four stepped-quality samples of the same thickness was obtained. Sets were prepared from sheets of 0.0212, 0.0312 and 0.0512 inch thickness, and their characteristics and preparations were described in the second quarterly report. Table 3 identifies the samples by number and lists the average value of the characteristics for all thickness values.

TABLE 3

TEST SAMPLE CHARACTERISTICS (Average for all thickness values)

Sample Type No.	Tensile Strength (psi)	Yield Strength (psi)	Hardness DPHN
1-A	43,000	41,500	98
2-A	36,000	31,000	76
3-A	31,000	23,500	60
4-A	22,500	12,000	46

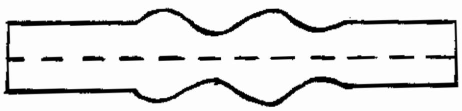
3.2.1 Lamb Wave Considerations

Considering a plane wave propagating with a velocity, c, and obliquely incident to a plate at an angle, Θ, from the surface normal, the rate of travel of the incident wave front along the plate surface is given by

$$V = \frac{c}{\sin \Theta} \qquad 1.)$$

Lamb's equations show that in a given type of plate material, and for a given value of plate thickness and test frequency, there exists numerous discrete values of V such that the plate will support propagation of a wave extending throughout its depth and travelling parallel to its surfaces. These values are denoted by V_p, and are termed the phase velocity characteristic of the particular mode excited. Alternatively, only at discrete values of Θ will a Lamb wave be excited.

In a given material, the values of V_p are dependent upon the product of test frequency and plate thickness, fD, and are related by two transcendental equations. One equation is used to describe material particle motion in elliptical orbits which produce a symmetrical distortion of the plate about its medial plane. Modes which produce this type of plate vibration are termed symmetric modes. The second equation is satisfied by the asymmetric modes which describe elliptical particle motions which result in the motions of the surfaces being out of phase with respect to the medial plane of the plate. Figure 7 illustrates the deformation produced by these two types of waves.



a.) Symmetric

b.) Asymmetric

Figure 7 LAMB WAVE MOTION

The group of wavelets that comprises the pulse propagate along the plate giving rise to a travelling zone of deformation, the intensity of which decreases with the travel distance. The attenuation increases with the test frequency, hence, it was desired to use as high a test frequency as practical. In addition, the attenuation is dependent upon the ratio of material particle displacement in the direction normal to the plate surface to that in the direction of propagation (horizontal). This latter characteristic proves of importance in immersion testing, which was chosen for preliminary experimentation as it permits uniform coupling and facilitates transducer positioning and determination of the angle of incidence.

If the plate is in contact with a surrounding medium as encountered in immersion testing, the Lamb wave radiates into the medium at the same angle required for Lamb wave excitation, this angle being given by

$$\sin \theta_{\ell} = \frac{c}{V_p} \qquad 2.)$$

Thus, in addition to being attenuated by the characteristics of the material, the wave dissipates energy by refraction into the surrounding medium.

A third source of attenuation is the loading of the plate imposed by its intimate contact with the surrounding media, which serves to restrict the motion of the plate normal to its surface. These sources of wave attenuation add to that due to the material, but it is known that modes with a phase velocity equal to the velocity of the longitudinal wave induce only horizontal motion of the surfaces. Because of this, testing under these conditions should reduce the loading effect due to plate submergence in water, and attenuation differences would be attributable to material characteristics. Thus, it was desired that preliminary experimentation be directed towards determining test conditions which would be relatively insensitive to water loading, and it was expected that this would occur at an incident angle corresponding to a phase velocity near that of the longitudinal wave velocity.

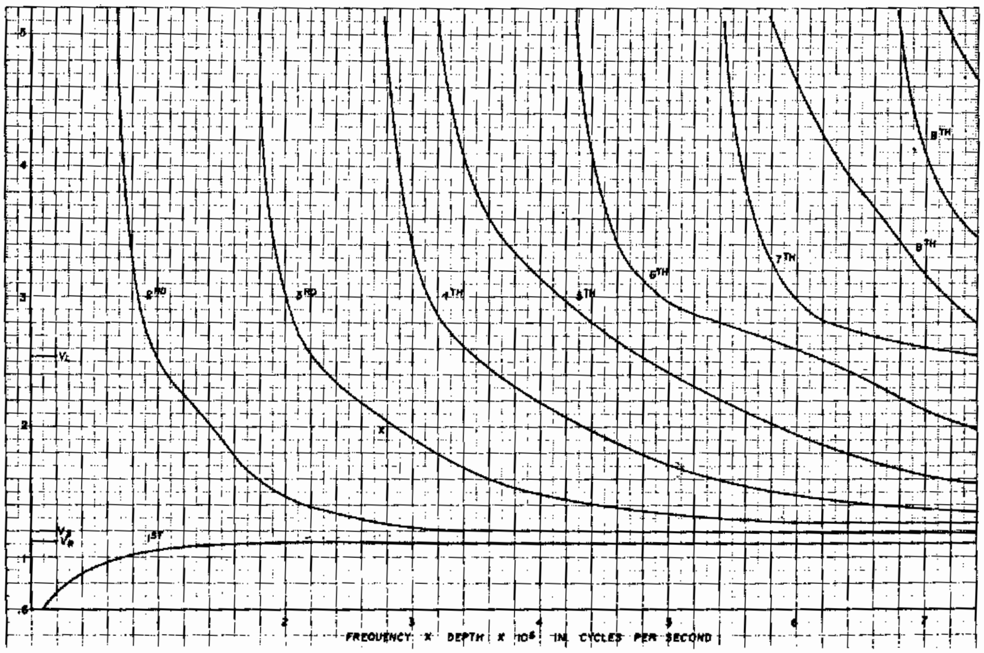
Firestone and Ling [3/] were the first to recognize the relationship between phase velocity and frequency-thickness product, and Worlton [4/] has plotted computer solutions to Lamb's equations for both the symmetrical and asymmetrical modes for numerous materials. Reproductions of the plots for aluminum are contained in Figure 8, but to facilitate experimentation, these plots were converted to plots of the incident angle (using a longitudinal wave velocity for water of 1.49×10^5 cm./sec. or 0.584×10^5 in./sec.) required to excite Lamb waves as a function of frequency - thickness product by using the relationship

$$\theta_\ell = \arcsin \frac{.584 \times 10^5}{V_p} \qquad 3.)$$

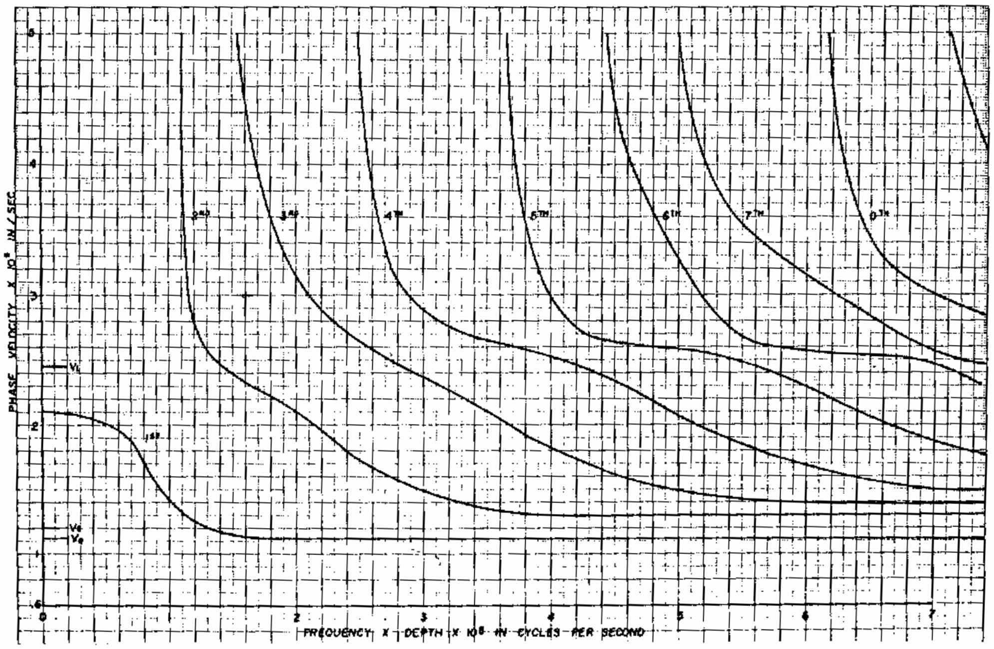
These plots are contained in Figure 9 and cover the range of fD products to 5×10^5 inch-cycles/sec., as 10 Mc. was the highest intended test frequency and 0.05 inches was the thickness of the thickest stepped-quality sample.

These sets of curves illustrate the relationship between V_p and fD, but V_p also is dependent upon the longitudinal and shear wave velocities of the material. These velocities are dependent upon the elastic properties of the material, and variations in these properties are reflected as changes in the positions of the curves of Figures 8 and 9. Indeed, the phase velocity relationship has been normalized with respect to the shear wave velocity by Grisby and Tajchman [5/] for a specific value of Poisson's ratio.

Differences in material properties could be detected experimentally by observing the incident angles at which Lamb wave modes were excited at a constant value of fD, or by holding the incidence angle constant and observing the frequency at which Lamb wave modes were excited. In the latter case, it is possible to use continuous wave transmission and measure the "frequency response" of a sheet behaving as an elastic wave filter.



a. Asymmetric



b. Symmetric

After Worlton[4]

Figure 8 LAMB WAVE MODES IN ALUMINUM

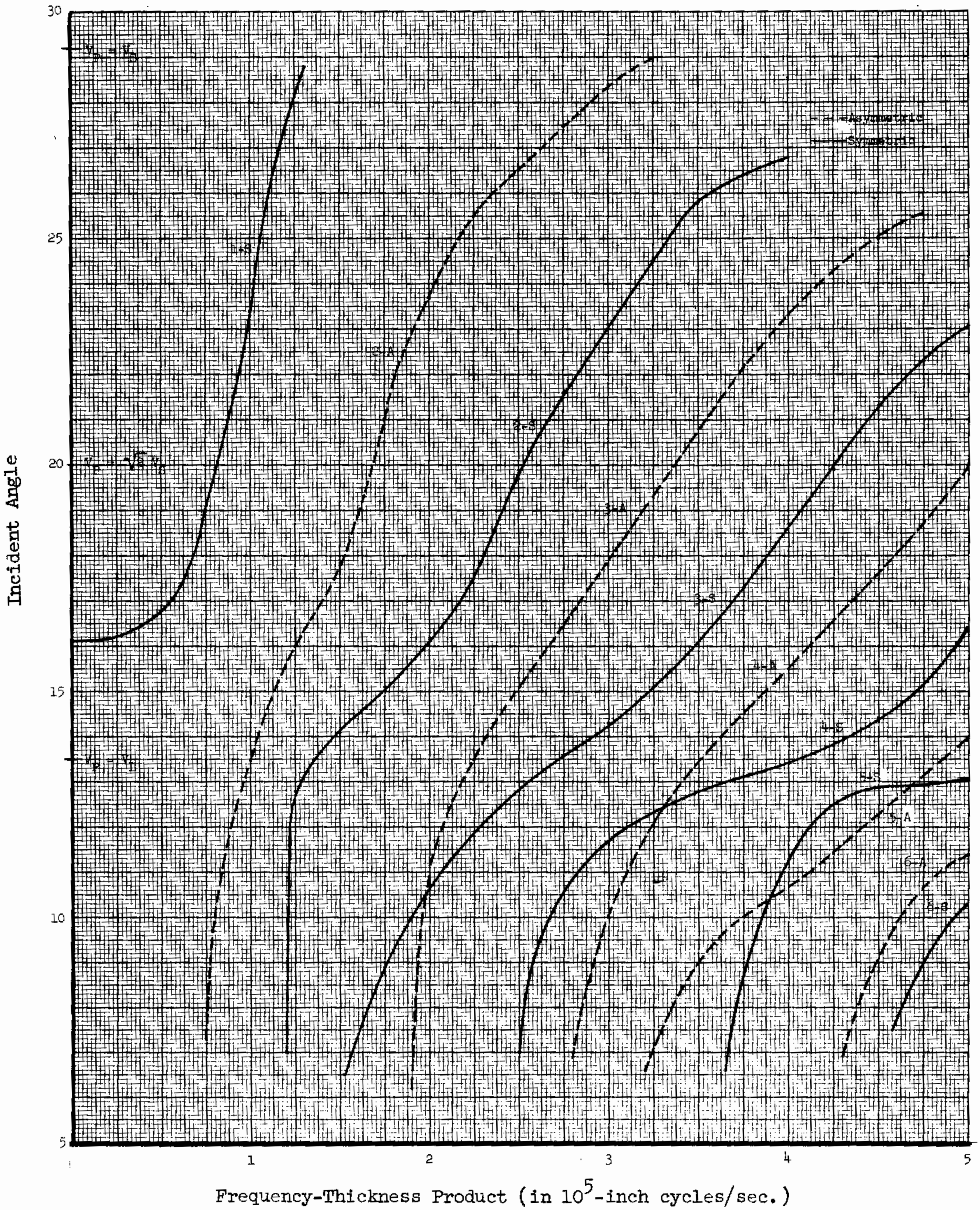


Figure 9 INCIDENT ANGLES (IN WATER) FOR LAMB WAVE GENERATION

3.2.2 Experimental Investigations

A test fixture designed for Lamb wave through transmission experiments consisted of two search tube manipulators separately supported on guide rails to permit variation in the separation distance between transducers. A self-locking setting of the incident angle was effected by a worm wheel drive, the 90:1 reduction permitting 0.1° resolution. The manipulators can be interlocked to permit manual scanning with the through transmission test. A second degree of scanning motion was permitted by a second set of guide rails. The transducers were 10 Mc. lithium sulphate types, of size 1/4" and 3/4". A photograph of the mechanism, which straddles a 30 gallon tank, is contained in Figure 10.

Tests with Stepped-Quality Samples

In general, the tests involved a laboratory procedure including waveform study as well as amplitude measurements as a function of transducer separation and incident angle. In addition, it was necessary to measure the propagation time of various observed echoes to determine their propagation velocity and substantiate the presence of the mode sought. Deviations from anticipated results were observed and necessitated checks of frequency and incident angle.

Lamb wave modes, using pulsed ultrasound, were readily generated and detected using a UW Reflectoscope, with a transducer separation distance of about 2-1/2" but the identification of different modes proved difficult at times as they may be separated by as little as one degree and the beam had some dispersion. A typical signal pattern is depicted in the upper trace of Figure 11a, the lower trace being a presentation of the received echo on a

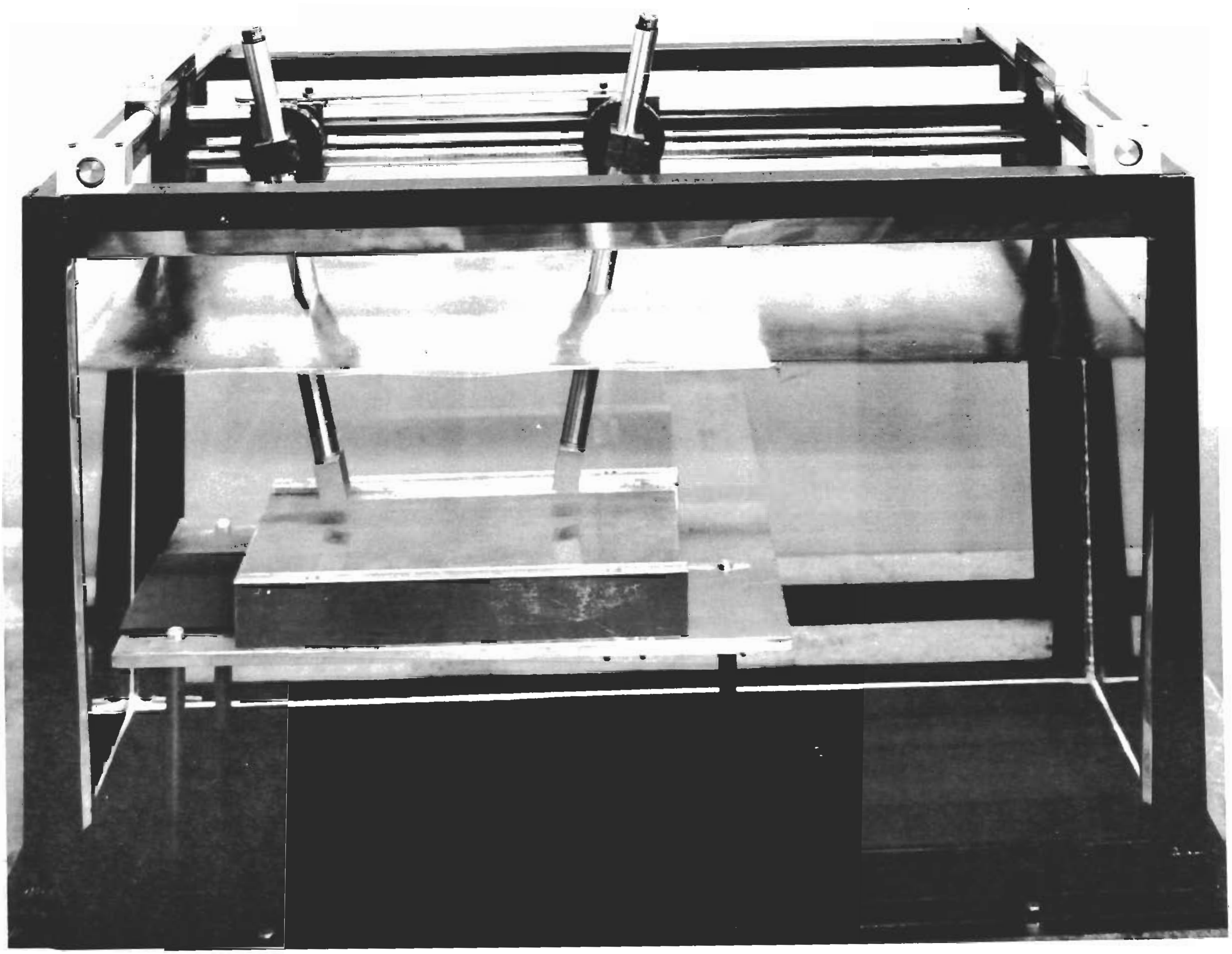
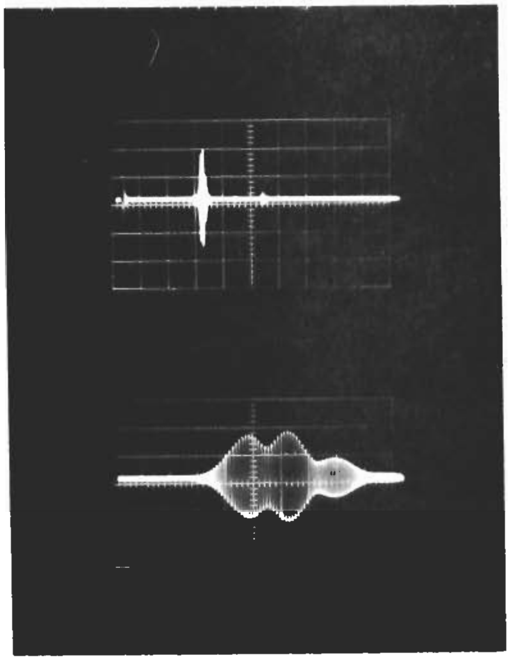
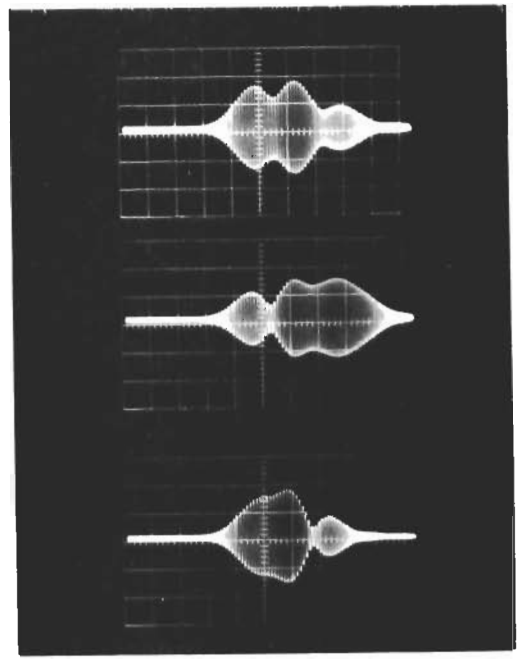


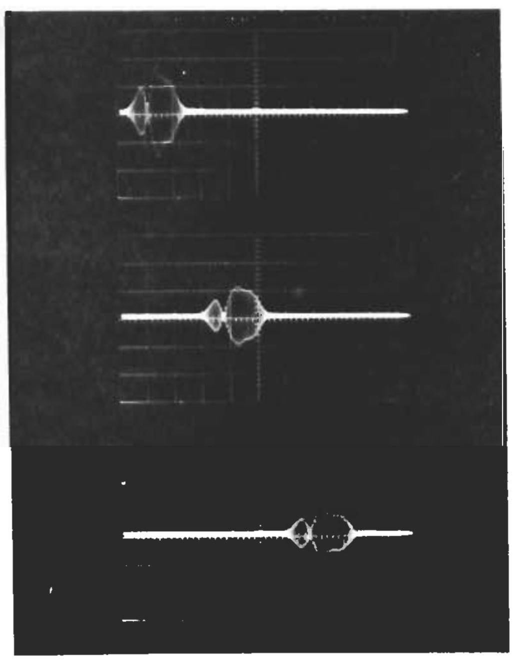
Figure 10. [illegible] TEST SETUP



a) Typical signal pattern



c) Effect of tuning



2-1/2"

3-1/2"

4-1/2"

b) Effect of travel distance

Figure 11 LAMB WAVE INDICATIONS ON THE UW shorter time basis. Several echoes appear to overlap each other in the lower trace.

The traces of Figure 11b show the effect of changing the separation distance, the pulse apparently dispersing (lasting for a greater time duration). However, it was observed (see traces of Figure 11c) that by tuning the network on the UW used to match the receiving transducer to the tuned amplifier, the shape of the echo pattern could be largely altered. This suggested that the groups of echoes being detected by the receiving transducer were of different frequencies and it was decided to use an untuned wide-band receiver arrangement to resolve this. The resulting instrumentation setup is illustrated in Figure 12.

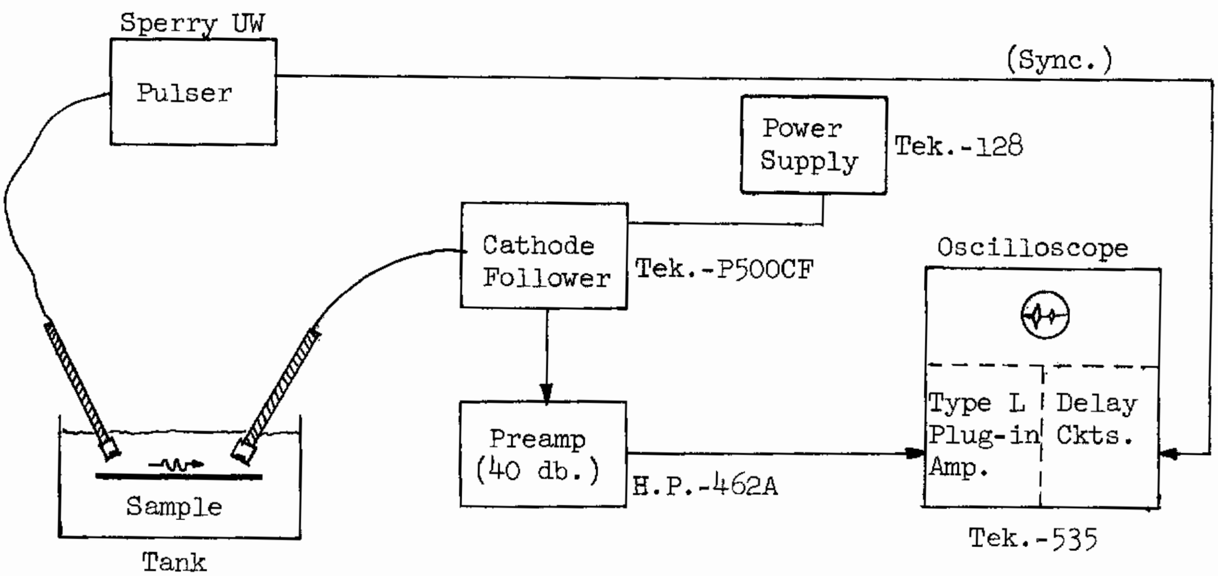
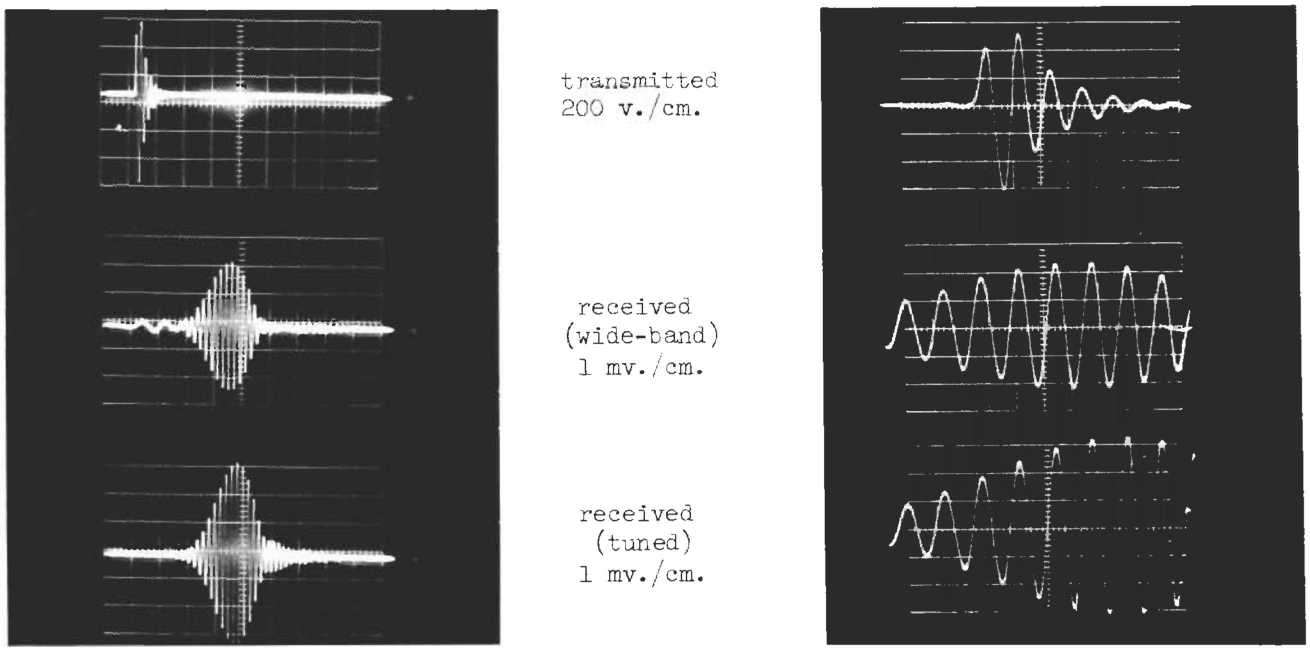


Figure 12 TEST INSTRUMENTATION

The traces of Figure 13 are signal indications observed with the 0.02" sample at an incident angle of 15.3°. The voltage on the transmitting transducer is shown in the upper traces while the receiving transducer waveforms are shown on the middle and lower traces. In the lower trace of Figure 13a the match network on the UW was interposed between the transducer and the cathode follower, and was observed to filter out the low frequency (about 1 Mc.) component visible in the middle trace, and enhance the amplitude and increase the width of the pulse at the transmitter frequency. The traces in Figure 13b at 0.1 us./cm. show that reception occurs at a frequency of about 7.75 Mc. while transmission is at a frequency of about 8.3 Mhz. These lower frequencies and apparent frequency shift are believed to be transducer anomalies.

With the wide-band setup, it was observed that several echoes, each of a different frequency, could be detected simultaneously. As the separation of the transducers was varied, these various echoes travelled at different rates and interacted to make resolution difficult. For example, consider the oscillograms of Figure 14a taken of signal indications obtained from a 0.05 inch sample at an incident angle of 14.4°.

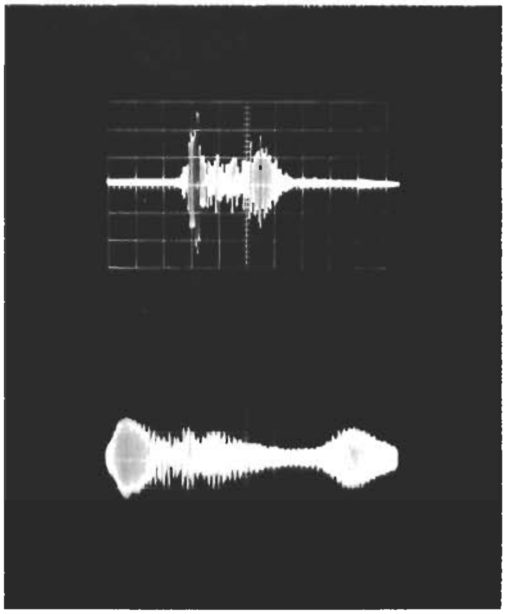
The transducers were separated about 2" for the upper trace, about 6" for the lower trace. The wide-band presentation makes it more difficult to resolve echoes discretely, but essentially two are present; in the upper trace, the first lies between the 3 cm. and 4 cm. grid lines and the second lies between the 5 cm. and 6 cm. grid lines. Both of these echoes are seen to disperse with increased travel distance, and in addition, it appears that they have different propagation velocities as they are separated about 2 cm. or 4 μs. in the upper trace, but are separated about 8 cm. or 16 μs. in the lower trace. The propagation velocity difference was then computed to be



a.) 0.5 μs./cm.

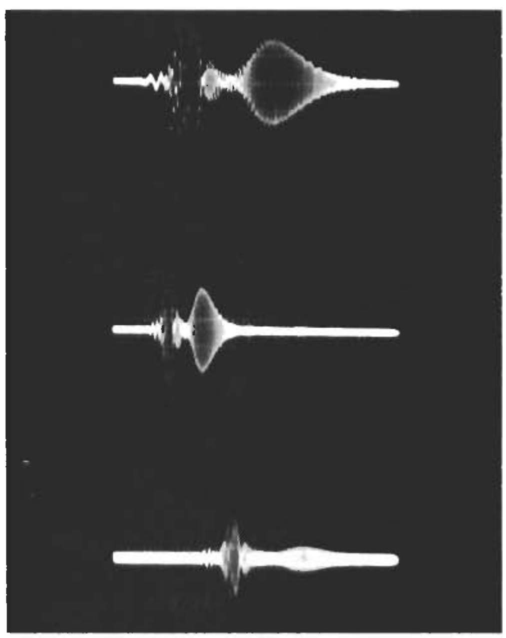
b.) 0.1 μs./cm.

Figure 13 SIGNAL WAVEFORMS



2 μs./cm.

a.) 0.0512" Sample



2 μs./cm.

5 μs./cm.

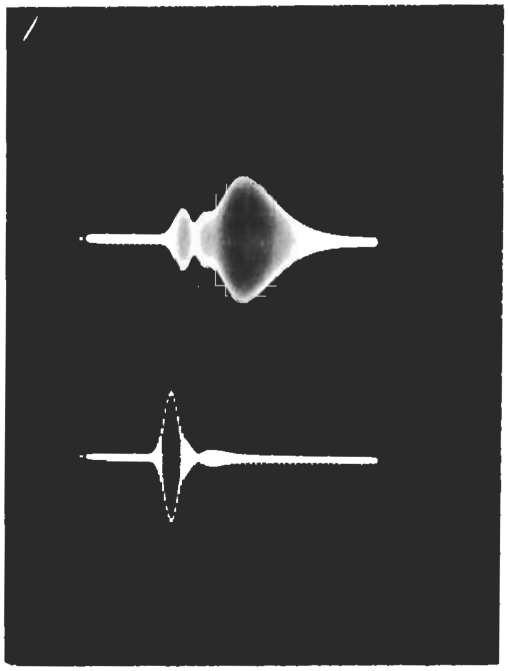
b.) 0.0312" Sample

Figure 14 WIDE-BAND INDICATIONS

about 1.0 x 10^5 in./sec. and lead to the conclusion that both the 4S and 3A modes were simultaneously being generated.

The oscillograms of Figure 14b were taken under the same conditions but with a 0.032" sample substituted for the 0.05" sample. The upper trace is displayed at 2 μs./cm. to better display the various frequencies observed; the lower two traces are displayed at 5 μs./cm. to illustrate the effect of pulse separation with a 2" increase in transducer separation distance. The oscillograms of Figure 15 show the effect of a 1.8° angular change during examination of a 0.02 inch sample. The echo observed at 15.3° incidence is identifiable from Figure 9, for a fD value of 1.7 x 10^5 inch-cycles/sec., as the 2S mode. However, as the angle was decreased to 13.5°, the echo amplitude decreased but the amplitude of a second echo increased to a magnitude several times that of the 2S mode. This echo is observed in the upper trace and is somewhat unidentifiable for at the fD product of 1.7 x 10^5 inch-cycles/sec. the next mode to be observed would be the 3S mode at an angle of 8.7°; a large deviation.

The preliminary experimentation with pulsed ultrasound gave rise to many observations worthy of pursuit, but was primarily intended to determine suitable conditions for performing attenuation measurements. It was found, as expected, that low attenuation was observed at angles near 14°, corresponding to a phase velocity equal to the velocity of a longitudinal wave. Propagation distances of 8" were obtainable, the signal to noise ratio being about 2:1 at that length of pulse travel. Additionally, low attenuation was observed at an angle



13.5° - 0.2 mv./cm.

15.3° - 0.5 mv./cm.

2 μs./cm.
0.0212" sample

Figure 15 EFFECT OF INCIDENT ANGLE

corresponding to a phase velocity equal to the velocity of the shear wave (about 29°). That proved surprising as this corresponds to a relatively large ratio of vertical to horizontal particle motion which accordingly should be largely affected by water loading.

The instrumentation utilized proved advantageous for attenuation measurements as it was possible to cover a 100:1 range of echo amplitudes and yet maintain measurement accuracy to 0.1 cm. of the oscilloscope measuring screen. In addition, it was possible to state the signal strength absolutely, in terms of transducer peak-to-peak output in millivolts, rather than normalize about the amplitude observed at an initial separation distance or instrument sensitivity. The noise level was observed to be about 60 μv. referred to the transducer output. Samples 1-A and 4-A were used for attenuation measurements as they differed the most in their characteristics as listed in Table 3. The test procedure consisted of plotting the signal strength at 1" intervals of separation distance until the signal and noise were of the same magnitude. Typical results are contained in the plots of Figure 16.

The results were obtained using the tuning network and a separation distance sufficiently large that surface reflections did not interfere with the Lamb wave. The attenuation in the 0.032 inch samples was not exponential as it was in the 0.05 inch samples. For the 0.05 inch plates, the attenuation coefficient was essentially the same for both samples 1-A and 4-A, this value being 7.3 db./inch. This similarity between samples of differing properties, as well as that of the 0.032 inch samples, leads to the conclusion that attenuation measurements under these conditions would not permit determination of

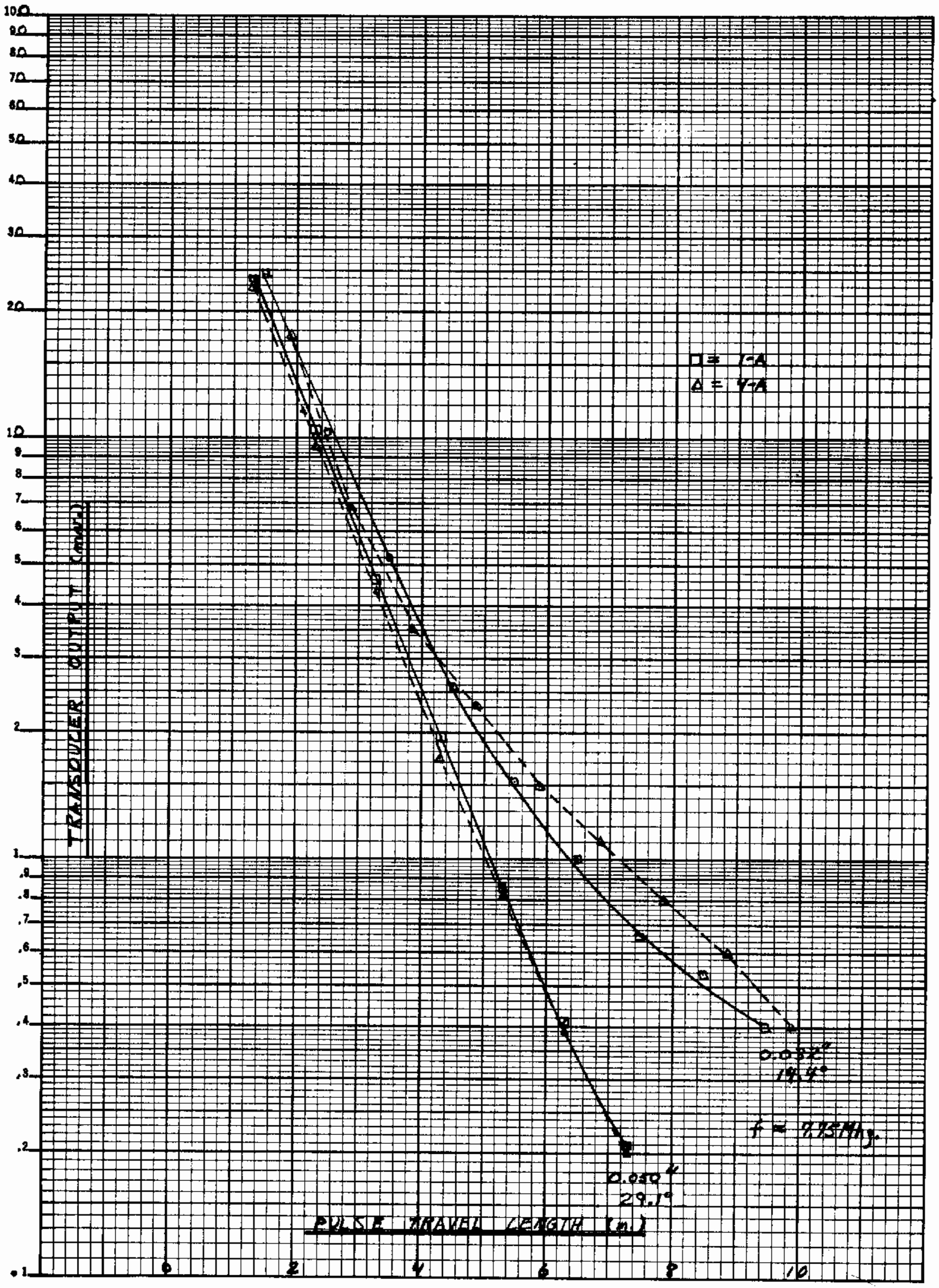


Figure 16 ATTENUATION MEASUREMENTS

material parameters. However, it is not known what portion of the attenuation is attributable to the water and that which is attributable to the material. If the water effect is high, attenuation coefficient variations due to material dissimilarity will be masked by the contribution due to the water. It is expected that the water contribution to attenuation was slight and that a contact test under similar conditions will yield similar results, however, this requires experimental verification that remains to be performed.

Continuous Wave Tests

Experimentation also was conducted with continuous wave ultrasound. The instrumentation utilized was the same as that shown in Figure 12 except that a Tektronix Type 190 constant-voltage signal generator was used to drive the transmitting transducer. A calibrated Hallicrafters SX-71 receiver connected across the preamp output was used to measure the frequency.

The low output voltage of the signal generator limited transducer separation to a maximum of about 1-1/2". At that distance, the signal-to-noise ratio was about 3 to 1 for typical indications. Better results were obtained at lower angles of incidence, a typical result being that illustrated in Figure 17 for an incident angle of 8°.

Two pronounced peaks were obtained as well as several smaller ones. By noting on Figure 9 the fD products corresponding to the intersection of the 8° line with the curves for the modes denoted in Figure 17, and dividing by the sample thickness of 0.0512 inch, the theoretical values of frequency were determined to be those illustrated by the solid lines in Figure 17. The agreement was fairly good except in the case of the 4S mode where a 0.2 Mc.

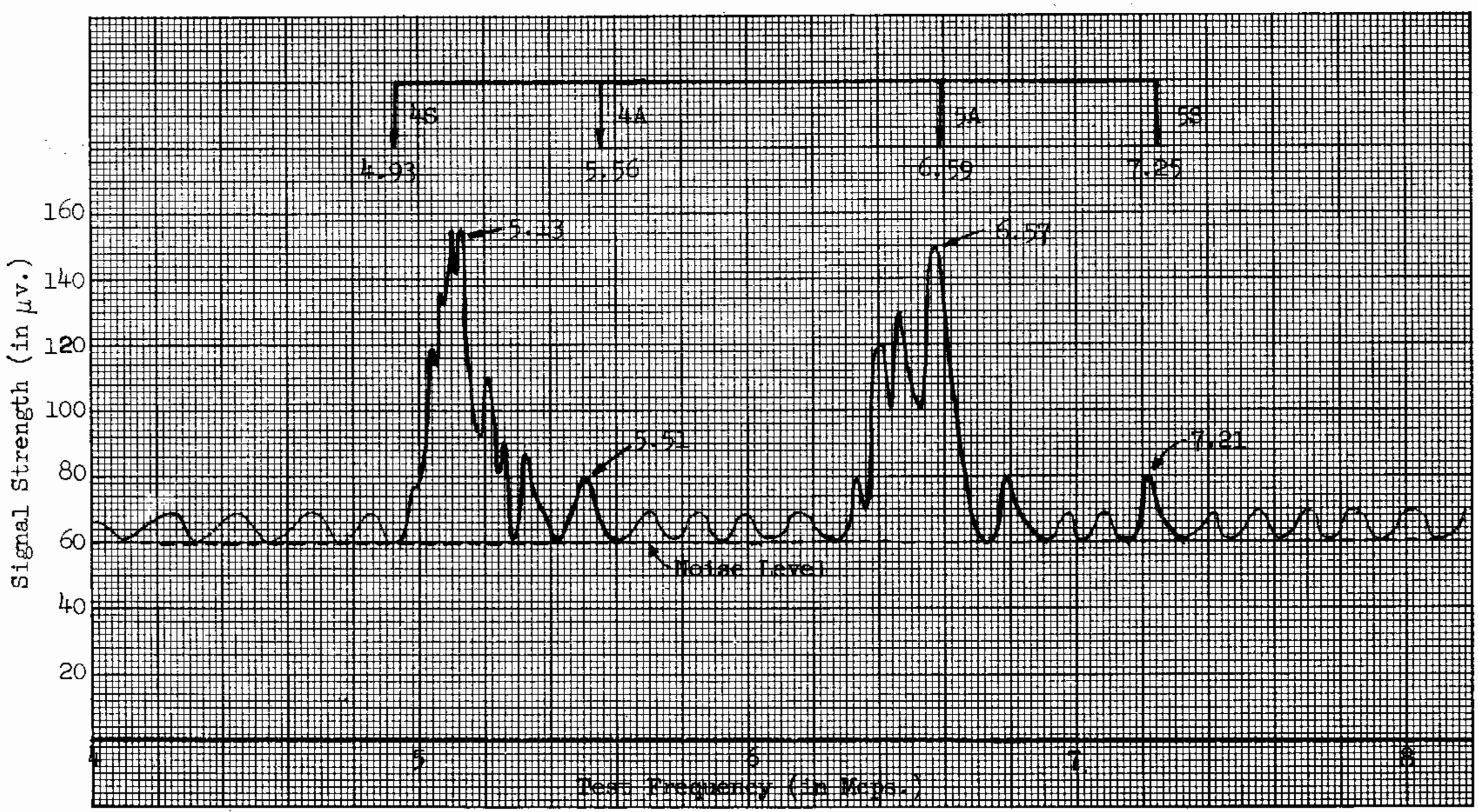


Figure 17 FREQUENCY RESPONSE - 0.0512" SAMPLE, 8° INCIDENCE

deviation is observed. Comparative measurements on different samples have not been made to this time as it was found that sufficient flexure of the sample in the support was present that a repositioning of the transducer over a different section of the sample gave rise to differing results. This was particularly true when large angles of incidence were used. Hence, refinements are being made in the test setup, and more definitive results will be contained in future reports.

Tests for Defects

Some preliminary testing also was performed to detect cracks and flaws. A 0.05 inch sample with a scribed line of about 10% depth was used as a sample. With one Lamb wave mode, the "defect" was detectable only when the plate was positioned with the notch on the same side of the plate as the transducers. With a second mode, the notch signal-indication was of the same amplitude whether the notch was face-up or face-down. In addition, it was observed that in one case, ultrasound appeared to radiate omnidirectionally from the notch into the water, while in a second case, the notch acted as a reflector and sent a Lamb wave traveling back towards the transmitting transducer.

The possibility of inspecting for lamination in thin material also was considered, using a F.M. system. As the frequency is varied, the lamination would be indicated by peaks such as those contained in Figure 17. Preparation for experimentation with this technique has begun, and progress will be discussed in future reports.

3.3 Electrostatic Testing

Magnetic NDT techniques have been used for a long time to inspect ferrous and other magnetic materials. An electrostatic test method can be thought of as the dual of magnetic test methods. This test would utilize the variation in electrostatic properties to detect flaws or material property variations.

A system was investigated wherein a charge was deposited on the surface of a nonconductor. If the charge distribution can be made to vary with the desired electrostatic properties, a convenient high resolution method of displaying the electrostatic variation exists because of the availability of finely divided charged particles used for electrostatic office copy machines. Experiments were performed to determine the characteristics of this test and its applicability to thin sheet testing.

A corona charger was constructed and charged particles procured. Figure 18 shows the general configuration of the charger.

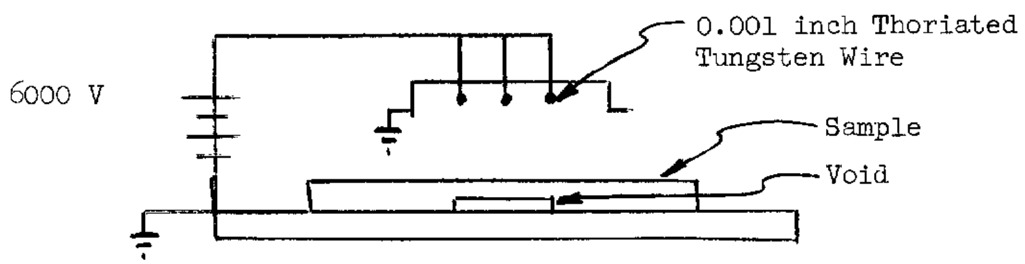


Figure 18 CHARGER CONFIGURATION

Since charge will not migrate laterally on a nonconductor, any charge variation achieved as a result of the test remains until it leaks off via the air or other leakage paths. This allowed the charged sample to be immersed and agitated in the fluid containing the charged particles while the charge existed on the surface of the sample.

A 1/8" phenolic sample with a 1" hole milled 1/16" deep in the opposite side was tested. The sample was charged by passing the corona charger over the sample. The charged particles showed that the charge was deposited evenly with no indication of the milled void. Other materials and flaw configurations were tried with substantially the same results. This result is due to the action of the corona discharge. For this type of charging the air acts as a conductor and spreads the charge evenly over the surface of the sample. Experiments utilizing a high potential between two plates with the nonconductive sample between did not show any tendency to move charged particles placed on the surface in response to the void. This can be explained because the permitivity of the phenolics tested was about 4; this is contrasted to the magnetic permeability of common steels, used for magnetic testing, being approximately 500 times as great.

A charge difference was achieved by introducing an increased conductivity on the surface of the sample. This increased the rate of charge leakage from an area. Although the experiments to date have not been able to produce a charge difference on the surface due to an internal inhomogeneity, the ability to find areas of surface conductivity change may be important.

One possible application for this effect is the inspection of nonconductive ceramic coated refractory metals. In this case, diffusion or ceramic material changes may influence surface conductivity. Future activity on electrostatic testing will be concerned with acquiring or simulating flaws in ceramic coated materials for test samples.

3.4 Other & Combined Techniques

Other techniques are being considered as part of the area of interest of this program. These techniques include thermal, special atomic particle techniques, and combined techniques such as eddy current and ultrasonics, and thermal and ultrasonics. Techniques included are those not previously used extensively in nondestructive testing or techniques not obviously applicable to thin sheet.

Some preliminary tests have been performed to detect the perturbation of a magnetic field through a conductor by an ultrasonic wave. There have been no positive results to date; however, an imporved experimental procedure will be utilized to examine this approach. The object of these experiments is to achieve a noncontacting readout for an ultrasonic test. These experiments are not looking at phonon effects for determining crystal lattice parameters but rather, a macroscopic effect.

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